Work Domain Modeling to Support Shipboard Command and Control

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Abstract

Shipboard Command and Control (C2) presents unique challenges for decision support. Tactical decisions require that the ship's Command Team be able to gain timely access to and comprehend the significance of large amounts of information that may impact the mission. While operations depend heavily on doctrine and standard operating procedures, many tactical details must be established in real time, particularly as unanticipated events or anomalous situations arise. This imposes significant cognitive demands on operators for active situation assessment and decision making, where benefits for performance improvements may be expected from incorporating advanced decision support systems and integrative work aids and displays. Cognitive Work Analysis (CWA) is a layered, systems-based analysis framework that specifically addresses system design to support operators in unanticipated situations. Its first layer is a work domain analysis (WDA), which develops hierarchical models representing the intentional, functional, and physical properties of the work domain, at different levels of abstraction, as well as the relations between these levels. In this paper, we discuss WDA's basic concepts and their application in a year-long study to tactical C2 for the Canadian Navy's HALIFAX Class frigate. We review the models that resulted and briefly describe some ongoing applications of the CWA approach in this work environment.

1. Introduction

Current efforts in Canada's defence research community to develop data fusion technologies for the shipboard environment hold significant potential for helping combat operators cope with the data explosion problem in modern warfare and increasing their battlespace awareness and decision speed and accuracy. For example, automated data fusion aids promise to enhance data and information integration, and thereby reduce the cognitive demands on operators in gaining and maintaining situation awareness. However, realising this potential will be extremely challenging.

The literature offers numerous examples that attest to the difficulty of designing effective computer-based support in cognitively demanding work environments. In fact, there is substantial evidence that an impoverished "solution" can lead to substantial decrements in the effectiveness of the joint human-machine cognitive system. Examples in the literature include:

- the burden associated with supervising automation as it performs an offloaded task can outweigh the benefits [1];
- performance decrements can result from automation-induced complacency (over-trust) [2] and biases that increase, rather than decrease, errors as operators come to rely on automated cues as a heuristic replacement for their own vigilant information seeking and cognitive processing [3]; and
- a partially automated system can induce more errors in cases where its knowledge is incompetent than if the operator is left in the loop and the system simply critiques the operator's performance based on recognising operator violations of intrinsic work constraints [4] (e.g., brittleness in the automated solution in the face of variabilities that are unanticipated by its designers where the system is being expected to function outside its area of competence; the operator now has to detect and diagnose these occurrences, when the situation really requires the operator to acquire a complex understanding of local conditions and develop novel solutions to resolve problems that arise).

Mistrust of a computer-based solution, leading to its disuse, neglect, or underutilisation, can be the result of a poor design (e.g., a high rate of false alarms in an alerting system) [5]. A proposed solution may also act as a barrier to the operator's expertise and engagement [6] leading to skill decay or dysfunctional skills.

An important aspect of these and a host of other potential problems has to do with the "fit" that exists between the work's cognitive demands, the design intervention or solution, and the operators that are supposed to be the beneficiaries of its support. Characteristic of a Cognitive Systems Engineering approach to cognitive system design, Woods and Hollnagel [7] suggest that the key to the effective application of computer technology for supporting humans in complex problem-solving worlds is to conceive, model, design, and evaluate the joint or interacting cognitive systems. They emphasise that achieving high work performance rests on adopting a problem-driven, rather than a technology-driven approach to tool development, based on first mapping the cognitive demands of the work environment. The overriding challenge for inserting computer-based support solutions into this environment is to design the joint human-machine system to obtain a performance that is greater than could be achieved separately by either the human (individual or team) or machine acting alone in the face of these work demands. In the tactical shipboard setting, this requires that we first develop a broad understanding of the work demands posed by Command and Control (C2) as a basis for design.

The C2 work environment possesses many characteristics that usually characterise a complex sociotechnical work system such as uncertainty, dynamism, team work, stress, risk, variable and unpredictable demands, and large and growing amounts of data to process. Complexity will undoubtedly continue to grow as a result of increasing complexity in threat scenarios (e.g., technological advances in threats, operations in littoral environments) and as the co-evolution of organisation, doctrine and technology underlying the revolution in military affairs [8] imposes increasing demands for agile and adaptive response to rapid change at all C2 levels. For example, the shift from platform-centric to network-centric warfare calls for the capability to self-synchronise forces in real time, from the bottom up, while at the same time respecting top down organising principles of warfare such as unity of effort, the commander's intent, and rules of engagement [8]. Operators at all levels, from the platform to the task force, will therefore need to deal with a growing diversity of situations or events spanning the familiar ones encountered routinely, to unfamiliar, but anticipated ones, to both unfamiliar and unanticipated ones. These latter ones, in particular, may call on operators to actively and adaptively frame ill-structured problems, assess the situation, and derive solutions. Now, more than ever, advanced decision support systems and collaborative or integrative work aids and displays are needed to help operators manage the increasing amounts of information in a way that creates flexible, knowledge-based problem solvers from naval command teams and harnesses their individual and combined expertise and adaptive capabilities to the full.

Techniques for representing work demands in cognitively demanding environments have evolved from normative approaches (first-generation), to descriptive approaches (second-generation), and more recently to formative approaches (third-generation) [9]. A formative approach starts by modeling, in an holistic manner, the intrinsic constraints that shape the work to be done, in the sense that such constraints must be satisfied if the work is to be performed effectively, regardless of the performing agent (human, machine, or both) of that work. These models are then used to identify novel possibilities for work organisation and support that may not be apparent from a description of the current work practice alone (a descriptive approach). This approach should also be contrasted with one founded on shaping the work as the designer perceives it should be (a normative approach). Design efforts based on a technology-driven approach generally adopt a normative perspective, with a focus on developing an essentially autonomous work agent to support an operator who is assumed to play a mostly passive or vetoing role in using the agent's services. The potential in a complex work environment for such an approach by itself to produce a "solution" with unexpected negative consequences for joint human-machine system performance should hardly be surprising, even if there is due diligence in the course of its development to make the interface to the "solution" as user friendly and comprehensible to the operator as possible.

This paper presents results from an ongoing investigation [10] of the feasibility and value of applying a specific formative work analysis framework, known as Cognitive Work Analysis (CWA) [9], to the design of support interventions for the C2 work environment of a HALIFAX Class frigate. We examine one aspect concerned specifically with the first of CWA's layers, a Work Domain Analysis. A Work Domain Analysis was conducted in a year-long study to develop a hierarchy to structurally represent the broadest limits of the domain's constraints that create tactical action opportunities on the HALIFAX Class frigate.

The paper is organised as follows. Section 2 presents the CWA framework, focusing on the key features of its first layer, which consists of a Work Domain Analysis. Section 3 outlines some of the principal differences with other applied domains for the application of Work Domain Analysis to tactical C2 for the HALIFAX Class frigate that influenced the form of the WDA models for this domain. The method that was followed to derive these models is also discussed. The models derived by the WDA are reviewed in Section 4. Two applications of the WDA's results are presented in Section 5. Finally, Section 6 provides conclusions and discusses ongoing work.

