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Work Domain Analysis: Theoretical Concepts and Methodology

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ABSTRACT

This report contributes to the development of a coherent theoretical and methodological approach for work domain analysis (WDA), the first phase of cognitive work analysis. The report: (1) addresses a number of conceptual issues relating to WDA, including differences in the approaches of Rasmussen, Pejtersen, and Goodstein (1994) and Vicente (1999); (2) proposes a methodology for performing WDA; and (3) illustrates the theoretical concepts and methodology for WDA with a work domain of a home – a 'system' that will be highly familiar to everyone. This research will help to: make WDA more accessible to researchers and practitioners who were not involved in the development of WDA or who cannot be apprenticed to experts in WDA; reduce the amount of time and effort it takes to perform WDA even for experts in WDA; and facilitate the application of WDA to large-scale industry projects. In addition, by making the methodology for WDA more explicit, this research will allow the methodology, or at least parts of the methodology, to be tested empirically.

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Executive Summary

Cognitive work analysis (Rasmussen, Pejtersen & Goodstein, 1994; Vicente, 1999) is receiving increasing attention as a promising approach for the analysis, design, and evaluation of complex sociotechnical systems. At the Defence Science and Technology Organisation (DSTO), we have applied cognitive work analysis (CWA) to a number of major Defence projects. We have used CWA to: define training needs and training-system requirements for the acquisition of a training system for F/A-18 fighter aircraft (Naikar & Sanderson, 1999); evaluate competing design proposals for the provision of an Airborne Early Warning and Control system to the Australian Government (Naikar & Sanderson, 2001); develop a team design for the Airborne Early Warning and Control system (Naikar, Pearce, Drumm & Sanderson, 2003); and develop training strategies to help F-111 pilots and navigators detect and recover from human error (Naikar & Saunders, 2003). The program at DSTO has demonstrated that CWA can be extended to applications beyond interface design and it has also demonstrated the practical relevance and feasibility of CWA for industry projects.

As a result of the research program at DSTO, the demand for the application of CWA techniques on Australian Defence projects is extremely high. The ability of DSTO to meet this demand, however, has been limited by the lack of a coherent theoretical approach and methodology for CWA. Due to these factors, the application of CWA is generally limited to researchers and practitioners who were involved in the development of CWA or who can be apprenticed to CWA experts (also see Lind, 2003; Vicente, 2000). In addition, due to these factors, CWA can be time consuming and effortful to perform even for experts in the area.

To address these problems with the application of CWA to Defence projects, the Chief Defence Scientist of DSTO approved a Key Initiative in Cognitive Work and Safety Analysis (CWSA) to commence in July 2003. The aim of this Key Initiative is to establish a DSTO Centre for CWSA to facilitate the application of CWSA techniques, including CWA, to the land, maritime, air, and joint environments. To achieve this aim, one of the major research directions of the Centre is to contribute to the development of a coherent theoretical and methodological approach for CWA.

In this report, we focus on the development of a coherent theoretical and methodological approach for work domain analysis (WDA), the first phase of CWA. We: (1) address a number of conceptual issues relating to WDA, including differences in the approaches of Rasmussen et al. (1994) and Vicente (1999); (2) propose a methodology for performing WDA; and (3) illustrate the theoretical concepts and methodology for WDA with a work domain of a home – a 'system' that will be highly familiar to everyone. This research will assist in: making WDA more accessible to researchers and practitioners who were not involved in the development of WDA or who cannot be apprenticed to experts in the area; reducing the amount of time and effort it takes to perform WDA even for experts in the area; and facilitating the application of WDA to large-scale industry projects. In addition, by making the methodology for WDA more explicit, this research will allow the methodology, or at least parts of the methodology, to be tested empirically.

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Neelam Naikar is a Senior Research Scientist at DSTO. Her major projects include the extension of cognitive work analysis to support the acquisition of complex, military systems, such as Airborne Early Warning and Control and F/A-18, and the application of AcciMap analysis and the critical decision method to enhance safety in complex, military systems, such as the F-111. Her current research interests include the development of theories and methods for analysing cognitive work and safety in complex systems. Neelam obtained a Bachelor of Science degree with Honours in Psychology from the University of New South Wales, Australia, in 1993 and a PhD in Psychology from the University of Auckland, New Zealand, in 1996.

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Robyn Hopcroft joined DSTO as a Human Factors Engineer in 2001 after graduating with a Bachelor of Behavioural Science degree with Honours from La Trobe University, Australia, in 2001. Robyn has worked on a variety of projects including the development of training interventions to improve safety in F-111 operations and the investigation of the usefulness of multi-layer displays for tracking of multiple objects. Her current research interests include the evaluation of advanced technologies for enhancing battle management command and control and the development of theories and methods for cognitive work analysis.

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Contents

1. Introduction

Cognitive work analysis (Rasmussen, Pejtersen & Goodstein, 1994; Vicente, 1999) is receiving increasing attention as a promising approach for the analysis, design, and evaluation of complex sociotechnical systems. Researchers have explored the use of cognitive work analysis (CWA) for: designing interfaces (e.g., Burns, 2000b; Burns, Bryant & Chalmers, 2000; Dinadis & Vicente, 1999; Gualtieri, Elm, Potter & Roth, 2001; Linegang & Lintern, 2003; Rasmussen, 1998; Reising & Sanderson, 1998; Vicente, 1992a,b; Vicente, Christoffersen & Pereklita, 1995); designing teams (e.g., Gualtieri, Roth & Eggleston, 2000; Naikar, Pearce, Drumm & Sanderson, 2003); evaluating design proposals (Naikar & Sanderson, 2001); analysing training needs (Naikar & Sanderson, 1999; Naikar & Saunders, 2003); and developing specifications (Leveson, 2000). The majority of studies on CWA have focused on its application to interface design.

At the Defence Science and Technology Organisation (DSTO), we have applied CWA to a variety of problems on a number of major Defence projects. We have used CWA to: define training needs and training-system requirements for the acquisition of a training system for F/A-18 fighter aircraft (Naikar & Sanderson, 1999); evaluate competing design proposals for the provision of an Airborne Early Warning and Control system to the Australian Government (Naikar & Sanderson, 2001); develop a team design for the Airborne Early Warning and Control system (Naikar et al., 2003); and develop strategies for training F-111 pilots and navigators to detect and recover from human error (Naikar & Saunders, 2003). The program at DSTO has demonstrated that CWA can be extended to applications beyond interface design and it has also demonstrated the practical relevance and feasibility of CWA on industry projects.

