Object Worlds in Work Domain Analysis: A Model of Naval Damage Control

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***Abstract*—This paper presents a work domain analysis of damage control on the Canadian Halifax Class frigate. Our analysis made use of the modeling construct of object worlds to help in defining the work domain to model and to help in understanding the results of this model compared to other work domain analyses developed in the naval domain. This paper makes a practical contribution through the presentation of a detailed example of work domain analysis in a new domain and a theoretical contribution by clarifying the use of object worlds in work domain analysis, analyzing the way in which object worlds can be understood in systems where the various stakeholders are closely coordinated and promoting object worlds as a way to control model scope.**

***Index Terms*—Abstraction hierarchy, naval damage control, object worlds, work domain analysis.**

I. Introduction

NAVAL damage control is the set of work practices related to identifying, managing, and suppressing damage sustained by a warship. For example, if a warship were to sustain a missile hit at its waterline, damage-control equipment and personnel would be deployed to assess the nature of the damage, contain and suppress any fires, and reestablish a watertight hull configuration. Although ships sustain damage relatively infrequently, the effects of damage can spread quickly, putting the ship and its crew at significant risk. To manage this risk, ships are designed with an infrastructure for damage control and maintain a crew of damage-control specialists. In cases of severe damage, crew members not already engaged in other critical tasks are seconded to damage-control duty, such as fighting fires, repairing the hull, or shoring up watertight bulkheads. Indeed, all crew members, from the cooks to the captain, train regularly for damage control.

The requirement to perform a work domain analysis of damage control arose in the context of ongoing efforts within the Canadian Navy to develop a future fleet of ships requiring smaller crews than those currently in operation but capable of fulfilling a broader set of missions (e.g., [1] and [2]). The goal is to develop ships that are "optimally" crewed by considering the whole-life cost of the ship (i.e., the total cost of the ship operations from procurement through the desired operational life to retirement) [3]–[5]. Personnel costs are one of the largest drivers of whole-life cost. Like many other navies around the world, the Canadian Navy is seeking to reduce personnel costs through appropriate up-front investment in technologies that reduce the crew required for a ship to fulfill its expected roles.

In addition to reducing the whole-life costs of their ships, the Canadian Navy must also ensure that operational capabilities are retained or enhanced as crew levels are reduced. Accordingly, Defence Research and Development Canada is currently developing techniques that will allow for simulation studies of the impact of different technology and crew complement combinations on operational capabilities.

Because the crew requirements for damage control are an important constraint on the overall crew level of a warship [3], Defence Research and Development Canada is currently focusing on ways to reduce the crew required to provide damage control [6], [7] and has also chosen damage control as the test-case for the development of techniques for simulation studies related to optimized crewing. The first step in the development of these techniques is the construction of a work domain model; that model will be used to support the design of scenarios that exercise the functions identified in representative ways and as a basis for the development of the framework for the simulation. It is hoped that the eventual simulation will allow for the early testing of the effectiveness of different levels of technology and crewing in confronting the damage-control scenarios within the work domain. Because the Halifax Class frigate has functional requirements for damage control similar to those for ships in the future fleet, damage control on the Halifax Class frigate was chosen as a relevant object of analysis.

This paper presents the results of a work domain analysis[1] that was performed to understand naval damage control. Although damage control has been the subject of previous human-factors studies [8]–[10] and work domain analysis has been applied to command and control in the naval domain [11], [12] and to the problem of integrating the concerns of damage

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[1]A work domain analysis describes the relationships between and among the physical components, functions, and purposes of an existing or envisioned system. It can serve as a functional analysis in a standard systems engineering process. Work domain analysis differs from other functional analyses in that it describes these relationships in a way that is consistent with how people conceptualize systems and manage complexity. Work domain analysis can complement other system-based approaches by introducing an operational perspective early in the design process.

control with those of antisubmarine warfare [13], work domain analysis has never been applied exclusively to naval damage control.

In this paper, we discuss how the concept of object worlds can inform and assist work domain analysis. Object worlds help in modeling work domains where multiple sets of stakeholders use the same objects but in different ways. Thus, an object world is a work domain defined with respect to a specific set of stakeholders. The use of object worlds for work domain analysis was first introduced by Rasmussen [14] and has recently been reviewed by Naikar *et al.* [15]; we hope to formalize this concept further. We also hope to show that the full consideration of the object worlds involved in a work domain is critical to developing a work domain model that is sensitive to the work concerns of a specific set of stakeholders while still respecting the basic tenet of work domain analysis that the work domain, and not the activity of actors within that domain, should be the object of analysis [16].

II. Rationale

Reducing the crew required for a ship function as critical and resource intensive as damage control requires rethinking the nature of that function from the ground up without assuming that damage control tasks of the future will be carried out in the same way as they are today. Cognitive task analysis has previously been applied to damage control with promising results [9] and was used to provide a decision-support tool that harnessed properties of expert decision making to communicate the damage-control relevant properties of an existing ship. While we appreciate the importance of experts' insights (we consulted with experts extensively on this project), decision-making practice in an existing system cannot be the sole input for the development of a new system. This design problem is better addressed by a work analysis framework that can discover the properties of a work domain independent of the way work is currently done or what Vicente [16] refers to as a formative approach to work analysis.

Work domain analysis meets these unique demands. The abstraction hierarchy,[2] which is the most common tool for conducting work domain analysis, produces a multilevel functional means–ends model of the work domain. Work domain analysis and the abstraction hierarchy are mature cognitive engineering frameworks discussed at length in the literature (e.g., [15]–[19]), and their use is well documented in both safety-critical industries (e.g., [16], [19], [20]–[23]) and military settings (e.g., [11], [15], [24]–[26]). Work domain analysis and the abstraction hierarchy are well suited to this modeling problem for six reasons.

1) Abstraction Hierarchy Models Are Actor Independent: Abstraction hierarchy models describe the functional possibilities of a work domain independent of the actors (i.e., humans or automation) chosen to work in that domain. Crewing and automation options can then be superimposed on the abstraction hierarchy during later stages of analysis. Because the abstraction hierarchy makes no assumptions about who (or what) will be performing the work, it leaves system designers with the latitude to determine the right mix of crew and automation to optimize a function and therefore reduce whole-life cost. In addition, the actor independence of the abstraction hierarchy reduces its susceptibility to bias from preconceived design solutions held by analysts.