2. Cognitive Work Analysis

Cognitive Work Analysis (CWA) provides a layered, analytical approach to representing the work constraints in an open, complex, dynamic work system. CWA arose from work first done in the nuclear power plant domain [9]. It has been successfully applied in process control [11] and petrochemical plant control [12] to name a few of its current application areas. However, it has so far received only very limited attention by the C2 R&D community [10].

Broadly speaking, CWA's focus on work constraints is based on two aspects of an underlying design philosophy for such work environments:

- Operator support tools should help in bounding the flow of work so that it evolves according to requirements for effective work performance, without unnecessarily overconstraining its performers.
- A work analysis should not start by making assumptions, ab initio, about the devices or tools themselves that are to be used to support the work since design concepts for such tools are expected to be developed as a result of the analysis.

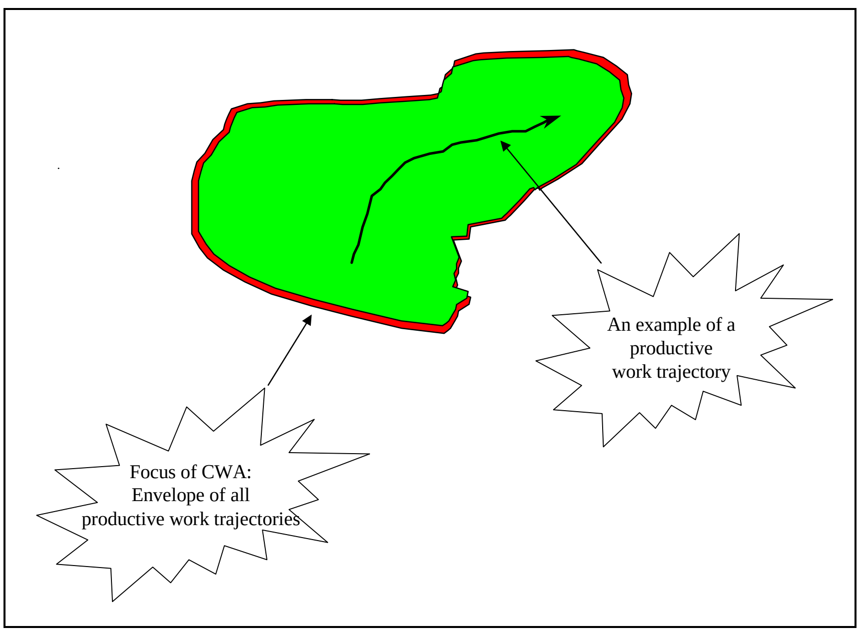

Figure 1: Modeling focus of Cognitive Work Analysis

The constraints that CWA aims to model are referred to as behaviour-shaping or intrinsic work constraints. For example, the CWA approach purposely leaves room for operators to dynamically adapt at their discretion, when possible, the way the work is performed without violating its intrinsic constraints. In practice, areas of operator adaptation that may be candidates for support can be related to several aspects of the work, including the tasks that correspond to the activities that are carried out to achieve specific goals, the strategies that are used to process or transform existing data and knowledge into new knowledge, and the organisational mechanisms that govern the distribution and sharing of the work. These various aspects are addressed separately in the various layers of the CWA framework.

This modeling focus in CWA on bounding the work flow so that it evolves according to productive "work trajectories" is illustrated in Fig. 1. The term "work trajectory" is used to denote a specific work flow in the envelope shown in the figure. Strictly speaking, however, the work trajectory that corresponds to a specific flow depends on the elementary components that are used to parse the flow into a time-sequenced collection of constituent elements that are of interest for the analysis, e.g., events, tasks, knowledge structures, strategies, decisions, and actions. The work trajectory may therefore be represented as a path made up of nodes and links between successive nodes, labeled by the elementary components employed in parsing the work flow.

Five different constraint layers are distinguished in a CWA, each one corresponding to a different type of behaviour-shaping constraint. A complete CWA begins with a Work Domain Analysis (WDA), followed by analyses of Control Tasks, Strategies, Social-Organisation and Cooperation, and Operator Competencies [9]. The first three layers relate to what Rasmussen [13] refers to as the "identification of activities" in the work system, and the last two to the "identification of agents or actors" that perform the work. This separates the characteristics of the work environment that must be satisfied from those of actors responsible for their satisfaction.

An important feature of the CWA framework is that there are specific conceptual modeling tools associated with each layer that can be used to represent the variabilities in cognitive demands among the work trajectories in an open, dynamic work system. It is expected that these tools and others would ultimately be part of a concrete and systematic methodological approach to organising this knowledge to allow undertaking a requirements analysis and design of work support tools. However, strictly speaking, extending CWA's concepts into a rigorous, codified engineering design process remains to be done.

As we have already suggested, the specific purpose of the models derived using CWA's tools is to permit analysing the cognitive demands of the work over the range of situations and contexts that operators can face. As one example of these variabilities in demands, we note that in routine or anticipated situations trained operators appear to recognise a situation as typical and base their responses on recognitional cue-action mappings and rules. This underlies Klein's recognition-primed decision model [6] and corresponds most closely to Rasmussen's notion of rule-based behaviour [13]. However, in less familiar or unanticipated situations, this is a problematic strategy. These situations call on operators to actively identify deep features of the situation, construct mental models of these features and their relations, formulate, diagnose and solve problems, and generate or adapt plans and procedures to determine course of action responses. This is the basis of what Rasmussen refers to as knowledge-based behaviour [13]. Rasmussen's skills, rules, knowledge (SRK) taxonomy [13] can therefore be used as a way of organising and analysing these various categories of operator performance.

2.1 Work Domain Analysis

We now examine in more detail some of the principal features of the first of CWA's layers, referred to as a Work Domain Analysis, which is the focus of this paper. The aim of a WDA is to develop a representation of the dynamic system that operators interact with in the course of their work. This dynamic system is also referred to as their work domain. The dynamic system and its components are considered from a teleological perspective, that is as realisations of design intentions for the purpose of satisfying specific needs or requirements. The representation is derived through an analysis that models the work domain's constraints by abstracting the system's high-level purposes or objectives and functional descriptions from its low-level physical details. System abstraction therefore plays a key role in developing a WDA representation.

Abstracting the knowledge about a system on various levels is a well-known way that operators use to understand and operate a complex system without being overwhelmed by its complexity [e.g., 14]. However, a WDA's treatment of a system's complexity has some distinguishing characteristics. First developed by Rasmussen and Lind to help nuclear power plant operators cope during plant disturbances [15], it integrates a variety of types of system knowledge, including intentional, causal and structural knowledge, as indicated in Table I, in a manner that is intended to represent the knowledge requirements of an operator engaged in goal-oriented, knowledge-based work on the system. Intentional knowledge for man-made systems deals with design intentions about how the system (or some subsystem) is objectively to satisfy its requirements. In other words, intentional knowledge permits relating requirements or needs to system objectives. Causal knowledge is concerned with interactions between subsystems. Structural knowledge is knowledge about the system's physical parts, their physical characteristics and topological connections.