As a result of the research program at DSTO, the demand for the application of CWA techniques on Australian Defence projects is extremely high. The ability of DSTO to meet this demand, however, has been limited by the lack of a coherent theoretical approach and methodology for CWA. Due to these factors, the application of CWA is generally limited to researchers and practitioners who were involved in the development of CWA or who can be apprenticed to CWA experts (also see Lind, 2003; Vicente, 2000). In addition, due to these factors, CWA can be time consuming and effortful to perform even for experts in the area.

To address these problems with the application of CWA to Defence projects, the Chief Defence Scientist of DSTO approved a Key Initiative in Cognitive Work and Safety Analysis (CWSA) to commence in July 2003. The aim of this Key Initiative is to establish a DSTO Centre for CWSA to facilitate the application of CWSA techniques, including CWA, to the land, maritime, air, and joint environments. To achieve this aim, one of the major research directions of the Centre is to contribute to the development of a coherent theoretical and methodological approach for CWA.

In this report we focus on the development of a coherent theoretical and methodological approach for work domain analysis (WDA), the first phase of CWA. The most comprehensive accounts of WDA to date are provided by Rasmussen et al. (1994) and Vicente (1999). These texts are invaluable resources for WDA, and CWA in general. However, due to a number of factors, these texts still leave WDA relatively inaccessible to many researchers and practitioners. First, the two texts appear to present somewhat different theoretical approaches to WDA. For instance, whereas Vicente advocates that work domain models should not contain representations of activity, many of the examples provided by Rasmussen et al. seem to do so. Second, the text by Rasmussen et al. is generally considered as difficult to read (e.g., Reising, 1999b). Third, although Vicente's book is highly readable, many of the theoretical concepts of WDA are explained in the context of DURESS, a thermo-hydraulic microworld simulation. Consequently, it can be difficult to extract the general principles of WDA from Vicente's book, especially if the reader is unfamiliar with thermo-hydraulic systems, and to apply WDA to new or different work systems.

Finally, both Rasmussen et al. (1994) and Vicente (1999) focus on theoretical concepts for WDA while providing only a comparatively limited discussion of a methodology for WDA. The nature of the methodological discussions in both texts is that of providing "hints" for WDA (Rasmussen et al., p. 55; Vicente, p. 171). The hints provided by Rasmussen et al. are limited to the sources of information that are useful for WDA. The hints provided by Vicente are limited to the process of constructing the abstraction-decomposition space, the main modelling tool for WDA. Neither set of hints is particularly comprehensive. Moreover, WDA involves many more steps than identifying the sources of information for the analysis and constructing the abstraction-decomposition space. For example, WDA also involves establishing the purpose of the analysis and identifying the boundaries of the analysis. While these and other aspects of WDA are referred to by Rasmussen et al. and Vicente in different parts of their books, and occasionally in some other papers on WDA (e.g., Hajdukiewicz, Burns, Vicente & Eggleston, 1999), these steps are not treated extensively or discussed in a logical sequence that highlights the relationships between the various steps for performing WDA.

As well as the texts by Rasmussen et al. (1994) and Vicente (1999), there are many other publications on WDA. Generally, these publications report particular applications of WDA or the results of empirical evaluations that compare a WDA-based approach to interface design to more traditional approaches to interface design (e.g., Burns, 2000b; Burns, Bryant et al., 2000; Dinadis & Vicente, 1996, 1999; Gualtieri et al., 2000, 2001; Linegang & Lintern, 2003; Naikar et al., 2003; Naikar & Sanderson, 1999, 2001; Rasmussen, 1998; Reising & Sanderson, 2002a,b). For several reasons, however, these papers also leave WDA relatively inaccessible to many researchers and practitioners. First, these papers provide very little information about how the WDA that was the basis of these studies were performed. Second, although these papers provide examples of WDA for a variety of work systems, as with Vicente's book, it is difficult to glean the general principles of WDA from these examples and to apply WDA to new or different work systems. Third, there appears to be some variation in different analysts' approaches to WDA. For example, many analysts seem to use different definitions for the levels of abstraction in an abstraction-decomposition space. The recent text by Burns and Hajdukiewicz (2004) contains more information about how to perform WDA and how WDA was performed for a variety of work systems. However, it can still be difficult to extract the general principles of WDA from the examples in the book and to apply WDA to new or different work systems. In addition, the book does not address differences in the approaches of Rasmussen et al. and Vicente to WDA.

One reason for the limited attention to a methodology for performing WDA is that the focus of scientists and practitioners to date has been on: explaining the theoretical concepts of CWA, as in the texts by Rasmussen et al. (1994) and Vicente (1999); evaluating whether WDA leads to better design products than other approaches to work or task analysis; and evaluating the feasibility and usefulness of WDA on large-scale, industry projects. This was probably a reasonable direction in which to proceed – there is no point in developing a methodology for WDA without first knowing what WDA is and what the benefits of WDA are. Vicente, in fact, explicitly discusses that for these kinds of reasons the lack of attention to methodology in his book was deliberate. Now, however, we have several resources for understanding the theoretical concepts of WDA as well as considerable evidence for the benefits of WDA from both laboratory and industry studies. It is therefore an appropriate stage in the evolution of the WDA framework to invest in developing a methodology for WDA.

This report contributes to the development of a coherent theoretical and methodological approach for WDA by: (1) addressing a number of conceptual issues relating to WDA, including differences in the approaches of Rasmussen et al. (1994) and Vicente (1999); (2) proposing a methodology for performing WDA; and (3) illustrating the theoretical concepts and methodology for WDA with a work domain of a home – a 'system' that will be highly familiar to everyone. This line of research will assist in: making WDA more accessible to researchers and practitioners who were not involved in the development of WDA or who cannot be apprenticed to experts in WDA; reducing the amount of time and effort it takes to perform WDA even for experts in the area; and facilitating the application of WDA to large-scale, industry projects. In addition, by making the methodology for WDA more explicit, this research will allow the methodology, or at least parts of the methodology, to be tested empirically.