2) Abstraction Hierarchy and Work Domain Analysis Are Well Suited to Complex Sociotechnical Systems: Damage control has all of the hallmarks of a complex sociotechnical system [16]. Most significantly, damage control encompasses a large problem space that involves significant hazard, involves a great deal of uncertainty, is prone to disturbances, and involves many complex interactions (e.g., water used to fight a fire in one compartment affects the overall stability of the ship; unexpected items in a compartment can cause a fire to spread unpredictably; sealing off a compartment could compromise functions critical to the current mission). The abstraction hierarchy and work domain analysis were explicitly developed for the analysis of these types of systems and provide a language that helps to make the many interacting levels of work in these systems understandable and relevant to follow-on human factor analyses.

3) Abstraction Hierarchy and Work Domain Analysis Are Well Suited to Domains That Are Susceptible to Unanticipated Faults: Although damage-control personnel tend to train for a set of stereotypical damage-control scenarios, real damage-control situations are always unique and have properties or interactions that might not have been anticipated by system designers. Abstraction hierarchy representations are particularly robust for this sort of domain because they go deeper than operators' strategies for solving particular problems to represent the constraints under which a system operates. An understanding of these constraints is important, particularly in the domain of damage control, where the ability to cope with unanticipated faults is the benchmark of success.

4) Abstraction Hierarchy and Work Domain Analysis Help to Identify Possibilities for Automation: In addition to representing the constraints of a work domain, an abstraction hierarchy model also represents a work domain's action possibilities or affordances [27], [28]. We anticipate that each affordance represents an atomic unit of work that could be assigned to automation or humans for action or that could be outsourced to another location (e.g., [29]). We plan to test this idea in future phases of this work.

5) Abstraction Hierarchy Readily Generalizes From Current to Future Systems: The abstraction hierarchy represents a single work domain fully at multiple levels of abstraction. Because it is likely that the functional purposes of damage control (i.e., the highest level of abstraction) are invariant across different ships or different generations of ships, it is likely that the high-level findings from an abstraction hierarchy will readily generalize to future systems. In future systems, details at the lower levels of abstraction will no doubt change (fire mains may not be in the same location and may provide different types of fire suppressants), but an abstraction hierarchy of a current system will likely provide a good structure for a future analysis. Whereas other analysis methods may also have this property,

[2]An abstraction hierarchy is the tool used to structure the content of a work domain analysis. To use an analogy: An abstraction hierarchy is to a work domain analysis as a decision matrix is to decision evaluation.

the readily generalizable high- to medium-level details of the abstraction hierarchy are easily peeled off of an analysis for later reuse because of the clean distinctions between them.

6) Abstraction Hierarchy Readily Generalizes From Current to Future Naval Doctrine: Changes in the naval doctrine related to damage control show promise to help in achieving optimized crewing [30]. The abstraction hierarchy captures the intrinsic constraints in a work domain, whereas naval doctrine is best viewed as a set of policy-based guidelines on the way the constraints of a workspace can be exercised (for example, current Canadian naval doctrine states that a fire-control boundary must be established around a fire within six min, even though it will typically take longer than six min for a fire to spread). Accordingly, the constraints of the work domain captured in an abstraction hierarchy should be robust across changes in naval doctrine.

In summary, the abstraction hierarchy provides a useful and actor-independent perspective of a complex work domain like damage control and should provide guidance that will identify opportunities for reducing crew levels[3] and make the system more robust in the face of unanticipated faults.

III. Method

A. Information Gathering

The first step in building an abstraction hierarchy model is to gather information about the domain to support the model building effort. There are typically three different sources of information about the domain—information in the literature about the domain in general, information in engineering design and operation documents about the specific domain as designed, and information obtained from interviews with operators about the specific domain in practice. We were fortunate to have a former marine systems engineering officer as a member of our analysis team, had ready access to a number of current navy staff (officers and noncommissioned members) at Canadian Forces National Defence Headquarters, consulted with damage-control training staff at the Canadian Forces Naval Engineering School, and were also able to participate in training exercises at the school. Through these resources, we gained access to a large literature on damage control and the Halifax Class frigate and tested our understanding against the insights of the operators that we interviewed. Those interviews were structured to allow us to gain perspectives from command and control (through interviews with two commanders) through damage-control management (through interviews with lieutenant commanders specializing in marine systems engineering and combat systems engineering) to damage-control operations (through interviews with an engineering chief). Finally, the analysis team spent two days interviewing the commanding officer of the Damage Control Division of the Canadian Forces Naval Engineering School, who helped us to understand the naval doctrine of damage control, the ship systems used for damage control, and the ways in which those systems are typically employed.

[3]An abstraction hierarchy can provide input to a variety of system design problems. It has been used predominantly to identify information requirements for the design of human–machine interfaces. It has also been used to identify requirements for training systems, as a means to evaluate competing designs, and to design teams, among others.

These information gathering activities produced a large volume of technical documentation, notes, discussion recordings, and transcripts that we relied on during the model construction phase.

B. Model Construction

After our planned information gathering was complete, we commenced with the construction of the abstraction hierarchy for damage control. Whereas the actual process followed was iterative, the steps we followed were roughly as outlined in the following sections.

1) Define the System Boundary: The first step in building an abstraction hierarchy is to define the boundary of the system to be analyzed. This was a challenge because it was first necessary to resolve the fact that damage control is not a work domain but is rather an object world of the more general work domain of the ship's systems. (The distinction between a work domain and an object world will be elaborated upon in Section IV.) Once this issue was resolved, the task of defining the system boundary was straightforward.

2) Identify and Arrange the Levels of Abstraction That Are Meaningful to Subject-Matter Experts: After defining the system boundary, we revisited the results of the information gathering activities to determine the levels of abstraction used by subject-matter experts in their descriptions of the work domain and their work in it. From this information, we confirmed that the standard levels of abstraction (functional purpose, abstract function, generalized function, physical function, and physical form) are relevant to damage control on the Halifax Class frigate. This provided the overall structure for the detailed model construction that followed.

3) Populate the Levels of the Hierarchy: With the foundational modeling decisions in place, we fleshed out the abstraction hierarchy model. In our analysis, the functional purposes and physical form issues were quite clear from our interviews with subject-matter experts, but it was not immediately clear how the functional purposes would work down to the affordances for damage control in each of the compartments on the ship. Initial failures to make connections at the middle levels of the hierarchy caused us to wonder if we had included some entities that did not belong in a damage-control abstraction hierarchy and/or excluded other entities that did need to be represented; this drove us back to refining the boundary of our analysis. Once our boundary properly accounted for the object world of damage control rather than the overlapping but larger work domain of ship systems, the remaining levels of the model were populated quickly.

