Cognitive Work Analysis of the Command and Control Work Domain

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Abstract

This paper describes how the Cognitive Work Analysis (CWA) approach has been applied to model both the Command and Control (C2) work domain and command decision making within that domain. CWA techniques use descriptions of the work domain (work domain analysis) and generic descriptions of C2 activities (activity analysis) to model decision making within the C2 environment. This paper will discuss the utility of this method, the insights gained and some of the difficulties of using this particular approach.

1. Introduction

Previous work done by this group has provided high level analysis of the C2 support environment in broad organisational, process and technology terms[1]. The previous analysis was intent focussed, scenario-based and essentially a time slice of C2 activity. The purpose of the work described in the current paper is to use CWA techniques on the data gathered in the C2 Support Study [Chin *et al*, 1997] to gain a more detailed understanding of the interrelationships between people, technology and systems as applied within specific C2 work domains.

[1] [Chin *et al*, 1997], [Chin and Clothier, 1998]

2. Approach

The approach was based on Cognitive Work Analysis [Rasmussen et al, 1994] [Vicente, 1999] [Sanderson, 1998] which is a systems-based approach to the analysis, design and evaluation of systems. Rasmussen et al. and Vicente believe that the design of information systems to support decision making necessitates a multi-faceted approach, relying on input from various disciplines. The CWA approach uses a systems-based approach to unify psychological models with models of the environment within which human activity takes place. This type of approach allows a richer description of the decision making environment and also allows a description of the set of relationships between intent, generic decision tasks, generic activities and available resources.

Rasmussen's approach developed from early research at Riso National Labroatory in Denmark into system performance and hardware reliability. He concluded that although hardware performance could in some cases be guaranteed with a very high level of reliability, overall system performance rarely achieved such high reliability levels. He concluded that technical reliability was only one of the critical aspects of system relaibility – the other being how the human was coupled to the technical aspects of the system. Rasmussen then developed a methodology which he found allowed insights into the overall reliability and performance of complex systems which included both people and technology.

From this background, the methodology known as Cognitive Work Analysis has developed. What this method attempts to do is to take a holistic view of a complex system within which evaluations of various aspects of the system can be assessed.

[Vicente, 1999] describes the overall approach as consisting of five interrelated phases of modelling:

1. *The work domain* – purpose and structure of the system being controlled
2. *Activity or control task analysis* – what needs to be done in the work domain
3. *Mental strategies* – the mechanisms by which control tasks can be achieved
4. *Social organisation* – who carries out the work and how it is shared
5. *Worker competencies* – the set of constraints associated with the workers themselves.

In principle there are many specific modelling techniques that could serve for each of these phases. However, the techniques most familiar to the CWA community are as follows

1. Work Domain Analysis, using the abstraction-decomposition space
2. Activity or control task analysis, using decision ladders
3. Mental strategies analysis, using flowcharting
4. Annotations of the models produced at other phases, indicating actors and their roles
5. The skill-, rule-, and knowledge-based behaviour distinction.

The CWA approach therefore provides an interrelated set of methodologies within which these differing aspects of a system can be mapped, examined and analysed. For example, CWA provides a means by which decision making within an environment can be associated with system goals and cognitive skills.

Figure 1 shows the three main areas of analysis involved in CWA – Work Domain Analysis, Activity Analysis and Strategies Analysis. The application of CWA to the C2 domain has only addressed the first two areas of analysis – WDA and Activity Analysis. These two steps are necessary precursors to the final analysis, and were carried out to assess the utility of the technique within the C2 domain. Although no modelling that would be recognisable to a cognitive scientists as cognitive modelling is produced in these first two steps, Work Domain Analysis and Activity Analysis nonetheless frame the needs, constraints and boundaries operating on the activity of any reasonable cognitive agent in the work domain of interest.