We start by providing a general theoretical introduction to CWA, WDA, and the abstraction-decomposition space. We believe that, like many other approaches to work or task analysis, a methodology for WDA cannot be completely specified. Therefore, it is important to have a sound understanding of the theoretical foundations of CWA, WDA, and the abstraction-decomposition space so that WDA is not performed in a way that is inconsistent with theory. Given that the texts by Rasmussen et al. (1994) and Vicente (1999) focus on theory, our theoretical introduction to CWA, WDA, and the abstraction-decomposition space is relatively brief. We focus instead, in the later sections of this report, on specific conceptual issues relating to WDA that have not been discussed comprehensively, or even at all, in the texts by Rasmussen et al. and Vicente, and on defining a methodology for WDA.

2. Cognitive Work Analysis

CWA is a framework for work analysis that is especially well suited for the analysis, design, and evaluation of complex sociotechnical systems (Rasmussen et al., 1994; Vicente, 1999). This framework recognises that an essential characteristic of complex sociotechnical systems is that they are dynamic. The dynamic nature of these systems is a result of several factors including the fast pace of technological change; the computerisation of work; and the high levels of integration and coupling of work systems which mean that changes in one work system quickly propagate to other work systems. Due to these factors, the goals and work demands of complex sociotechnical systems are frequently changing.

The CWA framework also recognises that another major characteristic of complex sociotechnical systems is that they have high levels of automation. Stable, routine conditions in these systems are handled by computer algorithms whereas the main role of human workers is to deal with novel or unfamiliar situations. Novel or unfamiliar situations pose a significant threat to system performance and safety (Vicente, 1999). However, because these are situations that were not, and even cannot be, anticipated at the time of design, workers cannot rely on pre-planned work procedures for dealing with the novel or unfamiliar conditions. Instead, dealing with these situations requires improvisation and creative problem solving by workers.

Given these and other characteristics of complex sociotechnical systems, the CWA approach recognises that the design of such systems cannot be based solely on assumptions about stable goals and work demands or on pre-planned work procedures for dealing with routine and anticipated events. Rather, design must support effective adaptation to new and changing conditions, especially those that cannot be predicted at the time of design. This means that the design of these systems must be flexible enough to allow workers "… to reconfigure patterns of behaviour, to modify effective routines, to combine elementary routines into new patterns, and to generate new work procedures on demand." (Rasmussen et al., 1994, p.31).

The CWA approach proposes that workers will be able to adapt effectively to new and changing work conditions if they are aware of the boundaries of acceptable performance. In essence, the boundaries of acceptable performance are defined by the objectives, work requirements, and resources of a work system. These are the fundamental constraints on workers' behaviour – workers must achieve the objectives and work requirements of the work system with the available resources. Within these fundamental constraints, however, workers have many degrees of freedom, or a large space of possibilities, for what to do and when and how. In other words, workers can adopt many different sequences of tasks or trajectories of behaviour to fulfil the objectives and requirements of a work system with the available resources. Therefore, as long as they have knowledge of the objectives, work requirements, and resources of a work system, workers can select and even create patterns or trajectories of behaviour to keep or bring a work system into a desired state while remaining within the boundaries of acceptable performance. In this sense, complex sociotechnical systems exhibit the features of closed-loop, adaptive systems (Rasmussen et al., 1994).

Designing to support adaptation therefore requires a framework for work analysis that can define the boundaries on acceptable performance. Table 1 shows that CWA consists of several phases of analysis for identifying the different types of boundaries or constraints in a work system. These phases of analysis are presented slightly differently by Rasmussen et al. (1994) and Vicente (1999). Using Vicente's labels for the phases of CWA[1]: WDA identifies the purposes, values and priorities, functions, and physical

[1] Although we use Vicente's (1999) labels for the phases of CWA, the descriptions of the types of constraints that are the focus of each phase are not Vicente's descriptions but our own descriptions based on our understanding of Rasmussen et al. (1994) and Vicente.

resources of a work domain; control task analysis identifies the activity that is required in a work domain (in order to achieve the purposes, values and priorities, and functions of a work domain with a given set of physical resources); strategies analysis identifies how the activity can be carried out; social organisation and cooperation analysis identifies who can do the work and how it can be shared; and worker competencies analysis identifies the perceptual and cognitive capabilities of workers that are required for performing the work described in the previous phases. CWA therefore spans the constraints imposed by the work domain or work context to the constraints imposed by the cognitive requirements of workers. In this report, we focus on WDA or, in other words, on the analysis of the boundaries or constraints that are imposed by the work context.

Table 1. The phases of CWA as they are presented by Vicente (1999) and Rasmussen et al. (1994) and the types of boundaries or constraints that are the focus of each phase of analysis.

Vicente (1999)	**Rasmussen et al. (1994)**	**Types of Boundaries or Constraints**
Work domain analysis	Work domain analysis	Purposes, values and priorities, functions, and physical resources.
Control task analysis	Activity analysis in work domain terms and activity analysis in decision making terms	Activity in terms of work situations, work functions, and control tasks.
Strategies analysis	Activity analysis in terms of mental strategies	Strategies for carrying out activity.
Social organisation and cooperation analysis	Analysis of the work organisation	Distribution of work including allocation of work to individuals; organisation of individuals into teams; and communication requirements.
Worker competencies analysis	Analysis of system users	Perceptual and cognitive capabilities of workers

3. Work Domain Analysis

3.1 Overview

The main aim of WDA is to model the constraints that relate to the purposive and physical context in which workers operate. The purposive context imposes constraints on workers by specifying the purposes that the work system must fulfil, the values and priorities that the work system must satisfy, and the functions that the work system must perform. The physical context imposes constraints on workers by specifying the physical objects that are available in the work system and the functional capabilities and limitations of the physical objects. The purposive and physical work context together define the fundamental problem space of workers by specifying the purposes, values and priorities, and functions that must be achieved by a work system with a given set of physical resources. Within the constraints imposed by the purposive and physical work context, however, workers have many options or possibilities for action in the work domain.

A point that is sometimes not appreciated about WDA, and about CWA in general, is that constraints are modelled in terms of categories – as opposed to examples or instances (Rasmussen et al., 1994). Hence, WDA models categories of purposes, values and priorities, functions, and physical resources rather than instances of purposes, values and priorities, functions, and physical resources. To illustrate, a category of function that is afforded by a home is cooking. There are many examples or instances of cooking, such as boiling pasta, baking a cake, simmering a casserole, and frying fish. WDA does not represent these specific instances of cooking but instead represents the general category of cooking. The examples or instances can be seen as members of the categories modelled by WDA. As a result, the relatively small number of categories modelled by WDA can capture or accommodate a large variety of instances. WDA therefore does not model the actual functioning of work systems in particular instances but produces a generalised representation of a work domain. This approach is necessary for complex sociotechnical systems or, more specifically, closed-loop, adaptive systems because it would be very complex, if not impossible, to represent the actual functioning of work systems in all possible instances given that goals, work requirements, and work conditions are frequently changing.