4) Determine the Structural Means–Ends Connections Between Adjacent Levels of the Hierarchy: Damage control involves a great deal of problem solving from the low levels of abstraction that describe the compartments on the ship to the high levels of abstraction that help operators to prioritize damage-control efforts across multiple instances of damage. For this reason, the structural means–ends links were a key part of the analysis and they were considered and filled in at the same time as the nodes at each level of the abstraction hierarchy.

5) Determine the Causal Connections Between Nodes in the Same Level of the Hierarchy: Problem solving in damage control involves consideration of highly coupled and interlinked issues. For instance, pumping water on a fire can put the fire out but will also reduce the reserve buoyancy of the ship. To represent the importance of these causal links, the last high-level modeling effort was to determine the causal links at each level of the abstraction hierarchy so that the tradeoffs inherent in damage control could be captured.

C. Model Review, Refinement, and Documentation

After the initial development of the model, it was further refined through three separate reviews with subject-matter experts and project stakeholders, resulting in the final model presented in this paper. The model was also documented in detail [31].

IV. Results

In spite of our information gathering activities, several initial attempts to construct an abstraction hierarchy of damage control failed. We had a good understanding of the functional purpose level of the abstraction hierarchy from our discussions with subject-matter experts, and this was reflected in naval doctrine. From here, we could decompose the means to these purposes at the levels underneath. For example, it was clear that one of the purposes of damage control was to maintain the ship's stability, and the abstract functions underneath that purpose (i.e., reserve buoyancy, structural integrity, and positive righting arm) were clear from our information gathering activities. We also understood that the physical form level should catalogue the actual spaces of the ship with respect to their damage-control relevant properties. From here, we could abstract the ends for these forms at the levels aforementioned.

Unfortunately, we were unable to link these two in a way that captured the unique perspective of damage control. When decomposing downward from the functional purposes, it was difficult to control our scope so that we covered only items that were relevant to damage control. Abstracting upward from the physical forms was likewise difficult because it was unclear how the details of the lower levels of the model would abstract cleanly into the abstract functions and functional purposes that we thought existed at higher levels. We tried many different options (at one point, we even tried to construct an abstraction hierarchy of damage that we thought we might be able to pair with an abstraction hierarchy of the ship), but our results were less than convincing. As we grappled with this problem, we finally realized that our analysis was misguided from the beginning because we had improperly defined our object of analysis.

A. Work Domains, Stakeholders, and Object Worlds

A work domain is the set of physical and functional constraints on purposeful action in a work context. These constraints are event independent [32] and cannot be exhaustively identified through the analysis of worker tasks in that context. Thus, the only proper foundation for work domain analysis is a work domain that is defined without reference to any tasks undertaken in it. In this "pure" sense, "damage control" does not refer to a work domain. References to damage control either implicitly or explicitly define it as a set of tasks that occur either to prevent or respond to internally or externally induced damage. For example, the Ship Standing Orders for the Halifax Class frigate define damage control with respect to a set of damage-control tasks [33]. In an academic treatment, Schraagen [8, p. 227] defines damage control as "a Command and Control task, consisting of a cycle of processes." Damage control is not event independent and, therefore, for the purpose of work domain analysis, is not a work domain.

Because damage control is not a work domain, we had to determine the work domain on which the tasks of damage control impinge. To do this, we made reference to work domain analysis efforts in the area of stakeholders and object worlds [34] (for a review, see [15]). The main idea is that a work domain may have many stakeholders that each view the work domain differently. For instance, a work domain analysis of network management found that stakeholders affiliated with the network owner operated under a different view of the work domain than nonaffiliated stakeholders [35]. Thus, each stakeholder had a different view or object world of the same work domain.

Applied to our context, damage control can be viewed as one of the object worlds of the work domain of the Halifax Class frigate ship systems. Other object worlds in the same domain include, but are not limited to, the following.

1) Combat Systems Engineering: Combat systems engineering is the object world related to the maintenance of a ship's systems and infrastructure that are directly related to combat, including sensors and munitions.

2) Marine Systems Engineering: Marine systems engineering is the object world related to the maintenance of all ship systems and infrastructure that are not directly related to combat. For example, marine systems engineering is concerned with the ship's hull, engines, and power generation and distribution infrastructure.

3) Command and Control: Command and control is the object world related to the coordination of the ship, its crew, and its equipment as required within an environment that possibly includes other friendly or hostile ships and objects to meet the current mission objectives.

The relationship between these object worlds is dealt with in more detail in what follows.

B. Work Domain Versus Object World Boundaries

Once we established that damage control is an object world in the work domain of ship systems, it was necessary to consider the boundaries of our analysis. Because our analysis was of an object world within a work domain, there were two boundaries to determine—the boundary of the work domain of ship systems and the boundary of the object world of damage control.

Establishing the boundary of the work domain was simple and straightforward. The boundary of ship systems is the ship's

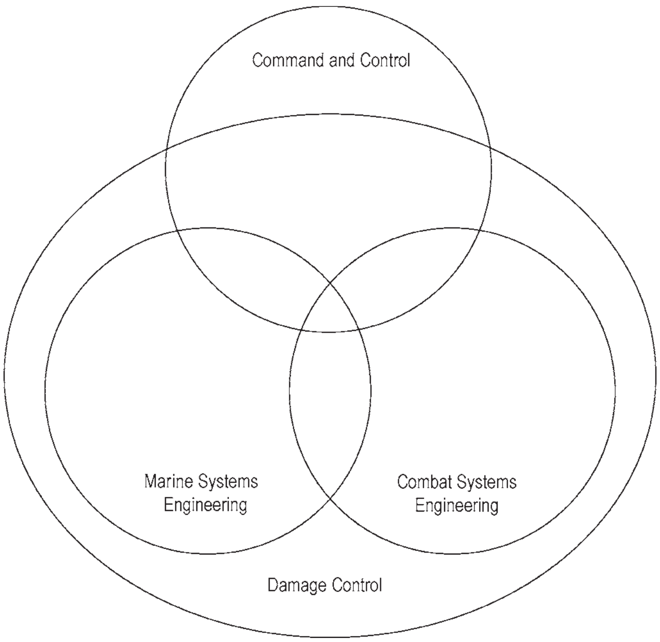

Fig. 1. Object worlds within the work domain of ship systems.

hull, deck, and superstructure and any objects on or attached to the same. Items external to the ship, like weather, the sea, contacts, and projectiles, were determined to be a part of the environment and thus placed outside of the system boundary. (Note that this definition of the boundary of the Halifax Class frigate's systems agrees with the boundary of the work domain of ship systems implicitly outlined in [11].)