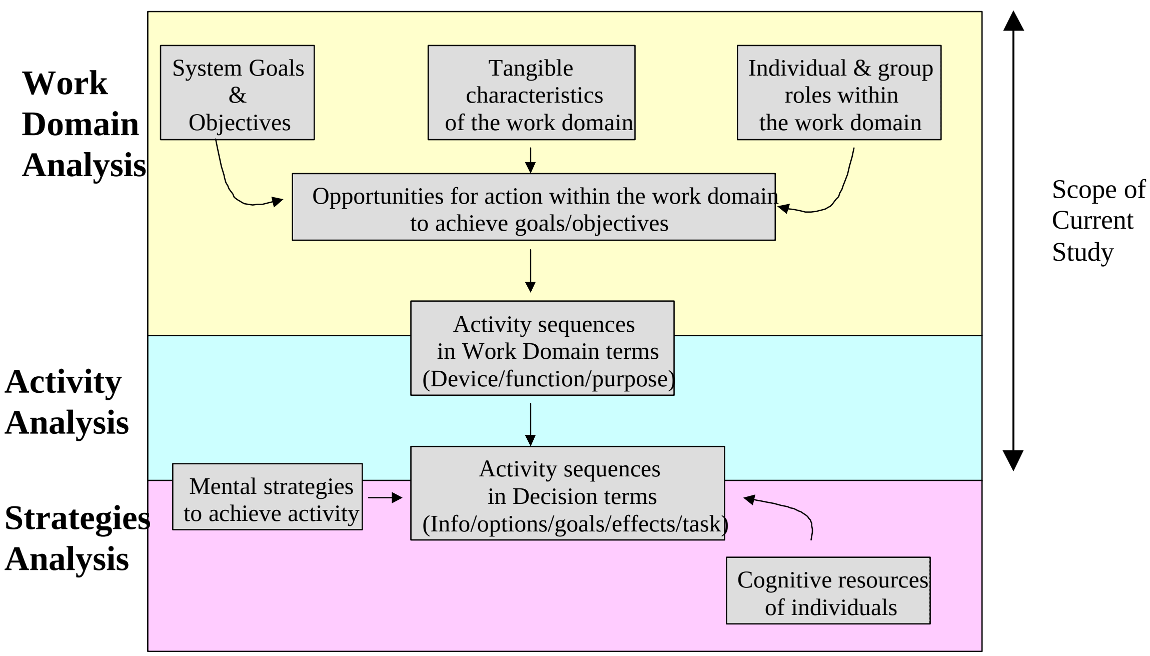


Figure 1 Three key areas of analysis in CWA and contributing elements.

The goal of the present exercise was to assess whether this framework would provide a representation that would connect C2 information with its purposive use within the context of the Australian Defence Force (ADF) C2 environment.

The initial analysis has examined the following:

1. A work domain analysis of C2 – which is essentially an event independent representation of the work environment and the artefacts within it
2. A work domain analysis of C2 with sample activity paths superimposed – which details prototypical activities by which the functional purpose of the system is realised.
3. Activity analysis of C2 in decision making terms.

The findings of these analyses were presented in a DSTO report [Sanderson & Watson, 1999]. A discussion of these findings and the utility of the outcomes is presented in this paper.

3. Work Domain Analysis of the C2 Domain

The WDA of the Australian Defence Forces' (ADF) C2 domain was based on work performed by [Rasmussen, 1998] in the context of SEAD-UAV systems. We produced an abstraction-aggregation space as shown in Figure 2. The two dimensions of abstraction and aggregation fix the 'space' or the terrain upon which purposeful activity occurs.

3.1 Means-Ends Relations

The Y axis of Figure 2 is the Abstraction axis and describes why the system exists, what priorities and values have been embedded in it, what its functions are, and how it is physically made up. This axis is often referred to as representing means-ends relations.

Definitions of the five levels of abstraction are as follows:

- *Functional purpose* – the ultimate reason that the ADF work domain exists.
- *Priority measures* – the priorities that must be given, the values that must be preserved or the resources that must be conserved for the ADF to work effectively.
- *Generalised functions* – the everyday functions of the ADF, where the physical aspects of the work environment conjoin to become possibilities for action in order to achieve the higher-level purposes of the ADF, subject to the ADF's priorities and values.
- *Physical functions* – the physical functioning of the physical objects in the system which offer agents in the system some possibilities for action
- *Physical objects/configuration* – the literal physical form and configuration of devices, objects, sensors and information technology in the work domain.

3.2 Part/Whole Decompositions

The X axis of Figure 2 shows the levels of aggregation and represent a decomposition of the work domain from its wholes into its parts.[2]

[2] Abreviations: CDF: Chief of the Defence Force; ADHQ: Australian Defence Headquarters; COMAST: Commander Australian Theatre; HQAST: Headquarters Australian Theatre; JFC: Joint Force Commander; ADF: Australian Defence Force.

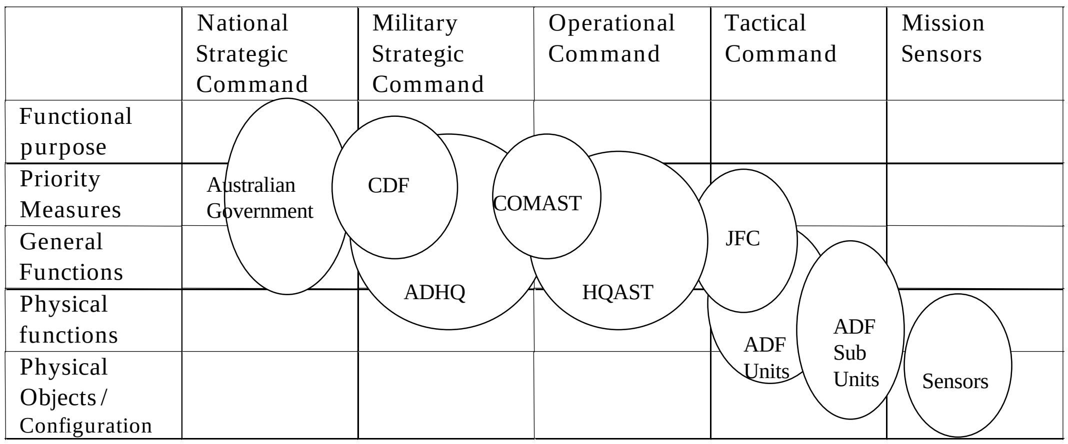


Figure 2. A decomposition of the work domain with ellipses showing differing focus for differing levels of command.