A key characteristic of WDA is that it is event-independent (Vicente, 1999). In other words, the categories of constraints identified by WDA are relevant to many different situations, including novel or unanticipated events. To illustrate, the purposes of a work system do not change from situation to situation nor do the physical resources that are available in the work system. Therefore, when confronted with novel or unanticipated events, workers can rely on their knowledge of the work-domain constraints to explore a variety of ways for dealing with the situation while remaining within the boundaries of acceptable performance.

The work-domain constraints determine the "regularity" of a work system's behaviour (Rasmussen et al., 1994, p.49). Specifically, by defining the conditions that a work system must respect regardless of situation, the constraints allow workers to predict how a work system will respond and to plan their activities in a variety of circumstances. To illustrate, in a work domain of a home, a purpose or objective of the inhabitants may be to save money by ensuring that their total income is greater than their total expenses. This constraint allows inhabitant A to predict how inhabitant B is likely to respond if their average income is $500 per week, their average expenses are $450 per week, and inhabitant B is faced with a decision about whether to engage in a hobby that will cost approximately $100 per week. This constraint also allows inhabitant B to plan his/her activities (i.e., explore his/her options and make a decision) in this situation. Similarly, the physical resources of a home, such as the number of rooms, the number of beds, and the number of alternative temporary bedding arrangements can be used to plan how many guests it is possible to accommodate on weekends and to predict how many guests the inhabitants are likely to invite.

Rasmussen et al. (1994) discuss how work systems can be characterised along a continuum in terms of the nature of the constraints that determine the regularity of their behaviour. The nature of the constraints can be causal or intentional. Causal constraints have their basis in physical laws such as the laws of nature. Intentional constraints have their basis in social laws, conventions, and values such as organisational objectives, formal or informal rules of conduct, and actors' intentions and work practices. Where a work system falls along the causal-intentional continuum will depend on the relative degree or weight of the causal and intentional constraints in the work system. If a work system is primarily causal, it means that its behaviour is mainly determined by causal rather than intentional constraints. If a work system is primarily intentional, it means that its behaviour is mainly determined by intentional rather than causal constraints. Many technical systems (e.g., industrial process plants) are primarily causal so their behaviour can be predicted or planned on the basis of the laws of nature. Many social systems (e.g., universities) are primarily intentional so their behaviour can be predicted or planned on the basis of social laws, conventions, and values. However, the location of a work system along the causal-intentional continuum will also depend on the purpose or focus of the WDA. A home can be classified as primarily causal if the focus of the WDA is on modelling the technical system that provides shelter. Alternatively, the same home can be classified as primarily intentional if the focus of the WDA is on modelling the social system that promotes the wellbeing of inhabitants.

3.2 Comparison with Standard Techniques for Task Analysis

WDA offers a significantly different approach to work analysis compared with standard techniques for task analysis. Whereas WDA focuses on analysing the boundary conditions or constraints of a work system, task analysis focuses on describing workers' tasks or trajectories of behaviour (e.g., Kirwan & Ainsworth, 1992). Task analysis is event-dependent because trajectories of behaviour can only be defined for specific situations with known goals and work requirements. Consequently, task analysis can only specify the information or knowledge that workers need for dealing with routine or anticipated situations. In contrast, by focussing on the analysis of constraints, WDA offers an event-independent approach to work analysis that can identify the information or knowledge that workers need for dealing with a wide variety of situations, including novel or unanticipated events.

These and some other distinctions between WDA and task analysis can be illustrated by example. Consider the analysis of a home. Task-analysis techniques will focus on analysing the trajectories of behaviour in a home. Because this approach is event-dependent, the results of a task analysis will be highly dependent on the number and types of observations that are made, for example, the number and types of time periods in which a home is observed (e.g., morning, day, evening, night) and the number and types of people who are observed (e.g., inhabitants, visitors, tradespeople). Hence, although a task analysis may reveal that the inhabitants of a home typically enter the house through the front door, it may not reveal that the inhabitants enter the house through a window when they forget their house keys. In general, task-analysis techniques are more likely to identify the trajectories of behaviour that occur in routine or commonly occurring situations while missing the kinds of behaviours that occur in less familiar, novel, or unanticipated situations.

In contrast to task analysis, WDA will focus on analysing the constraints or boundary conditions of a home. So, for example, WDA will focus on identifying the location of the walls, doors, and windows of a house. These constraints are event-independent and can capture the multiple possibilities for action in a home in a wide variety of situations. For instance, the constraints may reveal that people can enter a home through the front door, back door, windows, and chimney. WDA can therefore accommodate both routine behaviours and new behaviours that may occur in unexpected situations, such as entering the home through the window in the event of forgetting the house keys.

The distinctions between WDA and task analysis can also be illustrated by considering the trajectories of behaviour inside a house. People can obviously adopt an infinite number of trajectories for moving from one part of a house to another. It would therefore be very difficult, if not impossible, to identify all of the trajectories for movement through a house. Hence, task-analysis techniques will generally be limited to identifying typical or commonly occurring trajectories of movement. In contrast, WDA can capture all of the possibilities for movement through a house by identifying the constraints associated with the physical structure and layout of the house.

The examples that we have just discussed focus on how the physical context of a home can shape people's behaviour. However, the purposive context of a home can also shape people's behaviour. For instance, the objective of saving time will constrain whether people decide to cook a meal or order a take-away meal. Similarly, the objective of saving money will constrain whether people decide to paint their house themselves or to hire a painter. WDA can accommodate all of these possibilities for behaviour whereas, depending on the number and types of observations that are made, task analysis may only identify some of these behaviours. For example, task analysis may only identify the behaviour associated with cooking a meal and not the behaviour associated with ordering a take-away meal.