Table I: Abstraction levels and corresponding system knowledge types in a Work Domain Analysis

ABSTRACTION LEVEL	KNOWLEDGE TYPE
Purposes	Intentional
Functions	Intentional, Causal
Physical Form	Structural

To integrate these various knowledge types, a WDA develops a multilevel structure encapsulating multiple means-end views of the system. In a particular means-end view spanning two successive levels of the structure, an end on one level and its corresponding means on the next (lower) level are linked by a means-end relation[1]. For example, an end could relate to some objective that the system has a designed-in capability to accomplish (i.e., the end in this case corresponds to a specific design intention), and a means could relate to the capability itself. The system's goals, its purposes, are derived from the system's intentional knowledge. They are represented at the highest level of abstraction. Means are derived from the system's causal and structural knowledge. These are represented at the Functions and Physical Form levels of abstraction, respectively. A (system) function defines a role conceived by the system's designers that it can play in achieving its purposes [16]. For this reason, the system's purposes are also referred to as its Functional Purposes. As indicated in Table I, a function represents both

[1] These links, and their corresponding knowledge types, are not shown in Table I.

intentional and causal types of system knowledge. Entities represented in the Physical Form level are the system's physical means of realising its functions. In general, means-end relations will be many-to-many: several functions may be involved in achieving one purpose; one function may satisfy several purposes; one function may be realised by means of several different physical entities; and one physical entity may be used in effecting several different functions.

This type of system representation, combining the various abstraction levels and the means-end relations between these levels, provides a reasoning structure that should be useful to operators performing knowledge-based tasks like diagnosis, problem solving, planning, and decision making, and reasoning about causes and consequences of disturbances and operational deficiencies, that require detecting, framing and formulating problems, assessing the situation, or reasoning about the goals they want to achieve or how the system's functions, resources and equipment currently at their disposal can be used to achieve those goals. For example, the means-end relations can be used to answer 'why', 'what', and 'how' questions in problem diagnosis and planning: a link from an object (the 'what') on some level to the one above indicates 'why' the object exists, and to the level below 'how' the object is achieved or realised.

Consistent with the idea illustrated in Fig. 1, we suggest that a complete WDA representation of a system should delimit the full range of trajectories for goal accomplishment that the system affords operators and should also provide a means of satisfying their knowledge requirements about the system in the course of following these work trajectories[2]. From the viewpoint of an operator interacting with the system while performing a knowledge-based task, one can interpret this property in two parts as follows. A WDA representation of a system is complete if:

i) any work trajectory for a goal-oriented, knowledge-based task can be mapped onto a path in the system representation formed by model entities and means-end links between these entities (Mapping Property); and

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[2] Lind [17] has recently argued that one problem for a WDA is that there is as yet no process for building a WDA model, or for revising, modifying and validating that model. A clearer defining statement of precisely what it is a WDA sets out to represent is a necessary step toward resolving this problem. Although it undoubtedly raises the problem of "verifying" the conditions involved, the notion of a complete WDA representation, as defined by the conditions expressed in (i) and (ii), may be helpful here. While completeness is defined there with respect to all cognitive trajectories for goal accomplishment, it may also be helpful to narrow the conditions to specific classes of trajectories, according to the type of knowledge-based tasks on the work domain involved, e.g., those related to situation assessment about the system versus those involved in determining action responses or system interventions. This may be useful in targeting the knowledge acquisition work underlying model development to the specific WDA model to be built, and in design work for tying the purpose of that model to the specific set of cognitive demands that are to be supported. We mention, however, that examining these ideas in the context of their application to the HALIFAX Class frigate has not yet been done. The present discussion of the properties of a complete WDA representation is only meant as a first stab at developing the concepts necessary for developing a better understanding of a WDA's contribution to the design of support systems in this environment.

ii) the system knowledge required or used in following the work trajectory is represented in the models of the entities that are encountered during the traversal of the path in the system representation that corresponds to the work trajectory (Knowledge Base Property).

Of course, in a specific application, this property of a WDA representation, as a map of productive work trajectories through the work domain and as a system knowledge base for these various trajectories, can only be expected to hold for the knowledge types that the representation captures. We note that this property can be seen to provide the motivation for a number of concrete applications of a WDA. For example, the results of a WDA have been used to determine the content and structure of an operator's display, an approach that has been shown experimentally to lead to improved problem diagnosis and more effective control strategies in a process control environment [17]. More specifically, the Ecological Interface Design framework for interface design for complex sociotechnical systems [11,17] proposes developing this type of system representation explicitly in the operator interface as an external system representation to support the operator's knowledge-based problem solving interactions with the work system. .In our current applications to the HALIFAX Class frigate, we have exploited this property to show how a WDA can be used in a model-based approach to determine information requirements for tactical operators on the HALIFAX Class frigate and to evaluate a decision support system for this platform. These applications are discussed in Section 5.

Separating a system's purposes and functions from its physical form as in a WDA system representation has another advantage worth mentioning. It divorces the physical means available for instrumenting the system (i.e., its sensors and actuators), which are technology-paced in their evolution, from its purposes and functions, which will evolve entirely independently based on user function requirements. This separation should be a useful feature of a system's representation when conducting an analysis of the impact of systemic changes at one or more of its levels[3].

Table I summarises only the rudiments of a system's representation that may be captured in a WDA. In practice, additional levels of abstraction, and even dimensions of analysis, can be involved. For example, a part-whole dimension can be used to provide various levels of system resolution and refinement at each level of abstraction. Rasmussen's own work on its application to process control systems suggests that five levels of abstraction are useful for representing such systems [18]. In this case, one interpretation is that the level of the system's Functions shown in Table I has been developed into three sublevels of functional abstraction: Abstract Function, Generalised Function, and Physical Function. The full set of five levels can be summarised as follows [9]:

- Functional Purpose: Purposes for which the system was designed;
- Abstract Function: Intended causal structure of the system's functions in terms of mass, energy, information, or value function flows;

[3] A full representation useful for such an analysis of the HALIFAX Class frigate might be derived by developing a mission-operator-technology functional system architecture combining mission requirements, operator functions, system functions, and technological realisations into an integrated, means-end framework. However, such possibilities have not as yet been explored.

- Generalised Function: Basic functions and processes that the system has been designed to achieve;
- Physical Function: Characteristics of the system's physical components and the connections between them; and
- Physical Form: Appearance and spatial location of the system's physical components.

Rasmussen refers to this system representation as an Abstraction Hierarchy [18]. In [9], Vicente uses the Abstraction Hierarchy as the conceptual modeling tool for the WDA layer of a CWA. Lind has also developed this modeling approach as a framework for reasoning in supervisory control of complex dynamic process plants [16]. However, although it is derived from similar origins and with similar motivations, he refers to his development of this type of system representation as a Multilevel Flow Model (MFM). This reflects MFM's principal application to date in continuous processing systems that can be described by combining at the functional level various structures, called flow structures, of mass and energy flow functions.

Finally, it is worth noting that both the semantics and structure of this type of system representation are a continuing source of research and debate among its various proponents. For example, Lind [19] argues that Rasmussen's Abstraction Hierarchy suffers from both methodological and conceptual problems (see also footnote 2). In view of this, it is not surprising that the details underlying a WDA and its framework for system representation may need to be evolved, refined, or even developed further as the range of its application domains expands and new requirements are uncovered in these domains. We have certainly found the need for this in our own application of WDA to naval C2.