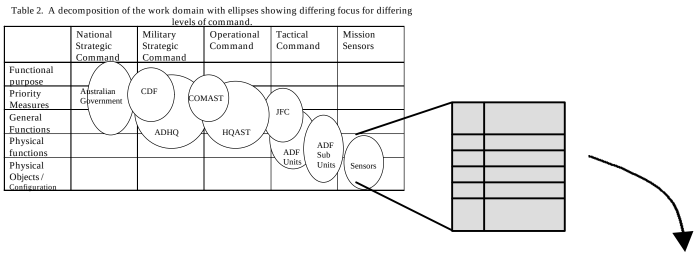
In terms of Figure 1, this table represents

- the tangible characteristics of the work domain
- individual and group roles within the work domain
- a framework within which opportunities for action to achieve goals can be more closely specified.

Figure 2 treats stakeholder domains (CDF, JFC, ADF subunits, etc) in the context of C2 for the whole of the ADF, viewed as a unifed system. Taken at the highest level of abstraction, the Australian Government would provide the values and priorities for the physical objects of the system – ADF units and subunits – to achieve their functional purposes.

The Australian Government and CDF also have general functions, physical functions or physical objects to deal with on a more immediate basis – and these analyses take place within their own particular sub-domains. Likewise, ADF subunits have a functional purpose and priority measures and values within their own particular sub-domains.

An example of an Abstraction- space for the sensor subdomain is given in Figure 3. As is shown, the typical five levels of abstraction are nested within the sensor region of the Table at top left, and the sensor region is nested within a larger abstraction-aggregation space.



	Mission Sensors
Functional purpose	• Support of operations according to mission plans
Priority Measures	• Cost-effective missions • Accuracy of information • Speed at which information can be passed to higher command • Security of information gathered
General Functions	• Collection and distribution of tactical intelligence on both friendly and enemy situations • Collection and distribution of battlefield intelligence
Physical functions	• Collection of visual and electronic information • Transfer and retrieval of information • Sensing within physical characteristics • Management of sensor rotational down time due to maintenance
Physical Objects/ Configuration	• Number and types of sensors available

Figure 3. Abstraction-Aggregation space for the sensor work domain.

3.3 Abstraction Hierarchies (AH) for Stakeholders

The next step is to examine the means-ends relationships between the levels of abstraction within each region of Figure 3 being analysed. In the current study, means-ends relations were shown by node-link representations, or lattices. The lattices show how purposes, priorities, functions and materials might become instantiated. They also show how physical objects and their functions are put to use, or "exploited", at the generalised function level to achieve the functional purpose of the work sub domain in the light of its goals and priorities.

The entries in the abstraction space shown in Figure 3 shows the '*what*' for each level but not why each entry exists or how it is supported. The Abstraction Hierarchy lattices in Figure 4, however, do show the 'why' and 'how' for each level of the sensor sub domain. At each node in the lattice, links running *up* from a node show *why* the node exists, and links running *down* show *how* it is instantiated.