4. Abstraction-Decomposition Space (ADS)

The abstraction-decomposition space (ADS) is the main tool for modelling the purposive and physical work context or problem space of workers. Table 2 illustrates that the ADS structures the problem space of workers along two orthogonal dimensions – the abstraction dimension and the decomposition dimension[2]. The abstraction dimension is typically shown along the vertical axis of the ADS whereas the decomposition dimension is typically shown along the horizontal axis of the ADS. The abstraction dimension is also referred to as the abstraction hierarchy or means-ends dimension whereas the decomposition dimension is also referred to as the decomposition hierarchy or part-whole dimension. An example of an ADS of a home is presented in Table 4 and discussed in detail in Section 4.4. However, readers may want to review Table 4 now because it may help them to appreciate some of the concepts of the ADS that we discuss in the following sections.

[2] The ADS in Table 2 has five levels of abstraction and three levels of decomposition. However, as discussed in Sections 5.1 and 7.1 of this report, the number of levels of abstraction and decomposition in an ADS can vary.

Table 2. A generic ADS with five levels of abstraction and three levels of decomposition. The shaded cells illustrate that workers tend to reason or adopt models along the diagonal of the ADS.

	Whole System	Subsystems	Components
Functional Purposes			
Values and Priority Measures			
Purpose-related Functions			
Object-related Processes			
Physical Objects			

4.1 Abstraction Dimension

The abstraction dimension typically structures the problem space of workers in terms of five levels: (1) the purposes of the work system and the external constraints on its operation (functional purposes); (2) the criteria that the work system uses for measuring its progress towards the functional purposes (values and priority measures); (3) the general functions of the work system that are necessary for achieving the functional purposes (purpose-related functions); (4) the functional capabilities and limitations of physical objects in the work system that enable the purpose-related functions (object-related processes); and (5) the physical objects in the work system that afford the object-related processes (physical objects). The top three levels of abstraction, which model the purposive properties of the problem space, define the reasons for the work system's behaviour. The bottom two levels of abstraction, which model the physical properties of the problem space, define the resources for the work system's behaviour. The abstraction dimension therefore integrates a global, top-down view of human purposes with a detailed, bottom-up view of physical resources.

Although the different levels of abstraction in the ADS describe the same work domain, each level of abstraction uses a different set of concepts to represent that work domain[3]. Viewing a work domain at different levels of abstraction is therefore like viewing the work domain with different conceptual lenses. For instance, the first level of abstraction provides a view of the purposes of the work domain, the third level of

[3] Each level of abstraction has a different *language* for representing the concepts at that level. The language of the different levels of abstraction is discussed in Section 5.3.

abstraction provides a view of the functions of the work domain, and the bottom level of abstraction provides a view of the physical world of the work domain. The conceptual lenses at each level of abstraction therefore change the view of the work domain when moving up and down the abstraction dimension rather than removing or adding details about the work domain.

Studies by Rasmussen (1979) have shown that workers spontaneously shift their view of the work domain, from purposive models to physical models, to match their task demands. Workers will adopt purposive models when viewing their task demands in terms of the purposes to be achieved. On the other hand, workers will adopt physical models when viewing their task demands in terms of the physical resources that are available for performing the tasks.

4.1.1 Means-Ends Relations

The relationships between the different levels of abstraction in the ADS are means-ends relations. These relationships, which can be characterised in terms of a how-what-why triad (Rasmussen et al., 1994; Vicente, 1999), are illustrated graphically in Table 3. In the table, Purpose-related Function A specifies *what* is under consideration. Relationships from Purpose-related Function A to the level below, in this case Object-related Processes B and C, indicate the means or *how* Purpose-related Function A can be engineered or implemented. Relationships from Purpose-related Function A to the level above, in this case Values and Priority Measures D, specifies the ends or *why* Purpose-related Function A is present in the work system. This how-what-why triad can be applied by starting at any level of abstraction in the ADS.

Studies by Rasmussen (1979) have shown that operating or reasoning in a work system involves exploring the available means for achieving the immediate ends. Therefore, the level of abstraction at which workers formulate their work requirements at any given point in time specifies *what* should be done. At the next lower level of abstraction, workers can perceive these work requirements in terms of the means for achievement, that is, *how* it can be done. At the next higher level of abstraction, workers can perceive these work requirements in terms of the ends to be achieved, that is, *why* it should be done.

Vicente (1999) emphasises that the means-ends relations between the different levels of abstraction in the ADS are structural means-ends relations rather than action means-ends relations. The latter describe the tasks or actions that are necessary for achieving certain goals whereas the former describe the purposive and physical context, or structure, within which actions occur and which in fact shapes the actions of workers[4]. To recast an example provided by Vicente, furnace and fireplace are structural means for achieving warmth because they represent the physical resources or physical context that can be used to achieve warmth. In contrast, going down to the basement and lighting the fireplace are action means for achieving warmth because they represent the tasks that can

[4] We have described structural and action means-ends relations in terms that are consistent with those that we have used earlier in this report. See Vicente (1999) for alternative descriptions of structural and action means-ends relations.

be used to achieve warmth. The physical resources that are available for achieving warmth will shape the tasks that carried out by workers.

Table 3. A generic ADS illustrating means-ends relations between some of the levels of abstraction.

	Whole System	Subsystems	Components
Functional Purposes			
Values and Priority Measures	Value and Priority Measure D		
Purpose-related Functions	Purpose-related Function A		
Object-related Processes	Object-related Process B; Object-related Process C		
Physical Objects			

In complex work domains, there are many-to-many means-ends relations between the different levels of abstraction. Models at lower levels of abstraction are related to a specific physical world which can serve several purposes. In the case of a home, a telephone line can be used to ring someone or to connect to the internet. Conversely, models at higher levels of abstraction are related to a specific purpose which can be met by several physical arrangements. For example, meals can be prepared by using a stove, a microwave, or an oven. The many-to-many relationships between the different levels of abstraction highlight that there are multiple options for action for fulfilling the objectives of a work system. If this were not the case, the work of the system would be totally predetermined and there would be no need for human decision-making.

The many-to-many means-ends relationships therefore reflect the complexity of the decisions or choices faced by workers. Given that a purpose or a function at a particular level of abstraction can be achieved by several alternative means at the level below (e.g., meals can be prepared with a stove, a microwave, or an oven), workers must decide which is the best means for achieving the purpose or function in question at any particular point in time. Moreover, several purposes or functions at a particular level of abstraction may require the same means for implementation at the level below and compete for the use of those means (e.g., ringing someone and connecting to the internet both require the use of a telephone line). Hence, workers must consider how using means or resources to fulfil a particular purpose or function may impact on achieving other purposes or functions in the work domain.