3. Applying Work Domain Analysis to the HALIFAX Class Frigate

To our knowledge, this is the first application of WDA to a naval work domain. In applying it to tactical C2 for the Canadian Navy's HALIFAX Class frigate, we realised that there were several aspects of naval C2 that differ from previous applications like nuclear power plant control that could make the application challenging, and indeed, could require further development of the WDA framework in order to handle this new domain. We outline some of the key differences from other domains that influenced the form of the domain representation that was developed.

Unlike a power plant that is easily established with respect to its purpose and boundary, these elements of a naval system can be very difficult to fix.

- A naval frigate can be tasked with a large variety of mission types. This makes it challenging to map mission and operator goals, considered as requirements to be satisfied using the frigate, to a fixed set of generic frigate purposes. This should be contrasted with a power plant which ultimately has a very clear purpose – the generation of electrical energy.
- C2 entails moving and controlling entities outside of the ship using the ship, its on-board or off-board organic resources, and other platforms and their associated resources also under its control. In addition, a frigate may operate in single ship or task group operations, involving a variety of C2 relationships between the frigate and its interacting parties depending on the mission and its warfare role in that mission. It does not make

sense, therefore, to draw the work domain's boundary at the ship's hull. For this reason, we modeled the domain as a loosely bounded system, including the frigate and other entities external to it, where these entities are not predetermined in the model and could in fact have a variety of purposes. In a specific operational setting, these entities could be pursuing goals that either support, oppose or are neutral to those of the frigate's own mission.

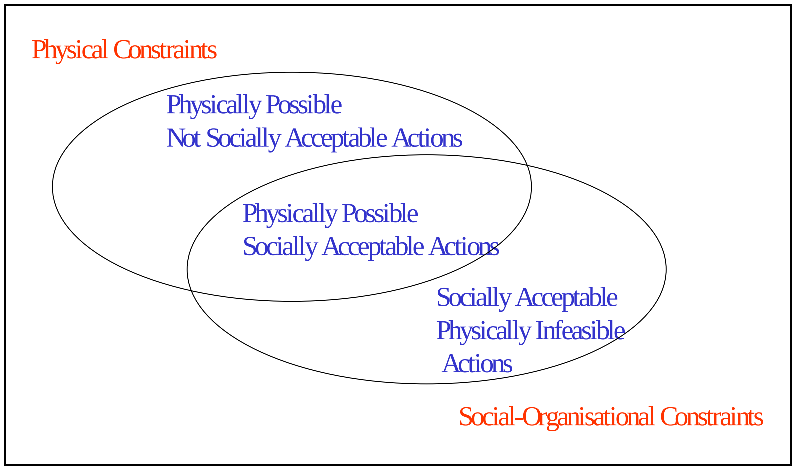

Figure 2: Role of Physical and Social-Organisational constraints in determining actions

Another important characteristic of the shipboard work environment is that any interaction between the ship and external entities is mediated through the natural environment. The natural environment can impose limitations on movement and constrain the use of sensors or weapons and impact their performance. A WDA model of this domain that did not include these factors would be ignoring a critical aspect of naval operations. To model the environment usefully, we therefore modeled it within the system boundary as a third type of model "entity".

A final key difference in this domain is that as well as managing its "physical" constraints, operators work within the value structure of their organisation. For example, constraints arising from national objectives and international law can limit actions beyond those that are achievable based only on the capabilities of the frigate's physical resources. While values and priorities have been included in work domain models of other domains before, the treatment of values has not been detailed. We found it necessary to make their role in relation to the domain's "physical" constraints more explicit than is the case in previous applications. We have done this by making a distinction between the domain's physical constraints, the domain's "hard constraints", which cannot be broken, and its social-organisational constraints, its "soft constraints", which can be broken but probably will not or should not be. A good example of a soft constraint is a rule of engagement (ROE) which is designed to remove any legal or semantic ambiguity that could lead a military commander to violate policy about the use of force by inadvertently under-reacting or overreacting to an action in a situation. How these two types of constraints impact the space of potential action is shown in Fig. 2. As can be expected with a constraint hierarchy, adding more constraints reduces the action envelope, reflecting the intersecting constraint space shown in the figure.

3.1 Method

With a domain this complex, it was not possible to create a set of work domain models in a single modeling exercise. We chose instead to go through several iterations, starting first with a skeletal framework of the work domain and increasing in model complexity. At the skeletal level (Section 4.1), the main objective was to isolate the principal parts of the model and to determine a boundary for the system that would be analysed in this first study. The second iteration provided more details of the physical work domain (Sections 4.2 and 4.3). The third iteration incorporated social-organisational (Section 4.4) and information gathering constraints (Section 4.5) into the model.

Knowledge acquisition sessions to derive the data for the models used a variety of operational level and training documents dealing with the principles and procedures of maritime warfare. Various quasi-structured interviews of Subject Matter Experts (SMEs) among the Command Team in the HALIFAX Class Operations Room, and in doctrine, training, naval planning, and system engineering, were conducted. As well, a number of complete training exercises were observed in a land-based training simulator and on board a frigate engaged in simulated air attacks as part of harbour exercises. The latter was augmented by a field trip on a frigate involved in simulated air, surface and subsurface warfare exercises in a task group setting over the course of a three day sea trip between Norfolk, Virginia, and Halifax, Nova Scotia. This was used to capture work domain constraints that would not be available in a simulator or through interviews. The field trip also helped confirm modeling work in progress at the time.

Table II: Contribution of information sources by model entity

Model Entity	Information Source
Functional Purpose	High-level design documents for existing system; naval planning personnel; Command Team
Abstract Function	WDA from other domains; textbooks; naval trainers
Generalised Function	Training publications; textbooks on physical processes; Command Team; ship observations
Physical Function	Low-level system design documents; documents on the frigate's combat control system; data fusion documents; training publications; combat system integrator; ship observations
Physical Form	Physical design documents; direct observations on ship
Social-Organisational Constraints	Articles and books on naval doctrine; naval history; general military doctrine and history; naval planning and policy personnel

Table II shows how the various knowledge acquisition activities contributed to developing the work domain models, by itemising the information sources for the five abstraction levels that we used. These levels correspond to Rasmussen's five abstraction levels for process control systems [18]. They are detailed in Section 4. We also include a separate row in Table II for the WDA's social-organisational constraints.

CWA models constructed at each stage were evaluated in further interviews with SMEs to correct misconceptions, fill in gaps in the models, and generally test their validity. Validation also involved walking SMEs through a training scenario to make contact with the elements of the model and identify model deficiencies, and, in a final phase, having them complete detailed questionnaires testing out various aspects of the final versions of the models, including model completeness and frequency of consideration of model elements across a variety of mission types.

4. Results of the Work Domain Analysis

We review here some of the modeling results, concentrating on their general features and focusing only on the portions specifically related to the frigate. Additional details about the models appear in [20].