Our next concern was to establish the boundary of the object world of damage control with respect to the other object worlds in the work domain. As can be seen in Fig. 1, damage control is the largest object world in the work domain of ship systems and includes all ship spaces because none is immune from damage. Marine systems engineering, combat systems engineering, and command and control include only a subset of the ship's spaces in their respective object worlds. (The object world of command and control also includes entities outside of the ship and the ship's environment [11], but these are outside of the ship systems' work domain boundary.) The primary purpose of damage control is to restore the ship to the state necessary for command and control, marine systems engineering, and combat systems engineering to meet their objectives.

The consideration of the two boundary types was important because it helped us understand which objects to include in our analysis and how to include them. Prior to determining the boundary of the work domain of ship systems, we did not understand if certain objects that do not reside on the ship but that sometimes serve damage-control functions (e.g., onshore fire-fighting equipment) should be included in our analysis. Prior to the recognition that damage control is one of the object worlds in the work domain of ship systems, it was difficult to decide how to include objects like the engines (which are also important to the command and control object world) or power generation and distribution (which is also important to the combat systems engineering object world) in our analysis. However, once we established that damage control was a part of the work domain of ship systems, the boundary of that work domain implied that objects that were not a part of ship systems are outside of the scope of the abstraction hierarchy. Similarly, once we recognized that the object world of damage control was concerned with the damage-control relevant properties of everything within the work domain boundary, we better understood how to model objects that were also important in other object worlds.

Because the broader objective of this paper is to design new ship systems for damage control that will help to reduce crew requirements, we had to exclude a number of items within the work domain boundary from our analysis. This includes fire mains, fitted and portable fire-fighting equipment, and smoke and heat sensors. In addition, because the characteristics of a ship's power distribution network can have a large effect on the work of damage control, the physical form of the power distribution network was also excluded from our analysis. To control scope, we also did not include nuclear, biological, chemical, and radiological defense in our analysis. Although these threats add important constraints to the work domain, they are layered on top of the regular damage-control constraints and do not change them. When required, these concerns can be added to the model without disrupting its overall structure.

C. Abstraction Hierarchy

The abstraction hierarchy of ship systems from the perspective of damage control is shown in Fig. 2. It includes five levels of abstraction as follows.

1) Functional Purpose: This level of the abstraction hierarchy describes the purposes that the work domain is intended to achieve. The first three functional purposes, which are stability, maneuverability, and mission effectiveness, are based on the slogan of the Damage Control Division of the Canadian Forces Naval Engineering School, "to float, to move, to fight" [36]. In other words, the purpose of damage control is, first, to ensure that the ship is upright and stable, second, to ensure that it can maneuver out of or into harm's way, and third, to ensure that it can accomplish its mission. These three purposes, however, do not describe the object world of damage control in this work domain fully. Damage control also operates within a broader societal, political, and moral sphere that entails the three additional purposes of personnel safety, economic stewardship, and environmental protection. These three purposes describe societal [19] or external [15] constraints. These constraints are more subjective than the others and, therefore, may be de-emphasized in difficult or potentially catastrophic damage-control situations, when operators will use whatever resources are available to save the ship. In addition, economic stewardship in particular speaks to design-time concerns, again because during operations, operators will use the resources that have been provided, generally without regard to cost. Nonetheless, full success of the damage-control system over the lifetime of the ship requires that all of these functional purposes be met.

2) Abstract Function: These are the fundamental principles for fulfilling each of the functional purposes and range from the physical constraints imposed by requirements of reserve