As a result of the many-to-many relationships between the different levels of abstraction, workers' actions or decisions can have both intended and unintended effects on the work domain. For instance, a function at a particular level of abstraction can usually affect more than one end at a higher level of abstraction. Some of the effects at the higher level may be intended whereas other effects may be unintended. In the case of a home, cooking a meal (in contrast to buying one) will save money but it will also increase the time spent on chores. Saving money may be a desirable effect of cooking a meal but spending more time on chores may not. Workers must therefore consider both the intended and unintended effects of their actions or decisions on the work domain.

In routine or highly familiar situations, the means-ends relations that must be considered by workers are usually well established and stable. Decision making in these situations is relatively straightforward and reflects either skill- or rule-based reasoning (Rasmussen et al., 1994). For example, in a work domain of a home, people may know the effects of eating out more than once or twice a week on their savings so that making a decision about whether to eat out or not on any particular occasion may be relatively straightforward. On the other hand, in novel situations, workers must explicitly explore all possible means-ends relations, given the particular conditions, and select the means that are best suited for fulfilling the objectives at hand. For example, in a work domain of a home, inhabitants may need to explicitly consider all possible means-ends relations in deciding whether to accommodate an elderly parent at home or in a nursing home. Additional means-ends relations may be revealed in these situations as previously unobserved effects of particular states or decisions on the work domain. Decision making in these situations can be relatively challenging or demanding and is characterised by knowledge-based reasoning (Rasmussen et al., 1994).

Finally, reasoning about the propagation of means-ends effects in a work system is necessary for ensuring that the actual state of a work system is in line with its desired state. Effects at the higher levels of abstraction will redefine the desired state of the system and propagate downwards whereas effects at the lower levels of abstraction will redefine the actual state of the system and propagate upwards. In a work domain of a home, changing an objective from saving $50 per week to saving $100 per week will redefine the desired state of the system and propagate downwards affecting inhabitants' decisions about whether meals are prepared at home or bought from a restaurant. Alternatively, changes to the physical resources of a home, such as the breakdown of the dishwasher, will redefine the actual state of the system and propagate upwards influencing inhabitants' decisions with respect to how they redistribute the amount of time they have available for chores.

4.2 Decomposition Dimension and Part-Whole Relations

The decomposition dimension represents the problem space of workers at different levels of detail. Table 2 shows an ADS with three levels of decomposition: whole system, subsystems, and components. At the first level of decomposition, the problem space is described for the entire system as a single whole. At the next level of decomposition, the problem space is described for each of the subsystems. At the third level of decomposition, the problem space is described for each of the components. Therefore, at the whole system level of decomposition the work domain is represented at a very coarse level whereas at the component level of decomposition the work domain is represented at a very fine-grained level.

The relationships between the different levels of decomposition are part-whole relations. Lower levels of decomposition are *parts of* the higher levels of decomposition – the components are parts of the subsystems which are parts of the whole system. Conversely, higher levels of decomposition are *wholes of* or *composed of* the lower levels of decomposition – the whole system is composed of subsystems which are composed of components. Therefore, in moving across the axis from left to right, the whole system is decomposed into its parts. In moving across the axis from right to left, the components are aggregated into meaningful wholes.

Each level of decomposition represents a different level of resolution for viewing a work domain. As described by Vicente (1999, p. 158), moving from left to right is like "zooming in" because each consecutive level offers a more detailed view of the same work domain whereas moving from right to left is like "zooming out" because each consecutive level offers a less detailed view of the same work domain. Hence, whereas the abstraction dimension of the ADS represents the different conceptual lenses with which workers can view a work domain, the decomposition dimension represents the level of resolution of the conceptual lenses.

The decomposition dimension reflects the span of attention of workers. Studies by Rasmussen (1979) have shown that workers spontaneously shift their span of attention, from the entire system to single components, to match their task demands. Workers will adopt coarse models of the system when viewing their task demands in terms of the control of the entire system whereas they will adopt finer models of the system when viewing their task demands in terms of the manipulation of individual components.

4.3 Coupling of the Abstraction and Decomposition Dimensions

Each cell in the ADS, which is defined by a particular level of abstraction and decomposition, offers a complete but different representation of the same work domain (Vicente, 1999). To illustrate, consider the top left cell and the bottom right cell in the ADS in Table 2. The top left cell represents the purposes of the whole system whereas the bottom right cell represents the physical form of individual components. Both cells offer a complete representation of the same work domain – the top left cell describes all of the purposes of the whole system whereas the bottom right cell describes the physical form of all of the individual components in the work system. However, each cell offers a different representation of the same work domain – the top left cell offers a purposive model of the whole system (coarse, purposive model) whereas the bottom left cell offers a physical model of individual components in the system (fine-grained, physical model).

Similarly, contrast the bottom left cell with the bottom right cell in the ADS. Both cells offer a complete representation of the work domain – the bottom left cell describes the physical form of the whole system whereas the bottom right cell describes the physical form of all of the individual components in the work system. Even though both cells offer a physical model of the work system, the two representations are different – the bottom left cell offers a physical model of the whole system (coarse, physical model) whereas the bottom right cell offers a physical model of individual components in the work system (fine grained, physical model). [5] These illustrations are similar to ones that appear in Vicente (1999).

We mentioned earlier that studies by Rasmussen (1979) have shown that experienced workers spontaneously switch between different models of the work system in order to match their task demands. Depending on their task demands, workers can adopt purposive or physical models of the work domain; this is reflected in the abstraction dimension of the ADS. In addition, depending on their task demands, workers can adopt coarse or fine-grained models of the work domain; this is reflected in the decomposition dimension of the ADS. However, the studies by Rasmussen also showed that when the conceptual lens with which workers view a work domain changes from purposive to physical models, the level of resolution at which workers view the work domain also changes from coarse to fine models and vice versa. Similarly, Vicente et al. (1995) have shown that when people are reasoning about a work system at higher levels of abstraction (e.g., functional purpose) they tend to use coarser levels of description (e.g., whole system). Conversely, when people are reasoning about a work system at lower levels of abstraction (e.g., physical objects) they tend to use finer levels of description (e.g., components). As a result, people tend to reason or adopt models along the diagonal of the ADS (see shaded cells in Table 2). Hence, although the two dimensions of the ADS are conceptually orthogonal, they are actually coupled in practice.