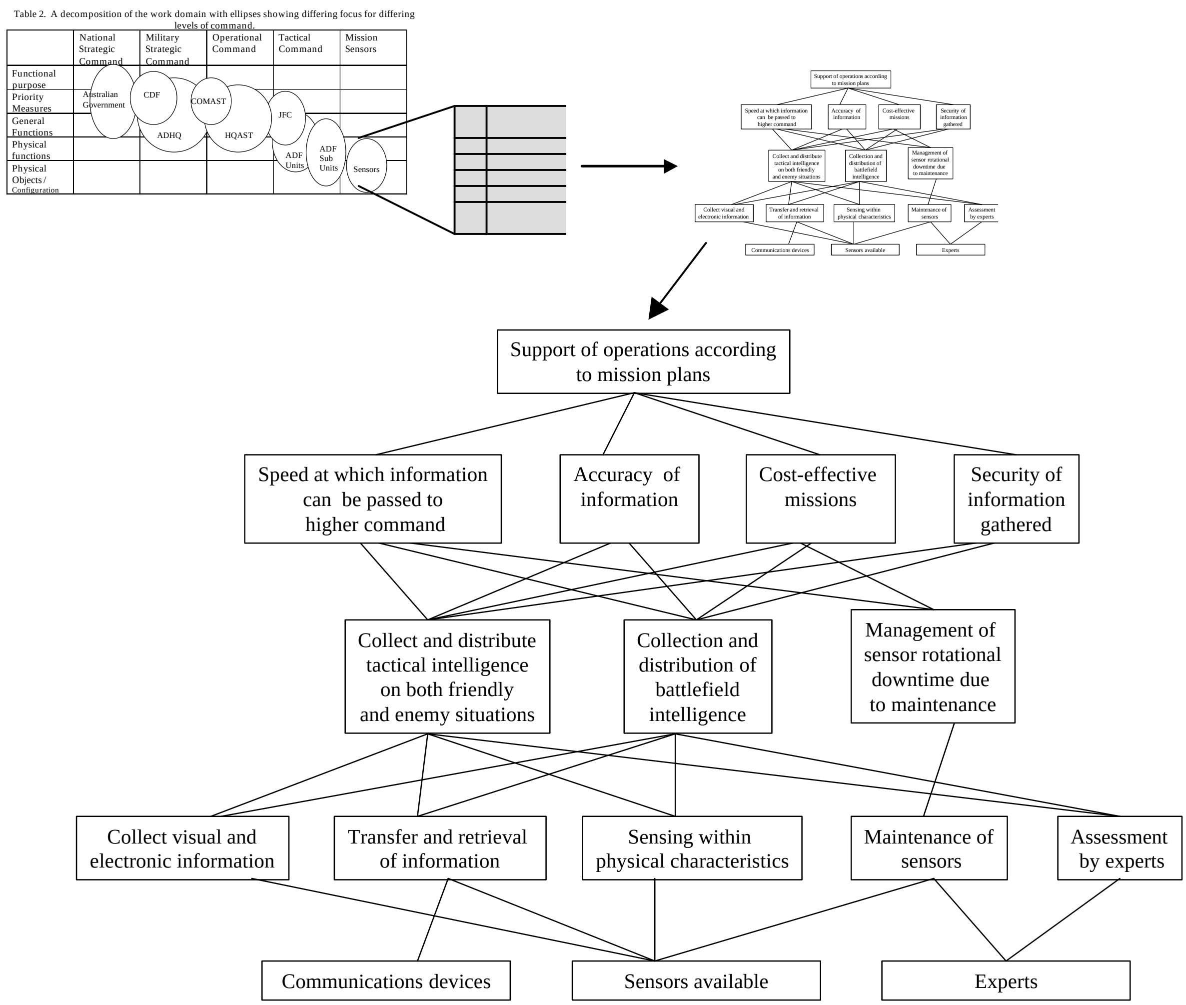


Figure 4 Abstraction hierarchy for the Sensor Level

Figure 4 shows the possibilities for action *within a single sub domain*. Abstraction hierarchies for the other sub domains were also constructed and then means-ends relationships *between the sub domains* were developed. The example used in Figure 5 below shows the stakeholders within a C2 structure communicating and exercising command across levels in a strictly hierarchical arrangement. Commands issuing from a hierarchically superior sub domain in some physical form (bottom level) relate to a particular functional purpose (top level) in the hiearchically subordinate sub domain.