4.1 The Skeletal Model

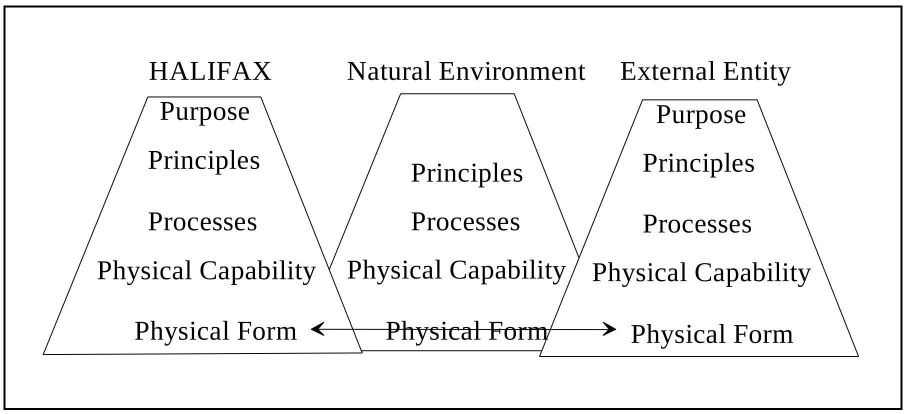

Figure 3: Three part skeletal model

Consistent with our remarks in Section 3, three principal parts of the model were identified at the skeletal level, consisting of the HALIFAX Class frigate, natural environment, and external entity. These are shown in Fig. 3. The part designated by the external entity is not predetermined in the model. It is only represented generically, as a placeholder for any class of purposeful entity, or groups of such entities (e.g., ships, aircrafts, missiles, submarines, torpedoes), that would need to be considered as part of the work domain because in a particular operation their presence in the ship's external environment could impact in some way the execution of the frigate's mission (e.g., the frigate can impact, or be impacted by, an external entity through messages, emissions, or the use of weapons or other measures involving the entity). In a manner compatible with their purposes, such entities could be pursuing goals that support, oppose or are neutral to those of the Command Team, depending on their mission. The three parts of the model interact with each other physically through the level of physical form. This means that they sense each other beginning with their physical form, and they can also physically make contact with each other at this level.

Five levels of abstraction have been used to develop the model as shown in Fig. 3. Using the terminology from Rasmussen's levels of abstraction for process control systems [18] (see also Section 2), these five levels are:

1. Functional Purpose: the Purpose of the frigate or external entity. (Not modeled in the case of the natural environment.)

2. Abstract Function: the basic causal Principles underlying system functioning that govern how the system's basic purposes are achieved and how the system functions.
3. Generalised Function: the Processes that can be involved in system or subsystem operation, as well as the processes that govern subsystem interactions.
4. Physical Function: any Physical Capability relevant to naval operations.
5. Physical Form: the Physical Form, condition, state, location, and interconnection of the components that realise the system's functioning.

4.2 The Physical Work Domain

Table III shows in more detail the general 3-part model of the physical work domain.

Table III: General model of the physical work domain

Level	HALIFAX	Natural Environment	External Entity
Functional Purpose	Maximise sea control, achieve movement, survive		Achieve mission, survive
Abstract Function	Flow and balance of mass, energy, and resources	Flow and balance of mass, energy, creation of entropy	Flow and balance of mass, energy, and resources
Generalised Function	Processes of moving, launching resources, managing watertightness, generating signals	Air, water, land and electromagnetic processes	Processes of moving, launching resources, managing physical integrity, generating signals
Physical Function	Capabilities of equipment, engines, weapons, decoys	Capabilities of air, water, land to permit movement, signal propagation	Capabilities of equipment, engines, weapons, decoys
Physical Form	Physical location, condition, shape, size, markings of equipment	Physical location, shape, size, appearance of environmental features	Physical location, condition, shape, size, markings of equipment

We modeled all three parts at five levels of abstraction, with the exception of the natural environment. The level of Functional Purpose captures the design intention of the work domain. This did not apply to the natural environment which we considered as not having a design intention in the same sense as a man-made artifact. The frigate's purposes were modeled at a generic level to permit mapping the diversity of its mission types (escort, patrol, screening, antisubmarine warfare, etc.) onto those purposes. For the frigate, we defined sea control as purposes outside of its relocation for controlling a designated area. Sea control captures the frigate's purpose to gain information on the control area and, if called for, to exert influence on other parties in that area.

At the Abstract Function level, we modeled flows of mass and energy for all three parts. For the frigate and external entity, we included the flow and balancing of resources, which is a specific type of mass flow. We included resources as a separate model entity at this level because resources cannot easily be changed from one type to another. With the natural environment, we included the creation of entropy, as a natural constraint that cannot be broken. The creation of entropy describes the tendency of the environment to gradually move towards a state of disorder.

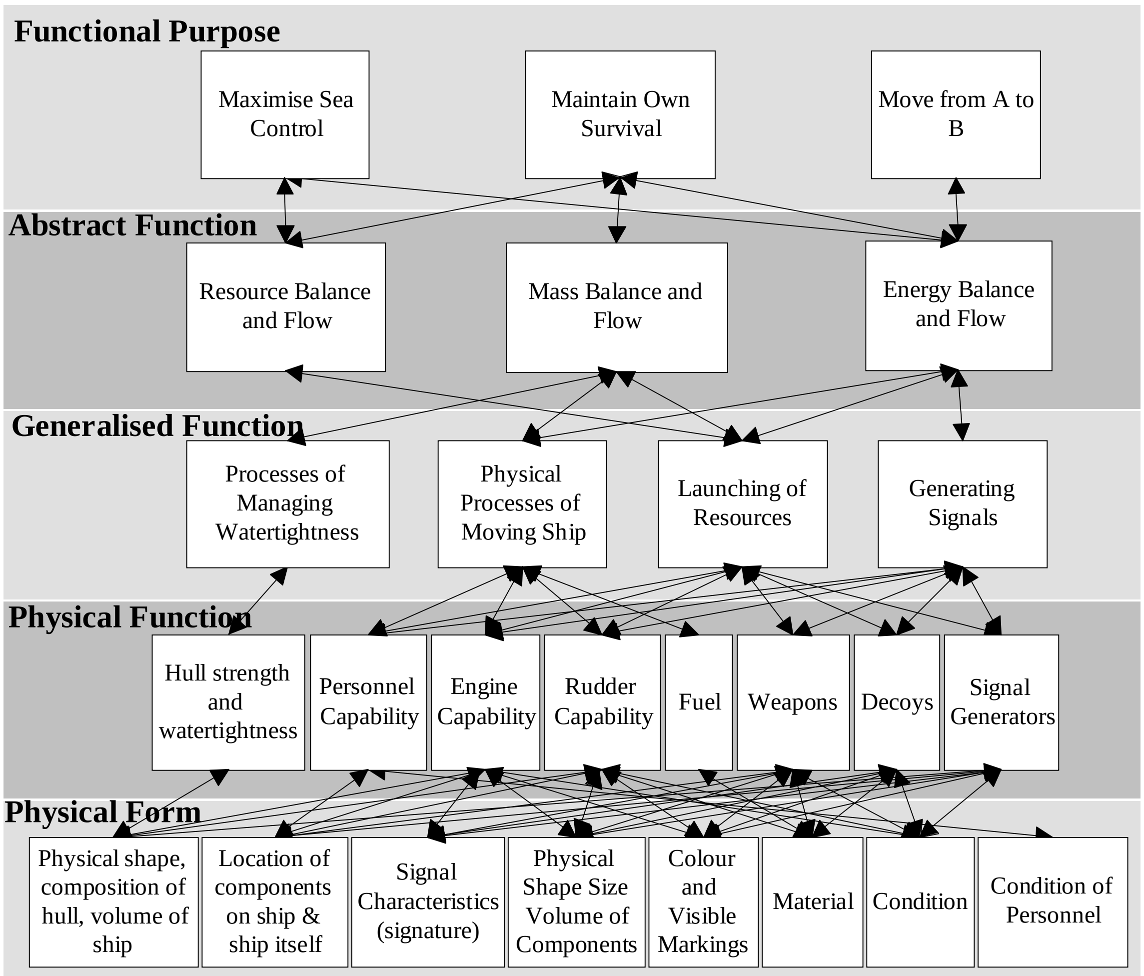

Figure 4: A model of the physical constraints for the HALIFAX Class part of the WDA

The Generalised Function level models system processes. In the case of the frigate and the external entity, the primary physical processes are those of moving, launching weapons or decoys, and generating signals deliberately or as a result of using other equipment. The natural environment has processes of precipitation, movement of air, land and water, and signal generation.