This mechanism of adopting coarse levels of resolution at higher levels of abstraction and fine levels of resolution at lower levels of abstraction offers a way for coping with complexity in the work domain (Vicente, 1999). When small parts of the work system have to be considered, workers can zoom into the details about individual components offered by lower-level conceptual models. However, when larger parts of the work system have to be considered, workers can zoom out so that the details are aggregated into higher-level conceptual models and they are not overwhelmed with the detail associated with individual components.

Finally, several studies have demonstrated that the ADS provides a model of the problem space of workers that is capable of accommodating a very large number of problem-solving trajectories for dealing with a variety of situations, including those that may be required to deal with novel or unanticipated events (e.g., Rasmussen & Jensen, 1974; Vicente et al., 1995). In these studies, workers' verbal protocols while performing various tasks were mapped onto the different cells of an ADS model of that work domain. The paths that workers took through the ADS reflected the levels of abstraction and decomposition that workers were thinking about in performing those tasks. The studies showed that workers adopted different problem-solving trajectories even when they were performing the same task and that all of these trajectories could be accommodated by an ADS model of the work domain. In addition, the studies showed that the ADS could accommodate the problem-solving trajectories that were associated with a variety of tasks in the work domain.

[5] For an alternative illustration of how each cell in the ADS offers a complete representation of the work domain see Section 11.

4.4 A Sample ADS – Work Domain of a Home

Table 4 shows a sample ADS for the work domain of a home. Although this ADS was not created through a thorough process of WDA, it is sufficient for illustrating the conceptual issues and methodology for WDA that we will discuss in later sections of this report. The ADS of a home in Table 4 has five levels of abstraction and three levels of decomposition. Each level of abstraction provides a different conceptual view of the work domain of a home. For example, the first level provides a view of the purposes of the home, the third level provides a view of the functions of the home, and the last level provides a view of the physical objects of the home. Each level of decomposition provides a different level of resolution for viewing the work domain of the home. At the highest level of decomposition, the focus is on the whole house. At the next level of decomposition, the focus is on the rooms and subspaces in the house, in this case, the kitchen. At the third level of decomposition, the focus is on the individual contents and components in the house, in this case, the dishwasher.

Each cell of the ADS therefore represents the home from a particular conceptual viewpoint and at a particular level of resolution. For instance, take the cells at the purpose-related functions level of abstraction. The cell at the first level of decomposition represents the functions afforded by the whole house. The cell at the next level of decomposition represents the functions afforded by the rooms and subspaces in the house, in this case, the kitchen. The cell at the third level of decomposition represents the functions afforded by the individual contents and components in the house, in this case, the dishwasher.

The cells along the diagonal of the ADS in Table 4 have been shaded grey. As we discussed earlier, workers tend to adopt purposive models of the work domain when working at coarse levels of resolution and physical models of the work domain when working at fine-grained levels of resolution. Hence, workers tend to reason along the diagonal of the ADS.

In the remainder of this report, we draw on the ADS of a home in Table 4 to illustrate the concepts and methodology for WDA. The entries in Table 4 that we use in our discussions are shown in italics in the body of the report. Where examples are taken from the rooms and subspaces and content and components levels of decomposition, we state this explicitly in the text. Otherwise, readers can assume that the examples are from the whole house level of decomposition.

We also note that the entries in Table 4 are single-word or short descriptions of the categories of constraints in the work domain of a home. These entries are not always self-explanatory. For example, one of the functional purposes in the ADS of a home in Table 4 is *wellbeing*. This representation does not depict that we defined wellbeing as a mental and physical state characterised by health, happiness, and prosperity. In Section 12.6 of this report, we discuss the need for a glossary that describes the entries in the ADS in greater detail. Although we do not supply a glossary for the ADS of a home in this report, we provide more detailed descriptions of the entries in Table 4 when it is necessary for our discussions.

Table 4. A sample ADS of a home.

	Whole House	Rooms and Subspaces (e.g., Kitchen)	Contents and Components (e.g., Dishwasher)
Functional Purposes	Shelter, Well-being, Residential laws and regulations, Environmental protection.	Provision of meals and beverages, Financial savings, Time savings, Environmental protection, Safety, Health.	Cleaning, Financial savings, Time savings, Environmental protection, Safety, Health.
Values and Priority Measures	Total income greater than total expenses by *n* dollars per week, Chore time less than *n* hours per week, Leisure time greater than *n* hours per week, Minimise use of natural resources (e.g., water, power), Minimise risk of injury, Minimise risk of intrusion, Maximise privacy, Maximise hygiene, Maximise pleasure.	Expenses less than *n* dollars per week, Chore time less than *n* hours per week, Minimise use of natural resources (e.g., water, power), Minimise risk of injury, Maximise hygiene, Maximise nutrition.	Minimise expenses, Minimise chore time, Minimise use of natural resources (e.g., water, power), Minimise risk of injury, Maximise hygiene.
Purpose-related Functions	Meals and beverages, Rest, Recreation, Personal care and grooming, Housework, Maintenance, Administration.	Storage, Preparation, Cooking, Serving, Cleaning.	Washing, Rinsing, Drying.
Object-related Processes	Functional capabilities and limitations relating to: storage, preparation, cooking, serving, cleaning, laundering, sleeping, exercise, entertaining, showering etc.	Functional capabilities and limitations relating to: cooling, freezing, cutting, stirring, heating, washing, rinsing, drying, wiping, disposing etc.	Functional capabilities and limitations relating to: support of objects (e.g., dishes), flow of water, storage and release of cleaning chemicals, temperature selection, cycle selection etc.
Physical Objects	Inventory, material characteristics, and topography of whole house including layout of rooms e.g., kitchen, bedroom, bathroom, toilet, lounge room, study.	Inventory, material characteristics, and topography of kitchen including layout of fridge/freezer, cutlery, utensils, stove, oven, microwave, crockery, pots and pans, dishwasher, taps, drains, sinks, tea towels, kitchen table, clock, calendar, rubbish bin, broom, food processor etc.	Inventory, material characteristics, and topography of dishwasher including: Shelves, Pipes, Detergent dispenser, Temperature selection dial, Cycle selection dial etc.

5. Abstraction Dimension

Having provided a general theoretical introduction to CWA, WDA, and the ADS we now turn to examining specific conceptual issues relating to WDA and the ADS, starting with the abstraction dimension. Many of the conceptual issues we discuss in this report were identified as a result of the difficulties that we confronted both in performing WDA for complex, military systems and in learning about WDA from Rasmussen et al. (1994) and Vicente (1999). These conceptual issues must be considered by any analyst in performing WDA.