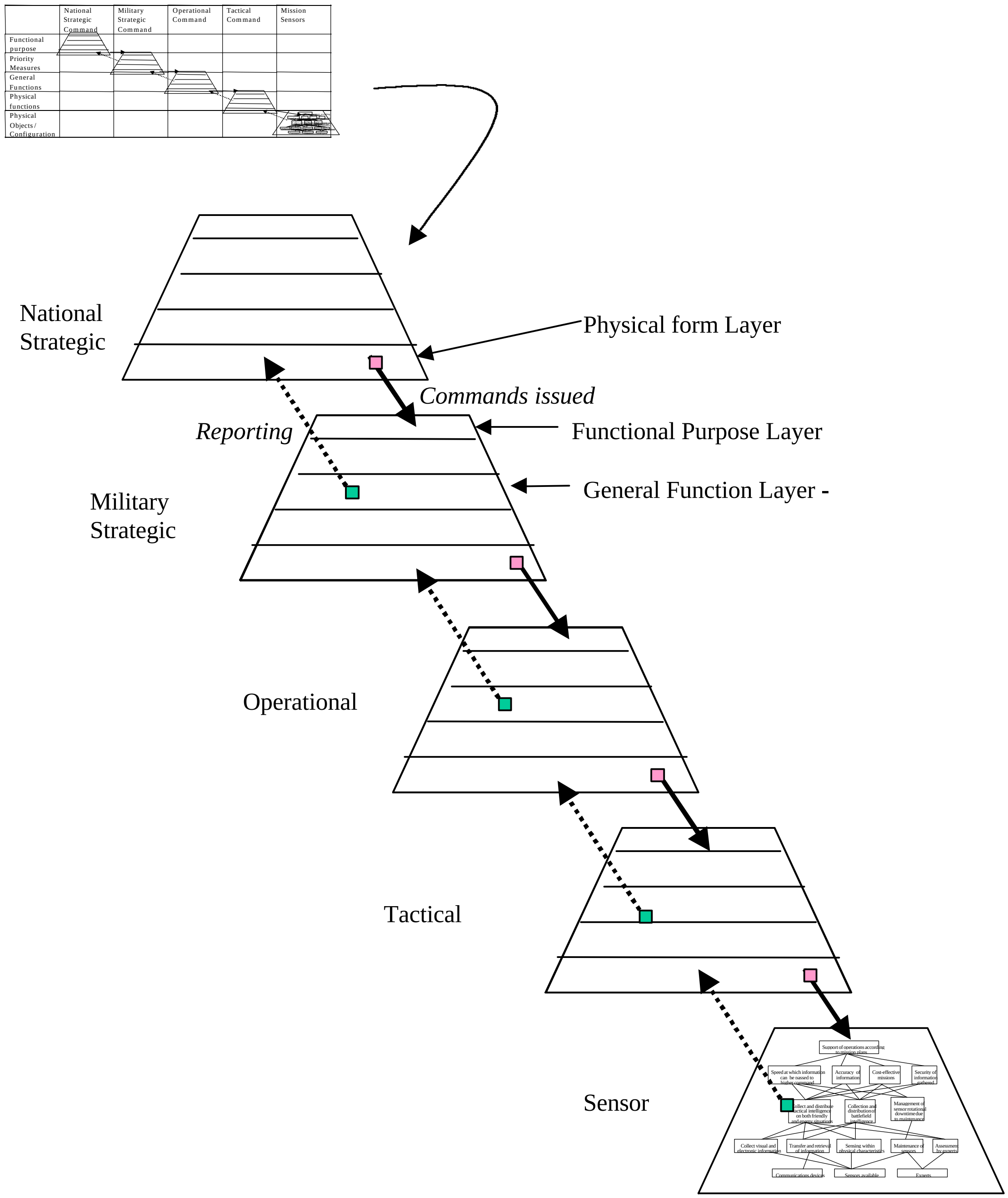


Figure 5 Means-Ends relationships across subdomains

The assumption here was that the different levels of C2 (or sub domains) communicate intentions and information through the physical form level. Intent is conveyed downwards in the form of commands (in some physical form) to the functional purpose level of the domain below. This intent is then used by the subordinate subdomain to formulate its priorities and values and to determine the relevant general function which would satisfy that command. Information about the conduct of general functions at a given C2 level is transmitted upwards to the physical form level of the subdomain above in the form of a report. Figure 5 shows schematically how the subdomain hierarchies were related. These linked structures show how information in a tangible form is connected to its purposive use within an integrated work domain.

4. Work domain analysis of C2 plus C2 activity paths

Although WDA builds an event-independent structure, it does highlight the opportunities for action. The next step in the analysis was to select a particular path through those opportunities – or to instantiate the structure with a particular scenario. It is important to note that with this scenario we are not providing a normative description of the flow of command, control, communication and information. Instead, the intention was to show how the work domain analysis, viewed as a broad formative account of the possibilities for action, can describe a particular configuration of the C2 system and how that particular configuration deals with a prototypical scenario.

The activities chosen were a specific case of the flow of command, control, communication and information between C2 levels. The chain of events involves a report from an infantry patrol moving up the chain of command shown in Figure 5 and being integrated with other forms of information until it reaches the National Strategic command level.

The arrows running upward in Figure 5 are a summary of multiple arrows in a larger format version which trace the flow of information about asset employment, the state of the world, plus sensor and intelligence information. The arrows run from the general function level – where such judgements are usually synthesised - through to the physical form level of the higher subdomain - since in the scenario we are instantiating judgments are conveyed through a physical medium.

Arrows running downward show commands being transmitted to other C2 levels through a physical medium. The commands have been generated through activity that takes into account the structure of the work domain, and are transmitted across C2 levels using physical forms such as documents, electronic communications media etc. When commands arrive at a subordinate level, actors instantiate that WD structure so that the functional purpose is fulfilled eg “Carry out tasks issued by a higher command.” A particular general function at that WD level is then chosen so that the WD’s functional purpose might be achieved.

Figure 6 shows a particular instantiation of the sensor level represented in generic form in Figure 5. The sensor activity being described relates to a human sensor – a patrolman. The general functions of the person on patrol are described as ‘collection and distribution of tactical intelligence…’; ‘collection and distribution of battlefield intelligence’; ‘management of sensors..’. These functions are achieved by using the physical objects: human body senses, radio and experts (ie trained observer) – to perform the physical functions: ‘collect visual and electronic information’; ‘transfer and retrieval of information’; ‘sense within physical characteristics’; ‘maintenance’; ‘assessment by experts’.

The general functions produce information which requires a decision to be made. This decision-related information is passed upwards (dots-dash lines) in a physical form to the Tactical/Sub-Unit C2 level above in the form of documents and database updates. The results of the decision making processes at the higher levels are passed back down to the sensor level (dashed lines) as physical documents in the form of commands and orders. These orders determine the priorities which form the basis for action choices at the general function level. Other influences on general functions are doctrine and output from expert systems at the level above as well as the direct intervention of staff from the Subunit level in the management of the patrolmen at the sensor level.

Figure 6 describes one of many possible sequences of activities which could take place within this particular sub domain. Again, the WDA shows the possibilities for action and is a framework for tracing how activity invokes the physical and purposive aspects of the work environment itself.