The Physical Function level is a description of capabilities. For the frigate and external entity, we described the capabilities of weapons, engines, decoys and other equipment. In the case of the natural environment, we modeled the capability of air, land, and water to permit locomotion and the transmission of visible, electromagnetic or acoustic signals.

For all three parts, the Physical Form level describes the condition, location, and appearance of objects in the work domain. For the frigate and external entity, we modeled the Physical Form of equipment. For the natural environment, we modeled the Physical Form of land and water, components of the natural environment.

The external entity model is quite similar to the frigate model, but more general. We have assumed that an external entity has a "designed for" purpose, with a mission to accomplish, and some level of resources with which to accomplish that mission. Depending on the nature of a specific entity, however, elements of the generic model of an external entity will be more or less relevant; for example, not all purposeful entities carry weapons.

4.3 Physical HALIFAX Model

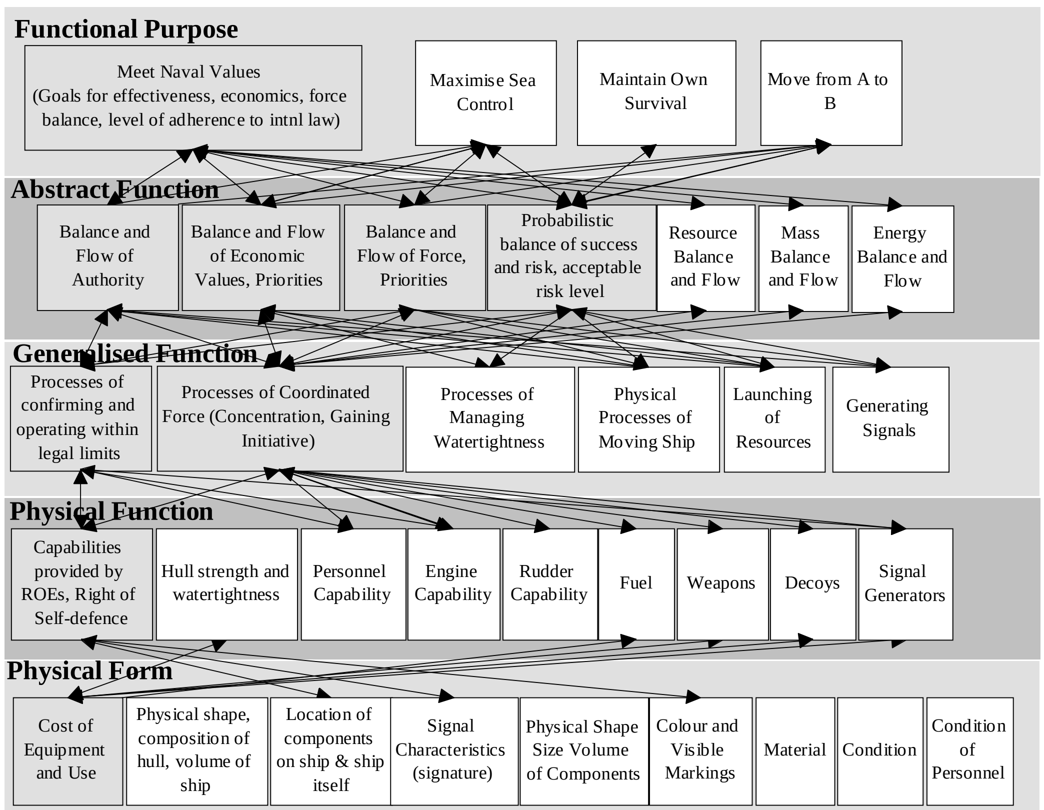

Figure 5: Integrating physical and social-organisational constraints for the HALIFAX Class frigate

Figure 4 shows a more detailed view of the physical constraints of the HALIFAX part of the WDA model. In particular, in this model, we have shown the means-end connections between the levels. The model can be traced through as a chain of functional reasoning. As a simple example, an engine has a certain size, form, and acoustic signature (Physical Form). It therefore will have certain capabilities to produce power or force (Physical Function) and acoustically can act as a signal generator. These capabilities contribute to the frigate's movement processes and signal generating processes (Generalised Function). Movement requires using energy through fuel to move the mass of the ship (Abstract Function). The ship cannot move farther than its fuel reserves will allow. The distance that the ship can move determines whether it can move to its next required location (Functional Purpose).

4.4 Social-Organisational Constraints

As discussed in Section 3, we modeled value-based properties of the work domain as social-organisational constraints. We chose to model them using the abstraction hierarchy and five levels of description. We integrated these constraints with the physical constraints to show a more complete model of the work domain. This is shown in Fig. 5, where only the links related to the added social-organisational constraints have been indicated. Model elements in the social-organisational constraint hierarchy appear in the grey boxes in the figure. Additional details on these constraints appear in [20,21].

4.5 Information Gathering Constraints

In addition to the physical and social-organisational constraints, we identified and modeled a third class of work domain constraint. We refer to this third class as the class of information gathering constraints. In Fig. 6, these constraints (dark shading) are shown integrated with the previous two classes of social-organisational (light shading) and physical (unshaded) constraints. Unlike the frigate's physical constraints which relate to its mass, energy, and resource flows, information gathering constraints stem from the frigate's need (part of its functional purpose) to gather information to allow the Command Team to understand the work domain and exercise Command and Control in accordance with the frigate's mission, role, and capabilities. The Abstract Function level of these constraints deals with the balance and flow of information, and the quality and completeness of those flows.