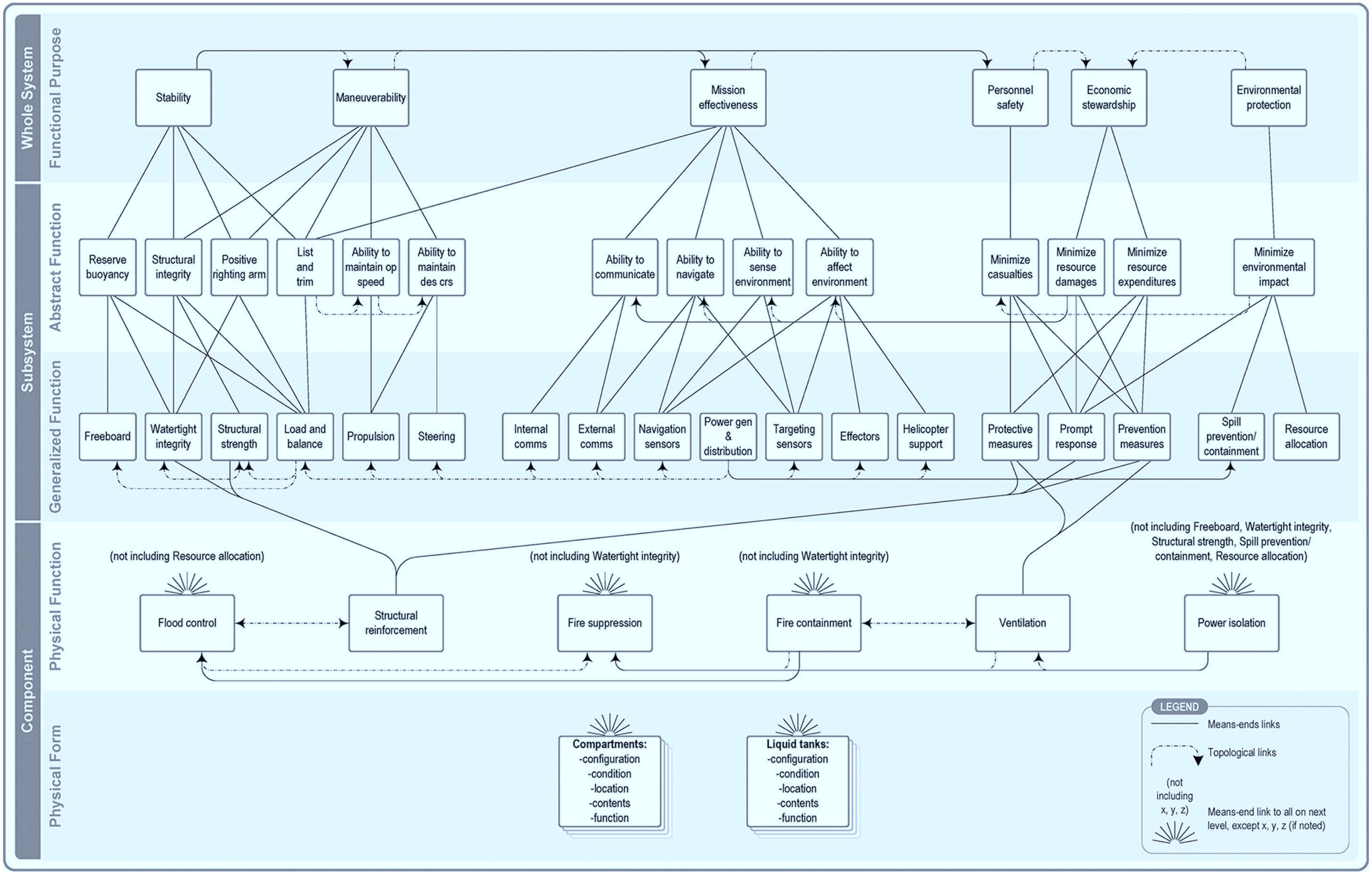

Fig. 2. Abstraction hierarchy of ship systems from the perspective of damage control.

buoyancy, structural integrity, positive righting arm, and list and trim to the constraints imposed by the necessity of maintaining various capabilities to value-based measures like minimize casualties, minimize environmental impact, and minimize resource damages. Whereas all operators may not normally think about the work domain at this high level of abstraction, it contains important considerations that need to be understood by both senior officers and ship designers. These abstract functions describe the full set of principles on which the object world of damage control operates within the work system.

3) Generalized Function: These are the ship properties and functions that the work domain aims to preserve. For example, to be operational, the ship must have adequate freeboard, watertight integrity, and structural strength, its load and balance must be maintained properly, and all of its mission systems must be maintained in an operational state. All of these must be satisfied while at the same time enacting protective measures, spill prevention/containment, resource allocation, rapid response, and prevention measures to ensure that the values of the domain are also preserved. This abstraction hierarchy level describes the work domain in terms familiar to operators and represents typical concerns encountered during the usual conduct of their work.

4) Physical Function: The physical function level of this abstraction hierarchy makes the transition from describing ship functions to describing the types of damage-control interventions available to restore those functions. At this level, the object world of damage control significantly filters how the work domain is viewed—damage control is not concerned with the functionality of, for instance, the ship's radios but only with how that functionality might be compromised by damage spreading across the ship. Accordingly, flood control, fire suppression, and fire containment ensure that the ship's functions are not compromised by water external to the ship or uncontrolled combustion, ventilation ensures that the ship's air is safe to breathe and can also be used to suppress fires, and power isolation is used to help in fighting fires. It should be noted that power isolation is an important concern in damage control—whereas isolating power to a compartment can make it safe to fight a fire in that compartment with water, it may also affect the ship's generalized functions.

5) Physical Form: The physical form level of this abstraction hierarchy includes all of the affordances of the compartments and liquid tanks on the ship that are relevant to damage control. At this level, each compartment or liquid tank is described with respect to its location in the ship, adjacency relationships with other compartments, flooding and drainage considerations, ventilation, contents, power supply, hazardous materials, and interconnections with ship systems (e.g., wiring). The abstraction hierarchy in Fig. 2 does not represent each compartment but rather treats them generically. Whereas we did describe 12 compartments at the physical form level to ensure that the proposed dimensions for the compartment descriptions were correct [31], it was not possible to describe all of the ship's compartments within the scope of our project.

In addition to the abstraction dimension, the abstraction–decomposition space of work domain analysis also includes a decomposition dimension that details the part–whole (or system-subsystem-component) relationships in the work domain. To capture this dimension, Fig. 2 also indicates the level of decomposition that applies to each level of abstraction. In addition, Fig. 2 also shows the structural means–ends connections between the levels of abstraction and the causal connections within each level.

TABLE I
COMPARISON BETWEEN SYSTEM LEVEL FUNCTIONAL PURPOSES OF DAMAGE CONTROL AND COMMAND AND CONTROL (FROM [11] AND [12])

Functional purposes within the object world of damage control	**Functional purposes within the object world of command and control**
Stability	Maintain own survival
Maneuverability	Move from A to B
Mission effectiveness	Maximize sea control Maximize information gathering
Personnel safety	Meet naval values: goals for Effectiveness, Economics, Force Balance, Adherence to law
Economic stewardship	
Environmental protection	

V. DISCUSSION

A. Stakeholders and Object Worlds in Military Systems

Recognizing that damage control is not a work domain, but rather an object world within the work domain of ship systems, was a key insight that allowed us to analyze damage control with a work domain analysis. We were not able to analyze damage control *per se*, because damage control is event dependent. Rather, we had to take a broader view to identify the work domain that damage-control activities are embedded in and then analyze damage control as an object world of that work domain.

To test the assertion that damage control is an object world within the more generic domain of ship systems, we anticipated that the types of models that would result were we to examine the object worlds of marine systems engineering, combat systems engineering, and command and control in the same work domain. At the level of functional purposes, the Naval Engineering Manual (an important reference for both marine systems engineers and combat systems engineers [37]) refers to the same basic doctrine as the damage-control slogan, "to float, to move, and to fight." These functional purposes were also familiar to all subject-matter experts we consulted with, combat systems engineers, marine systems engineers, and command and control officers[4] included. In addition, the Canadian Navy's current strategic plan [1, pp. 117 and 118] calls these purposes "basic Naval concept[s]." Burns *et al.* [11] found similar functional purposes in naval command and control, although their findings were worded differently (see Table I). In a second publication discussing the same work domain model [12], one additional functional purpose, Meet naval values: Goals for effectiveness, economics, force balance,

[4]While one could argue that all officers are part of the command and control structure, in the Canadian Forces, Maritime Surface officers have the specific responsibility for command and control concerns.