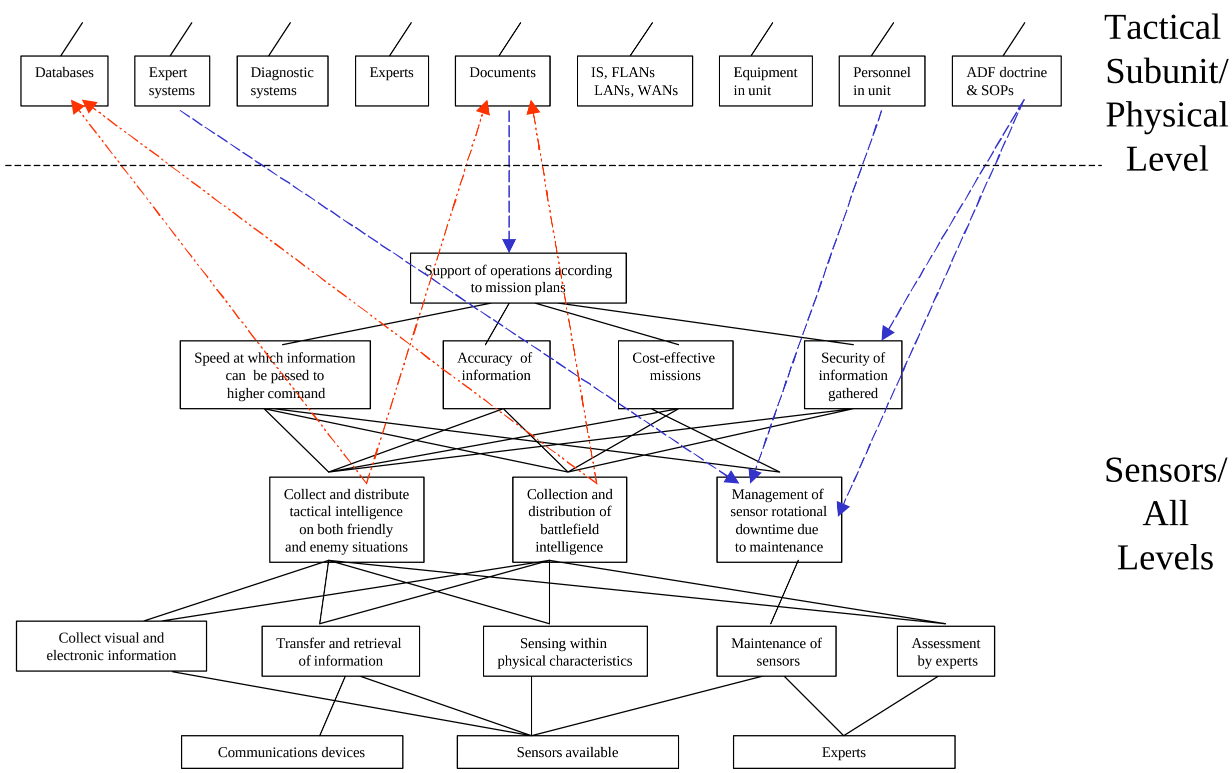


Figure 6 C2 activity (downwards) & Reporting Activity (upwards) in work domain terms

5. Activity Analysis in Decision Terms

In the previous section, activities were represented as instantiations of 'possibilities for action' that are available within a work domain, given how the work domain is constructed. In order to commit to a particular series of actions, decisions on a path through these various possibilities must be taken. The actors within the work domain must make choices about how to deal with any particular event. In CWA terms, such activities are termed Control Tasks. How information is gathered, a path of action chosen, and a means of action formulated can be framed with Rasmussen's Decision Ladder template (see Figure 7). Briefly, the decision ladder is a generic representation of the steps that may be involved in decision making [Rasmussen *et al*, 1994]. It is a "template" because it allows the analyst to show how a particular step is instantiated in the current case, and to show that for a particular decision, some steps may not be needed.

In [Chin and Clothier, 1998], we described C2 activity as consisting of three major components – Transforming (determining relevance of an event), Informing (relaying and receipt of information on the event) and Command/Intent (how intent is realised). The left side of Rasmussen's decision ladder could be described as the transforming aspects of C2, and the right side could be described as the implementation of intent, or command aspects of C2. The Informing aspects or information exchange, are detailed at various rungs within the decision ladder descriptions. Figure 8 shows that the generic labels in Figure 7 have been replaced with specific labels describing decisionmaking activities within the C2 work domain from the Sub Unit to the National Strategic levels.