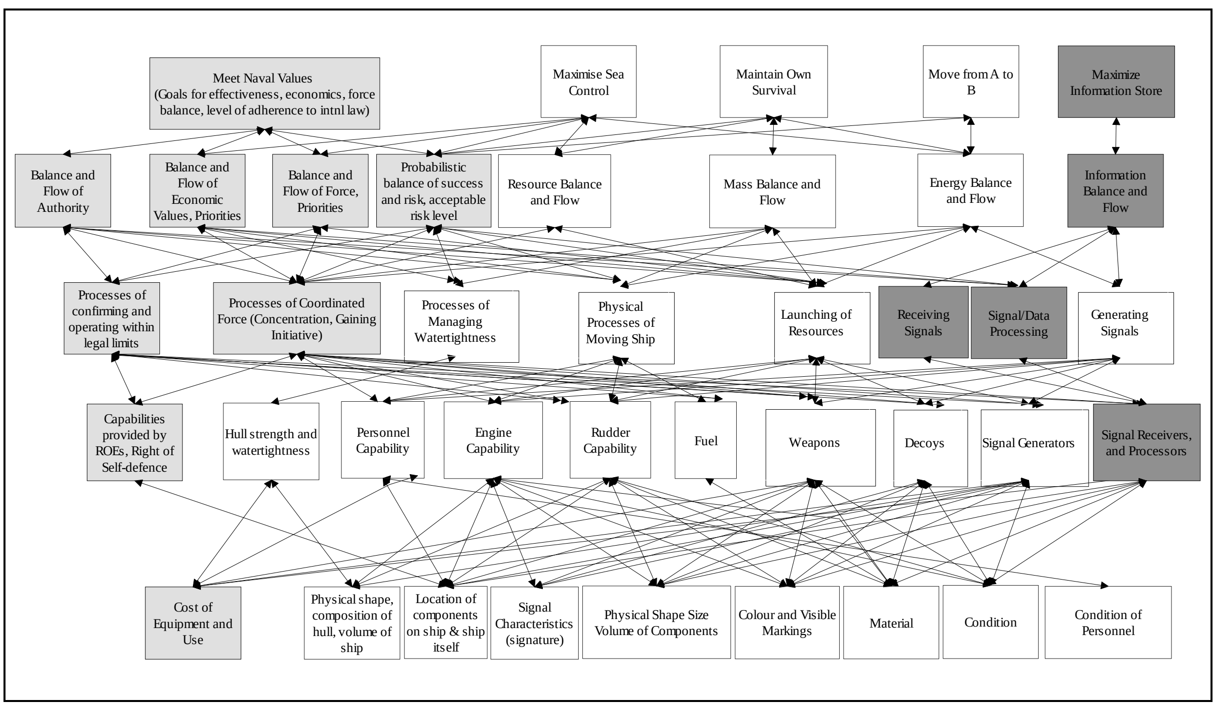

Figure 6: Integrating physical, social-organisational, and information gathering constraints for the HALIFAX Class frigate

Note that whereas active sensors are included in the physical work domain of the frigate (because of their ability to act on the work domain) through the process element, “Generating Signals”, and the capability element, “Signal Generators”, passive sensors are placed instead in the information gathering class via the process element, “Receiving Signals”, and the capability element “Signal Receivers”. In fact, these various model elements can also be viewed as representing processes and capabilities associated with using any active or passive information source internal or external to the frigate (e.g., internal platform sensors for assessing the status of the frigate’s systems, meteorological sensors for assessing the external environment, data links). Finally, note that since an active sensor in the physical constraint class also plays an information gathering role, these constraint classes overlap. This is consistent with the means-end relation shown in Fig. 6 between the “Information Balance and Flow” and the “Generating Signals” model elements.

4.6 Work Domain Interactions

We have already mentioned the power of a WDA representation to support knowledge-based reasoning. The power behind developing a 3-part model in this particular domain is that it also permits a description of work domain interactions that is useful. For example, the model can describe interaction in conflict, and also information gathering activities.

Interaction in conflict: In this case, the frigate and the external entity interact through the natural environment. The conflict arises due to the incompatibility of the frigate’s purpose and the entity’s purpose. Both apply their resources to each other, at the level of physical form, using them through a natural environment that may interfere with the situation. A strike by a weapon will change the components of the frigate at the level of physical form, may modify its capabilities, and impact whether the frigate can exert sea control.

Information gathering: The model provides a useful framework for defining information needs for operators. The natural environment and external entity side of the model present situation assessment needs related to the frigate’s external environment. For example, what is a contact’s purpose, and what are its capabilities? How are the frigate’s capabilities impacted by the state of the natural environment? Detailing these sides of the model provides a systematic way of identifying the information needs of the Command Team for establishing thorough awareness of the external situation. We illustrate this use of a WDA in Section 5.1.

5. Applications

We briefly review two of our applications to date of the results of this WDA for the HALIFAX Class frigate. As previously observed, they take advantage of the observation made earlier that a complete WDA representation of a system should be both a map of all productive, knowledge-based work trajectories through the work domain and a system knowledge base for these various trajectories. They illustrate how a WDA’s results can be used in a model-based approach to two problems: determining information requirements for tactical operators on the HALIFAX Class frigate (Section 5.1), and qualitatively evaluating display information about the work domain provided by a decision support system (Section 5.2). We note that these WDA applications are part of a larger project [10] exploring the application of the CWA framework to design for the

HALIFAX Class frigate which has also led to a preliminary storyboard of new display concepts for tactical decision support [22].

5.1 Derivation of Information Requirements

A work domain analysis is a precursor to the design of decision support. From the analysis conducted so far, many information requirements can be extracted even at this preliminary stage [23]. Each level of the work domain model specifies a certain kind of information which should be provided in information displays. In all, from the complete modeling exercise, we generated 132 unique design requirements in this manner.

We emphasise that the power of the WDA analysis here is that it provides a principled approach to deriving these requirements based on deep knowledge about the work domain that can be systematically represented in the WDA model. We summarise the requirements that were extracted by this approach, giving examples from each level of the work domain model.

Table IV: Examples of information requirements derived from the work domain models

Level	**Information Requirements**
Functional Purpose	Distance to mission goal, survival status, intentions of contacts
Abstract Function	Levels of energy and resource reserves, mass balance for frigate and contacts
Generalised Function	Environmental processes, movement, and launching processes for frigate and contacts
Physical Function	Capabilities of engines, weapons and decoys of frigate and contacts, capability of environment to restrict movement or interfere with signals
Physical Form	Visible markings, physical location of frigate, contacts, land, and water

Functional Purpose Requirements: This level requires displays of goal and intent. For the frigate this could mean destination location, and percentage of contacts identified within the area of control of the frigate. It also means knowing the intentions of contacts, their missions, and planned destination.

Abstract Function Requirements: Information displays should show balances and flows of elements that must be conserved. Displays of energy levels and flow, mass levels, and resources levels and expenditures would be information at this level. The Command Team of the frigate should understand their own resource use, as well as resource use levels of contacts.

Generalised Function Requirements: This level requires the display of process information. Information on the watertightness system, movement processes and launch processes should be displayed. Similarly, the frigate’s Command Team should receive this information on the contacts in their area of interest. To anticipate weather problems and deploy resources appropriately, temperature and pressure values for air and water would be useful.

Physical Function Requirements: This level specifies capability information that should be displayed. The capability of equipment on the frigate and on any contacts should be provided. As well, the capability of water to affect sonar readings, or air to reduce visibility are examples of environmental capabilities specified by the model.

Physical Form Requirements: The requirements derived at this level are for physical location and appearance information. The Command Team must know its location as well as the location of all contacts. Similarly the boundaries of land and water must be known, which includes shorelines and waterway depth. Physical markings are one way of identifying contacts and are another kind of information that should be available.

Table IV provides examples of these information requirements [23].