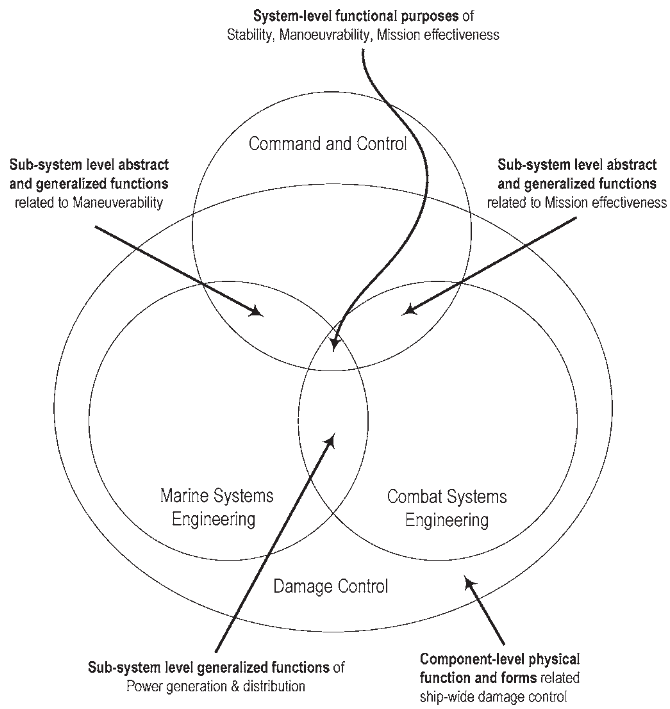

Fig. 3. Object world overlaps.

adherence to law, is also included. This functional purpose is similar to but broader in scope than the damage-control functional purposes of personnel safety, economic stewardship, and environmental protection. Thus, there is strong evidence of fundamental overlap between these object worlds at the level of functional purpose (Fig. 3).

This overlap is not complete. Burns *et al.* [11] found that command and control can only be understood with respect to the external entities of the environment and the contacts in the environment. This indicates that command and control can only perform its role by looking outwards. Damage control responds to command and control's interpretation of the outside world but does not directly interpret the outside world.

Marine systems engineering, combat systems engineering, and command and control share many of the same concerns as damage control. For example, marine systems engineering, combat systems engineering and damage control have a shared concern for power generation and distribution; marine systems engineering, command and control, and damage control have a shared concern for propulsion and steering; and combat systems engineering, command and control, and damage control have a shared concern for ability to sense environment and ability to affect environment. Again, the overlap at these levels is not complete; in fact, whereas significant, the overlap at these levels is less substantial than at the level of functional purpose.

The unique purviews of each object world would then be expressed at the levels of component physical functions and form. For example, marine systems engineering is concerned with maintaining the ship's engines in a state where they can provide propulsion to the ship, combat systems engineering is concerned with the engines only in their capacity to provide power to the mission systems that they are responsible for maintaining, and damage control is only concerned with making sure the engine spaces are free from floods, fires, and structural damage. There will be a higher priority for damage control to address damage in the engine spaces than in a store locker, but the concern of damage control in the engine spaces does not overlap with that of marine systems engineering and combat systems engineering.

The strong high-level overlap and increasing lower level disconnect between these object worlds contrast with Naikar *et al.*'s [15] observation that the limited number of object worlds documented in work domain analysis literature only exhibit overlaps at the level of physical form. In all of the research reviewed by Naikar *et al.* in which object world overlaps were discovered (network management, health care, an elevator firm, and an engineering design problem), the different stakeholders were involved with the same physical objects but had divergent goals for their involvement in the system. For example, in network management [35], network managers and equipment suppliers are each concerned with the same technical infrastructure but to advance different high-level goals fostered by their respective corporate affiliations (e.g., network managers want to make the most efficient use of their equipment, whereas equipment suppliers want to sell more equipment). In an engineering design problem [38], the stakeholders were ergonomics designers, structural engineers, implementers, end users, and management. Each of the stakeholders had different goals for participating in the design problem and different ways of approaching it, but they all worked on one common physical form—the artifact being designed. In these work domains, the physical form level of abstraction was the strongest area of object world overlap, implying that the dominant form of work coordination was bottom-up, emerging around the physical objects.

Navies, in contrast, have used top-down coordination to develop and maintain work practices and organization to allow many different actors to efficiently advance a shared set of goals. Work has been partitioned so that many different groups can work on different physical objects (or different aspects of the same physical objects) at lower levels of abstraction, all toward a single set of functional purposes. Naval systems (and perhaps military systems in general) are qualitatively different from the systems included in Naikar *et al.*'s [15] review because of the difference in direction of work coordination. Top-down coordination constrains the work of the various stakeholders by the goals to be pursued, whereas bottom-up coordination constrains the goals to be pursued by the physical forms of the objects being worked on. Thus, it is likely that the direction of work coordination in the work domain will determine the form of object world overlaps in that work domain.

This leads to the following hypotheses about object worlds and the ways in which they overlap.

1) In systems with primarily top-down coordination, object world overlaps should be strongest at the level of functional purposes.
2) In systems with primarily bottom-up coordination, object world overlaps should be strongest at the level of physical forms.

3) Perhaps obviously, in systems where two object worlds are observed to overlap completely, those object worlds have either been misidentified or should be merged into a single object world.

One objection to hypotheses 1) and 2) is that the type of object world overlaps depends not on the type of coordination in a work domain but on the granularity of the functional purposes included in the model. In this view, if appropriately high-level functional purposes are chosen (such as life, liberty, and the pursuit of happiness), all object worlds will show overlap at the level of functional purposes, independent of the type of work coordination imposed on the work domain. The counterargument to this objection is that a work domain analysis—and the functional purposes chosen—should represent "a fundamental set of constraints on the actions of any actor" [16, p. 149] within a work domain. For example, in the case of the engineering design problem analyzed by Burns and Vicente [38], three of the object worlds were within the same company and were presumably unified by the same company constraints of increasing profit and market share. However, Burns and Vicente did not include functional purposes at this level in their model, which is indicative of the fact that these constraints, although theoretically in effect, were not fundamental constraints on actions in the various object worlds of this domain.

B. Stakeholders and Object Worlds as a Dimension of Work Domain Analysis

Naikar *et al.* [15] point out that object worlds can be confused with the decomposition dimension of a work domain analysis and echo the recommendation of Benda and Sanderson [39] that, where object worlds are present, they should be viewed as a third dimension to the abstraction–decomposition space. In other words, in a work domain such as Halifax Class frigate ship systems, where four or more stakeholder groups (and hence, as many corresponding object worlds) exist, models can be built for each object world and then overlaid on one another. Where overlaps exist, the overlapping nodes of the abstraction hierarchy can be viewed as spanning multiple object worlds.

C. Stakeholders and Object Worlds as a Means to Manage Model Scope

One potential criticism of the use of object worlds is that it assumes some organization of work in an analysis that should be independent of work organization and actors [16]. We partially agree with this criticism. In an ideal world, we should have performed a work domain analysis of the entire Halifax Class frigate, not just its damage-control capabilities. This broader analysis would help to identify potential work synergies that will never be found if portions of the required work in that domain, like damage control, are analyzed by themselves.