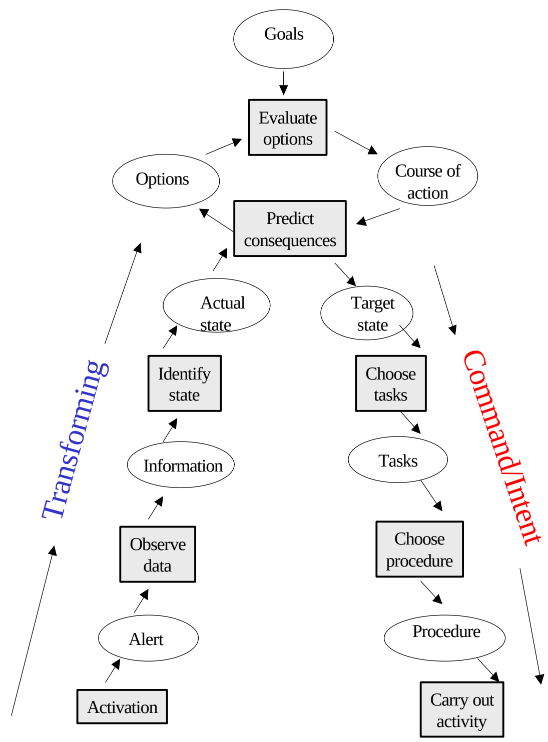


Figure 7 Generic decision ladder showing the basic information processed in a decision task

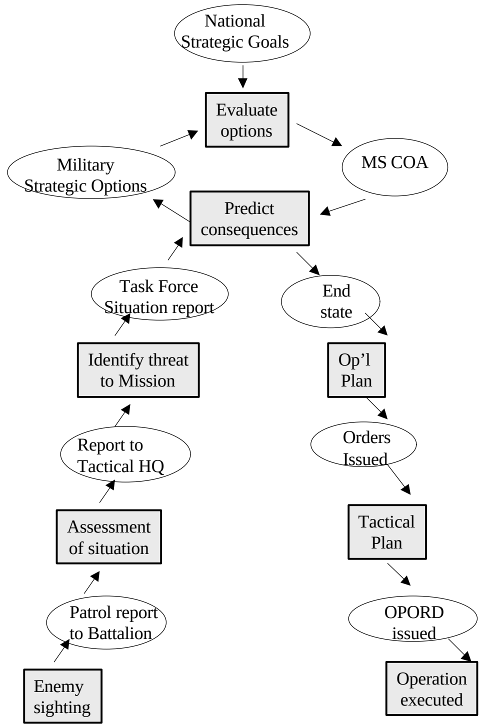


Figure 8 Overview decision ladder showing C2 decision tasks across levels of command

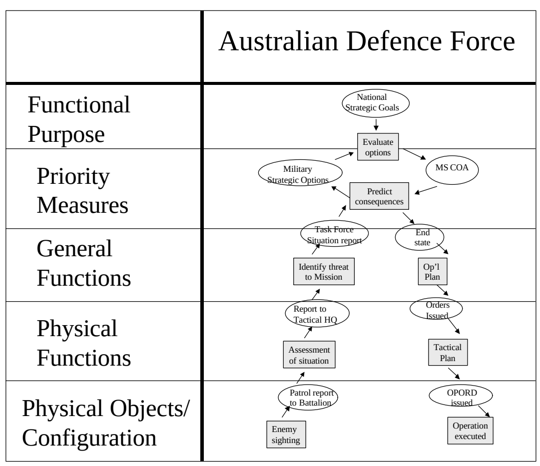


Figure 9 Aggregated C2 Decision Ladder within the Abstraction space

Each activity within the decision ladders can be broken down further into nested decision ladders – depending on the level of granularity required. For example, 'Identify State' (a single node on the generic decision ladder) could itself become a decision ladder which starts with information provided and ends with an activity which issues the current state of the system. In addition, decision activities may jump via shortcuts from one side of the ladder to another, or there may be iterations around particular activities. Again, the decision ladder is a formative template against which many possible literal decision trajectories can be represented.

The decision ladder in Figure 9 is a large-scale view, modelling the ADF as a whole decisionmaking entity and showing the progression of an event across the Defence hierarchy. Figure 9 can be broken out into a series of decision ladders related to the particular C2 work sub domains as depicted in Figure 10. This process is recursive and can be reapplied depending on the amount of detail required for the analysis.

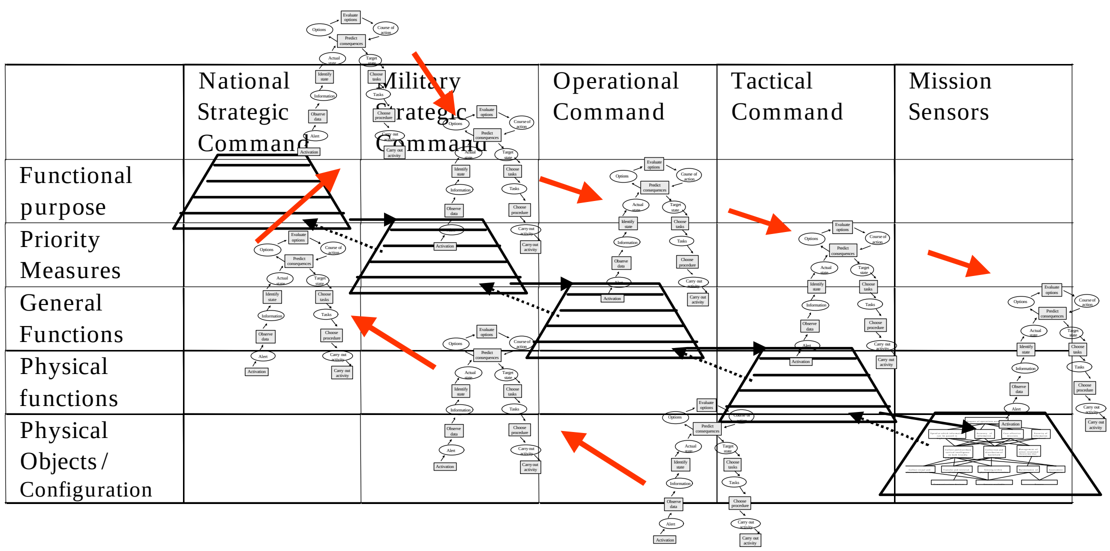


Figure 10 Nested Decision Ladders within the Work Domain and the Activity Analysis frameworks.