5.2 Evaluation of the TADMUS Decision Support System

A WDA provides representations of a dynamic work system to enable operators to reason efficiently about the system and make decisions about possible interventions, at the knowledge-based level. This suggests that the presence or absence of such representations in operator displays may provide a model-based approach to qualitatively evaluating the effectiveness of a proposed or existing decision support system. This is supported by some evidence in process control applications [17] of the effectiveness of basing display design on the products of a WDA. To demonstrate this use of a WDA for evaluation purposes, we used preliminary WDA results for the HALIFAX Class frigate to conduct a work domain review of the TADMUS (Tactical Decision Making Under Stress) Decision Support System (DSS) [24].

The TADMUS program was initiated in response to the accidental shoot-down of a commercial airliner by the USS Vincennes in 1988. One of the program's results was a DSS to support the decision making of command-level decision makers aboard an AEGIS class cruiser. Its design applied two intuitive models of decision making, feature matching and story generation, that experienced decision makers have been found to employ in time-pressured, critical situations to make rapid situation assessments and course of action selections. The DSS organises incoming data and displays it in a form that highlights important features and relations so as to reduce cognitive and attentional demands of operators. The DSS itself is organised into various display modules that carry out these functions. Notably, the design approach was not based on an approach of ensuring that a complete picture of the work domain would be presented to the operator.

We compared the DSS's display to the work domain model we derived for the HALIFAX Class frigate to determine the extent to which the information content and organisation of the TADMUS DSS corresponded to that of the current model. In a limited one-day review, it was determined that the DSS's display corresponds to only a small portion of the work domain model. The DSS presents information about the own ship and contacts primarily at the levels of generalised functions and physical functions, focusing mostly on weapons, sensors, and decoys. The DSS presents some information that can be used to assess level of risk. The natural environment is the least represented aspect of the work domain. In this manner, several elements of the work domain were identified that might be useful to add to the TADMUS display [25]. We emphasise, however, that determining whether these missing elements are indeed display requirements of the operators who are to benefit from this DSS would need to be based on a closer analysis of their workspace and decision requirements.

6. Conclusions

CWA has been specifically developed to meet the challenges of complex sociotechnical systems, but it has so far received limited attention by the C2 R&D community. While there are many reasons to believe that there is a good fit between the demands imposed by C2 and the characteristics of CWA, it is important to provide a basis for evaluating this degree of fit. This will develop an improved understanding of the value of CWA to ongoing efforts in Canada's defence research community to explore concepts for the design of support systems suitable for the tactical work environment of the HALIFAX Class frigate and for the integration of such systems into the architecture of its combat control system [26].

To this end, we demonstrated that a work domain model can be developed for a naval frigate. The model presented in this paper is unique in the Work Domain Analysis literature with its three part modeling of the frigate, the environment, and the external entities. This represents an extension of the original framework proposed by Rasmussen and is an innovative approach to modeling the interactive aspects of this domain. Based on this model, information requirements can be derived, suggesting a model-based approach to developing naval C2 support systems for enhancing human decision-making performance. A further step in this direction would be to explore more specifically the advantages of developing the WDA system representation explicitly in the interface to support the operators' knowledge-based interactions with the work domain. This would be along the lines proposed in the Ecological Interface Design framework [11,17]. The specific aim would be to examine how the WDA system representation might be used to support operators in building accurate mental models [27] of their work domain, and in reasoning with these models, as part of their situation assessment, problem solving, and decision-making activities. A partial first step in this direction has been taken in the work described in [22].

However, our experience has also shown that detailing a complete work domain model would be an extensive project requiring a significant investment in resources, time and funding. Balanced against the need already mentioned in Section 2.1 for further developments in the methodological and conceptual underpinnings of a WDA [19], this suggests that a focused application of CWA in this environment is called for, to give optimal value for analytical investment. Two such efforts currently being pursued by DREA are described in Section 6.1.

6.1 Ongoing Work

DREA is currently investigating using CWA in the HALIFAX Class Operations Room to model information exchange in collaborative work, and information flow and integration among the different teams in building and maintaining a tactical picture, concentrating on situations that call for operator adaptation of an existing plan, or established procedures, in the face of unforeseen circumstances occurring in real time.

Modeling Information Exchange: The objective is to study the feasibility and benefits of using the Work Domain Analysis of the HALIFAX Class frigate to model information exchange requirements in collaborative work (i.e., work that requires dynamic, interdependent and adaptive interaction toward a common goal) among key members of the Operations Room team over the course of a mission segment or threat response to serve as a basis for the design of computer-based tools to support these work demands.

The basic idea here is that if the WDA model is complete with respect to the Mapping and Knowledge Base Properties described in Section 2.1, we should be able to identify, by mapping operator work trajectories onto the WDA model, how these trajectories interact with respect to their information exchange requirements. For example, an analytical approach could look at how the knowledge requirements at intersecting points of overlapping work trajectories (with respect to the current operator organization) lead to information exchange requirements among the different operator specialisations by analysing the model components in the WDA model that correspond to these intersecting points. Information exchange arises, for example, when the outcome of information processing by one operator position is needed by the overlapping work trajectory of another position. Knowledge elicitation techniques in the Human Factors and Cognitive Psychology literature (e.g., [28]) could also be used to support or confirm an analytical approach. Analysing how such requirements are currently satisfied could then be used to identify in a model-based manner new ways of supporting these operator demands.

Modeling Information Flow and Integration: The objective is to develop Cognitive Systems Engineering models of information flow and integration in Maritime Tactical Picture (MTP) Compilation in the Operations Room of a HALIFAX Class frigate as a basis for the design of computer-based tools to support operators in building and maintaining the tactical picture. The MTP is the situation picture needed to support all aspects of tactical operations over an area of interest of a maritime commander. It provides a comprehensive picture that the commander can use as a tool to develop and maintain awareness of the battle space and make tactical decisions to achieve the mission. It is anticipated that operator support will involve incorporating advanced processing capabilities, based on data and information fusion, into their tactical picture compilation work [26].

These cognitive engineering models will be derived primarily, though not necessarily exclusively, from existing conceptual modeling tools in the CWA framework [9], or based on refinements, extensions, or adaptations of such tools as our understanding of this work environment's modeling needs is developed. As an example of the scope of the modeling work that may be considered, one modeling approach proposed by DREA that also has the advantage of building on the results of the existing Work Domain Analysis for the HALIFAX Class frigate is to first model the dynamic work flows in picture compilation tasks of individual operators using decision ladder models [9]. This would represent a Control Task Analysis [9] of individual operators' picture compilation work. To model vertical and horizontal data and information integration flows among the operators, the basic decision ladder tool could be extended to allow linking individual operator ladders, or their associated processing activities, to represent the full range of potential flows. In a further extension of the usual CWA tool set [9], goal dependencies and other goal-related constraints among operator tasks could be represented separately by various graph structures (e.g., an AND/OR tree structure). Coordination constraints among individual operator processes could also be separately represented graphically, with individual operator processes represented as nodes and links between nodes representing precedence or logical constraints on those processes. Graphically-based techniques and other techniques from the Knowledge Representation and Artificial Intelligence literatures could also be examined for their capability to represent other types of task constraints, task processing, coordination strategies, or knowledge requirements (e.g., use of Gantt-like bar charts to represent temporal task constraints, information flow maps to represent strategies as part of a Strategies Analysis [9]).

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