Whereas it is theoretically appealing, this viewpoint is problematic in practice. There will always be a broader system to analyze. For instance, if modeling damage control is insufficient, why stop at modeling the entire Halifax Class frigate? Why not model a naval task group, or a theatre of operations, or world conflict? Some stopping rule must be applied to allow for analyses of reasonably bounded scope.

The benefit of considering object worlds is thus twofold. First, the use of object worlds can help in applying work domain analysis on domains in which some work divisions must be assumed *a priori*. Second, because consideration of multiple object worlds makes explicit the ways in which other stakeholders hold their respective stakes in the work domain under analysis, they can help in identifying potential work synergies between stakeholders. Of course, a broader analysis would do this more effectively, but there are not always resources for a broader analysis. Explicit consideration of object worlds has the potential to make a broader range of problems tractable with work domain analysis by allowing analysts to work within the bounds defined by their resources or their ability to effect change.

D. Stakeholders and Object Worlds as a Means to Explain Model Differences

One final question remains: If work domain analysis is a reliable methodology, why was it necessary to conduct another analysis of damage control when these concerns were already included in the analyses of Burns *et al.* [11] and Linegang and Lintern [13]? Fortunately, the concept of object worlds can help in understanding the differences between, and the unique contributions of, each analysis. Although neither analysis used the language of object worlds, Burns *et al.*'s analysis was directed at the object world of command and control, and Linegang and Lintern's analysis aimed to foster functional integration between anti-submarine warfare and damage control to expand an existing object world (or perhaps even to create a new one). The different foci of these analyses determined their content. Because the object world of command and control extends beyond the work domain of ship systems, Burns *et al.*'s analysis had a broader system boundary than our analysis of damage control. Due to this broader boundary, although there is a good consonance between Burns *et al.*'s and our model at the level of functional purposes, it is difficult to find any lower level elements in Burns *et al.*'s model that can be traced uniquely to damage control. On the other hand, because the main affinity between antisubmarine warfare and damage control is the effect of damage on ship capabilities, Linegang and Lintern's model focuses on these effects but otherwise treats the control of damage as a low-level service. In contrast, the specific focus of our analysis on the object world of damage control resulted in a model that includes details of potentials for damage, effects of damage, and processes to control damage. As was argued in Section V-C, our focus on a specific object world helped us to exclude broader concerns that did not have a direct effect on the propagation or control of damage.

Whereas the fundamental difference between these three work-domain analyses relates to the selection (implicit or explicit) of object worlds for analysis, significant differences can also be attributed to differences in project objectives (overall system design for Burns *et al.*, display design for Linegang and Lintern, and simulation development for our model) and the flexibility of the technique of work-domain analysis. As Burns *et al.* observed, the modeling challenges of each specific project "must be handled in a manner that embodies the context of the problem, respects the construct of the chosen modeling approach, and maintains a vision of the ultimate goal of the project" [12, p. 16].

VI. Conclusion

The work described in this paper makes several contributions to the theory and practice of work domain analysis. First, it provides a work domain analysis of the damage-control object world of the work domain of Halifax Class frigate ship systems, contributing to the existing literature on applications of this framework. Second, when compared to Burns *et al.*'s work domain analysis of command and control on a Halifax Class frigate [11], it demonstrates that two work domain analyses performed on the same work domain, but by different analysts and for different purposes, generate consistent results, although at different levels of detail as determined by the project objectives. This is additional proof that work domain analysis is a reliable methodology. Third, it provides a more in-depth treatment of object worlds than is currently available in the literature:

1) It suggests that when the object of analysis for a modeling effort is defined in an event-dependent way (e.g, with respect to procedures, tasks, or planned responses), that object may be better modeled as an object world within a broader work domain.
2) It draws a distinction between work domain and object world boundaries, shows that these boundaries need not be the same, and discusses the way in which these two types of boundaries should be considered in the context of an applied modeling problem.
3) It provides a counterexample to the observation that object world overlaps tend to occur at the physical form level and suggests that the form of object world overlaps may be determined by the amount of top-down coordination imposed on a work domain.
4) It reinforces the idea that object worlds are best viewed as a third dimension of the abstraction–decomposition space of a work domain analysis.
5) It highlights object worlds as a useful tool to assist in the application of work domain analysis to domains in which work divisions must necessarily be assumed *a priori*.

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References

[1] *Leadmark: The Navy's Strategy for 2020*. Canadian Forces. [Online]. Available: http://www.navy.dnd.ca/leadmark/doc/index_e.asp

[2] *Securing Canada's Ocean Frontier: Charting the Course From Leadmark*. Canadian Forces. [Online]. Available: http://www. navy.forces.gc.ca/mspa_video-media/Securing_Canada_E.pdf

[3] United States General Accounting Office, "Navy actions needed to optimize ship crew size and reduce total ownership costs," U.S. Gen. Accounting Off., Washington, DC, Rep. GAO-03-250, 2003.

[4] J. Schank, R. Yardley, J. Riposo, H. Thie, E. Keating, M. Arena, H. Pung, J. Birkler, and J. Chiesa, *Options for Reducing Costs in the United Kingdom's Future Aircraft Carrier (CVF) Programme*. Santa Monica, CA: RAND Corp., 2005.

[5] P. S. Hamburger, J. R. Bost, and J. A. McKneely, "Optimized crewing for surface ships," in *Proc. Naval Surf. Warfare Tech. Dig.*, 1999, pp. 204–215.

[6] J. A. Hiltz, "Damage control and crew optimization," Defence R&D Canada–Atlantic, Dartmouth, NS, Canada, Def. Res. Devel. Canada–Atlantic Tech. Memo. TM-2005-010, 2005.

[7] J. A. Hiltz, *Damage control and optimized manning—The DRDC-Atlantic perspective*, 2005, Dartmouth, NS, Canada: Defence R&D Canada–Atlantic.

[8] J. M. C. Schraagen, "Requirements for a damage control decision-support system: Implications from expert-novice differences," in *Naturalistic Decision Making*, C. Zsambok and G. Klein, Eds. Mahwah, NJ: Lawrence Erlbaum, 1996, pp. 315–322.

[9] T. E. Miller, A. A. Armstrong, S. L. Wiggins, A. Brockett, A. Hamilton, and L. Schieffer, "Damage control decision support: Reconstructing shattered situation awareness," Naval Surface Warfare Center, Dahlgren, VA, 2002. Final Tech. Rep., Contract N00178-00-C-3041.