This type of representation can also be annotated with the possible *timespans* for a response to be generated. When used in conjunction with the WDA, decision ladders can be used to determine:

- Which agents make which decisions
- Which agents are in the best positions to make a decision
- Where the command structure supports timely decision-making
- Whether responses draw on the maximum available information
- Where decision support systems might be implemented to good effect[3].

6. Results

6.1 Advantages:

- Intent-driven analysis

The most useful aspect of CWA as a modelling approach is that it allows the analyst to move from a high-level conceptual view of a C2 situation, to a detailed information and object flow view, whilst maintaining an enterprise view of purpose, intent, goals and capability. This becomes important when trying to assess or review particular capabilities from an enterprise, operation or functional perspective.

[3] This is achieved by further decomposition of the work domain into human and computer domains. Having the two side by side shows where computers perform decision-making activity and where the change occurs on the decision ladder to human-centred decision-making.

- C2 inventory

CWA also allows a more studied approach to answering the question – ‘How much C2 support is enough?’. When information, systems and activities can be identified for probable task sequences, sufficiencies and gaps in IT and process capability can be more easily identified, attributed, justified and addressed in a systematic manner.

- Decision timeframes

Another useful outcome of this type of analysis is the identification of decision paths and their associated timeframes. Mapping actual and probable decision paths in response to actual or predictable events allows an identification of timeframes for decision making under varying conditions. When this is associated with the work domain analysis, the functional activity descriptions and the roles of the participants, there emerges the possibility of *identifying decision paths on a dynamic basis*.

For example, if time is the critical factor, what is the fastest, least constraining decision path possible which will ensure an appropriate decision is made? Or, if time is not a critical factor, which decision path will lead to a decision which best reflects the goals and values of the enterprise? If we can provide Commanders in Headquarters or in the field with the ability to identify an optimal decision path given a particular set of circumstances and particular set of criticality variables, the opportunities for more informed decision making could be facilitated.

- Friendly/unfriendly comparisons

Another application of the CWA approach is to do a comparative decomposition of both the friendly and unfriendly domains. This would be a more complex procedure but would certainly allow for the incorporation of enemy strength and goals in the overall analysis.

- Reuse of analytic products

We have found that the results of a major CWA-based analyses, such as the one performed here, can be used to solve a variety of different problems relating to analysis, modelling, design, and evaluation of human-system integration [Sanderson, Naikar, Lintern, & Goss, 1999]. Therefore there is considerable potential for re-use of the results of CWA analyses.

6.2 Drawbacks:

There are, however, some drawbacks with the CWA approach. These are:

- Required Skill Levels

There is a prerequisite level of knowledge, skill and experience in applying this approach. To deliver accurate information within a reasonable timeframe to an organisation, there is a requirement for skilled analysts as well as subject matter experts. If an organisation were to adopt this approach, it would need to train and retain analysts with a variety of CWA experience on an ongoing basis. However once developed, an analysis can be maintained and used across multiple problems relating to the system in question.

- Integrating other modelling approaches

As shown in Section 2, CWA integrates a set of modelling efforts that range from modelling the work domain (or work environment) in which activity takes place, to modelling the cognitive competencies of actors working within the work domain. A question that emerges is whether some of the modelling techniques proposed by researchers using CWA are intended to replace modelling techniques directed at similar questions, but based in other approaches, or whether different forms of modelling can coexist usefully.

It is possible that CWA is best viewed as an integrative framework, where useful insights come from dividing modelling into the five phases described in Section 2, and showing the integration between them. Where the models come from is probably less important than whether the models provide the information needed at each phase, and how effectively those models are integrated. While arguing the in-principle feasibility of this position, CWA researchers are only just starting to consider the practicalities of how legacy modelling efforts can be integrated with other modelling efforts under the CWA framework.

7. Future Work

There are two major CWA areas which were unexplored by the current analysis. The first is the comparative breakdown between friendly and unfriendly forces. [Sanderson and Watson, 1999] have suggested a framework within which this could be accomplished. The second, is to connect the current analyses of cognition-shaping or cognition-demanding factors from the work domain itself and the control tasks required within it, with descriptions of the cognitive activity of individuals and teams. We may be able to determine how cognitive abilities of individuals and the arrangements for distributed cognition within teams influence possibilities for action, and therefore success, within the C2 work domain.

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