[10] E. Runnerstrom, "Human systems integration and shipboard damage control," *Naval Eng. J.*, vol. 115, no. 4, pp. 71–79, 2003.

[11] C. M. Burns, D. J. Bryant, and B. A. Chalmers, "Boundary, purpose, and values in work-domain models: Models of naval command and control," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 35, no. 5, pp. 603–606, Sep. 2005.

[12] C. M. Burns, A. M. Bisantz, and E. M. Roth, "Lessons from a comparison of work models: Representational choices and their implications," *Hum. Factors*, vol. 46, no. 4, pp. 711–727, Dec. 2004.

[13] M. P. Linegang and G. Lintern, "Multifunction displays for optimum manning: Towards functional integration and cross-functional awareness," in *Proc. 47th Annu. Meeting Human Factors Ergonomics Soc.*, 2003, pp. 1923–1927.

[14] J. Rasmussen, A. M. Pejtersen, and K. Schmidt, "Taxonomy for cognitive work analysis," Risø Nat. Lab., Roskilde, Denmark, Risø Nat. Lab. Rep. Risø-M-2871, 1990.

[15] N. Naikar, R. Hopcroft, and A. Moylan, "Work domain analysis: Theoretical concepts and methodology," Australian Government, Dept. Defence/Defence Sci. Technol. Organization, Victoria, Australia, Rep. DSTO-TR-1665, 2005.

[16] K. J. Vicente, *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work*. Mahwah, NJ: Lawrence Erlbaum, 1999.

[17] J. Rasmussen, "The role of hierarchical knowledge representation in decision making and system management," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-15, no. 2, pp. 234–243, 1985.

[18] J. Rasmussen, A. M. Pejtersen, and L. P. Goodstein, *Cognitive Systems Engineering*. New York: Wiley, 1994.

[19] C. M. Burns and J. Hajdukiewicz, *Ecological Interface Design*. Boca Raton, FL: CRC Press, 2004.

[20] G. A. Jamieson and K. J. Vicente, "Ecological interface design for petrochemical applications: Supporting operator adaptation, continuous learning, and distributed collaborative work," *Comput. Chem. Eng.*, vol. 25, pp. 1055–1074, 2001.

[21] G. A. Jamieson, C. A. Miller, W. H. Ho, and K. J. Vicente, "Integrating task- and work-domain based work analyses in ecological interface design: A process control case study," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 37, no. 6, pp. 887–905, 2007.

[22] N. Dinadis and K. J. Vicente, "Ecological interface design for a power plant feedwater subsystem," *IEEE Trans. Nucl. Sci.*, vol. 43, no. 1, pp. 266–277, Feb. 1996.

[23] N. Lau, Ø. Veland, J. Kwok, G. A. Jamieson, R. Welch, C. M. Burns, and A. O. Braseth, "Ecological interface design for the secondary subsystems of a boiling water reactor," *IEEE Trans. Nucl. Sci.*, to be published.

[24] A. M. Bisantz, E. Roth, B. Brickman, L. L. Gosbee, L. Hettinger, and J. McKinney, "Integrating cognitive analyses in a large-scale system

design process," *Int. J. Hum.-Comput. Studies*, vol. 58, no. 2, pp. 177–206, Feb. 2003.

[25] N. Naikar and P. M. Sanderson, "Evaluating design proposals for complex systems with work domain analysis," *Hum. Factors*, vol. 43, no. 4, pp. 529–542, 2001.

[26] N. Naikar, B. Pearce, D. Drumm, and P. M. Sanderson, "Designing teams for first-of-a-kind, complex systems using the initial phases of cognitive work analysis: Case study," *Hum. Factors*, vol. 45, no. 2, pp. 202–217, 2003.

[27] J. J. Gibson, *The Ecological Approach to Visual Perception*. Mahwah, NJ: Lawrence Erlbaum, 1979 and 1986.

[28] G. L. Torenvliet, "We can't afford it: The devaluation of a usability term," *Interactions*, vol. 10, no. 4, pp. 12–17, Jul./Aug. 2003.

[29] E. Westermeijer, W. M. Post, W. Keijer, and M. P. W. Gillis, "Teleknowledge, knowledge-at-a-distance," in *Proc. 13th Int. Ship Control Syst. Symp.*, Orlando, FL, 2003.

[30] J. K. Pollard, E. D. Sussman, and M. Stearns, "Shipboard crew fatigue, safety, and reduced manning," U.S. Dept. Transp., Maritime Admin., Washington, DC, Rep. DOT-MA-RD-840-90014, 1990.

[31] G. L. Torenvliet, G. A. Jamieson, and L. Cournoyer, "Functional modelling, scenario development, and options analysis to support optimized crewing for damage control—Phase 1: Functional modelling," Defence R&D Canada–Toronto, Toronto, ON, Canada, Def. Res. Devel. Canada–Toronto CR 2006-090, 2006.

[32] K. J. Vicente and F. Tanabe, "Event-independent assessment of operator information requirements: Providing support for unanticipated events," in *Proc. Amer. Nuclear Soc. Topical Meeting Nuclear Plan Instrum., Control, Man-Mach. Interface Technol.*, 1993, pp. 389–393.

[33] *Maritime Command: Ship's Standing Orders (version AL6)*, Can. Dept. Nat. Defense, Ottawa, ON, Canada. undated.

[34] L. Bucciarelli, "An ethnographic perspective on engineering design," *Des. Stud.*, vol. 9, no. 3, pp. 159–168, Jul. 1988.

[35] R. Chow and K. J. Vicente, "A field study of collaborative work in network management: Implications for interface design," in *Proc. 45th Annu. Meeting Hum. Factors Ergonomics Soc.*, 2001, pp. 356–360.

[36] *Canadian Navy Damage Control Information Book for Halifax-Class Ships (Manual No. C-23-HFX-000/MS-002)*, Can. Dept. Nat. Defense, Ottawa, ON, Canada, 2003.

[37] *Naval Engineering Manual*, Can. Dept. Nat. Defense, Ottawa, ON, Canada, 2003. (Manual No. C-03-005-033/AA-000).

[38] C. M. Burns and K. J. Vicente, "A participant-observer study of ergonomics in engineering design: How constraints drive design process," *Appl. Ergon.*, vol. 31, no. 1, pp. 73–82, Jan. 2000.

[39] P. J. Benda and P. M. Sanderson, "Towards a dynamic model of adaptation to technological change," in *Proc. Australasian Conf. Comput. Human Interaction*, 1998, pp. 244–251.

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