5.1 Number of Levels of Abstraction

One of the main issues to consider in performing WDA is the number of levels of abstraction to include in an ADS. The five levels of abstraction that are commonly included in the ADS were developed by Rasmussen in the context of process control and manufacturing systems and then tested with hospitals and library systems (Rasmussen, 1998). Since then the ADS has been used to model a variety of other work systems, including aviation systems (e.g., Amelink, van Paassen, Mulder & Flach, 2003; Dinadis & Vicente, 1999; Ho & Burns, 2003; Nadimian, Griffiths & Burns, 2002); military command and control systems (e.g., Burns, Bryant et al., 2000; Hajdukiewicz et al., 1999; Lintern, 2002; Lintern & Naikar, 2002); medical systems (e.g., Hajdukiewicz, Doyle, Milgram, Vicente & Burns, 1998; Hajdukiewicz, Vicente, Doyle, Milgram & Burns, 2001; Watson, Russell & Sanderson, 2000); and network management systems (e.g., Burns, Barsalou, Handler, Kuo & Harrigan, 2000; Burns, Kuo & Ng, 2003; Duez & Vicente, 2003a,b). Although analysts have sometimes reported three (e.g., Burns & Vicente, 2000) and four (e.g., Bisantz, Roth, Brickman, Lin Gosbee, Hettinger & McKinney, 2003; Burns, Garrison & Dinadis, 2003) levels of abstraction, the majority of the ADS models have adopted Rasmussen's five levels of abstraction. Rasmussen has recently indicated that while at one stage he thought that the five levels of abstraction might have been an artifact of thermodynamic systems, he is now convinced that the five levels of abstraction are conceptually necessary and sufficient (in Reising, 2000). Vicente (1999), however, points out that although the five levels of abstraction have been useful for a variety of applications, there is no reason to believe that the same five levels of abstraction will be relevant to all work systems. If we accept Vicente's position, one difficulty is the lack of an explicit process for identifying the number of levels of abstraction for modelling the work system of interest (also see Lind, 2003). While this is a topic that can benefit from further research we believe that there is merit in beginning to outline such a process here.

Previously we discussed that the abstraction dimension structures the problem space of workers in terms of the different concepts that workers can use for reasoning in a work system. From this it follows that the number of levels of abstraction to include in an ADS can be determined by studying the number of conceptual levels in the reasoning space of workers. A variety of techniques can be used to study the different concepts that workers can use for reasoning in a work system. Rasmussen and Jensen (1974), for example, used verbal protocol analysis to study the reasoning space of workers as they carried out certain tasks. Other techniques that are relevant, and which we will discuss in greater detail in Section 12 of this report, include document analysis, interviews, and table-top analysis.

As we will illustrate shortly, the data that are obtained with these techniques can be studied for references to the properties of a work domain that workers can use for reasoning in a work system. Several sets of data collection exercises will generally be necessary with analysts using the work-domain properties that have already been identified, together with 'how' and 'why' questions, as a basis for identifying further work-domain properties. The work-domain properties in the data will usually be in the form of specific examples or instances. Therefore, once a comprehensive set of work-domain properties has been obtained, the process for identifying the number of conceptual levels that workers use for reasoning in the work system will involve grouping the work-domain properties into categories, sorting the categories into similar and dissimilar concepts, and then organising the concepts into a hierarchy of means-ends relationships.

To illustrate, in carrying out observations of a home, analysts may find that inhabitants refer to various activities like boiling pasta and making a casserole. Using these work-domain properties as a basis, analysts can explore 'how' the inhabitants are boiling pasta and 'why' they are boiling pasta and the same for making a casserole. The inhabitants may recount that they are cooking pasta because they got back late from work and that pasta does not take long to cook and that they boil pasta in a pot using a stove. Or they may recount that they are making a casserole because they had the day off work so they had more time to spend on cooking a meal and that they make a casserole using a casserole dish and an oven. From this data, analysts can identify that the work-domain properties of boiling pasta and making a casserole, which are specific instances of cooking, can be grouped into the general category of *cooking*. Analysts can also identify that *time* is a property that influences how people cook or what they choose to cook in the work domain. Moreover, analysts can determine that *cooking* is a function and that this is a fundamentally different concept to *time* which is a value or priority measure. On the other hand, *pot*, *casserole dish*, *stove*, and *oven* are similar concepts because all of these work-domain properties are physical objects in the home. The concept of physical objects, however, is different to the concepts of functions or values and priority measures. Analysts can then order the concepts into a hierarchy of means-ends relations. In the example discussed here, the hierarchy that is evident is: *pot/casserole dish/stove/oven – cooking – time*.

Constructing the abstraction dimension using this process involves adhering to a number of criteria. First, the representations at the different levels of abstraction must be of categories rather than of specific instances. Boiling pasta and making a casserole refer to specific examples or instances of cooking. Therefore, the general category of cooking should be included in the ADS rather than the specific instances of boiling pasta and making a casserole. Second, the representations in the ADS must not include action means-ends relationships (Vicente, 1999) or, in other words, sequences of tasks or trajectories of behaviour. An example of a hierarchy of action means-ends relationships for boiling pasta is: put water in pot – place pot on stove – light the stove

- boil water – add pasta. Instead, the representations in the ADS must be of structural means-ends relationships (Vicente, 1999) or, in other words, the physical and purposive context for boiling pasta. In the example discussed above, the physical context for boiling pasta includes physical objects such as stove and pot and the purposive context for boiling pasta includes the reasons for boiling pasta such as time.

The two criteria that we have just discussed are necessary for ensuring that the ADS is event independent. Rather than describing specific instances or particular trajectories of behaviour, the ADS must capture the multiple possibilities for action that are possible in the work domain. This is achieved through representing categories of constraints and structural means-ends relationships in the ADS.

A third criteria for constructing the abstraction dimension is that the levels of abstraction in the ADS must represent different conceptual viewpoints of the work domain rather than representing more or less detail about the work domain. To illustrate, if we represent cooking and boiling pasta at two different levels of abstraction in an ADS, boiling pasta simply adds more detail about cooking by providing a specific example of this function. This is a common mistake that novice analysts make in developing the abstraction dimension; that is, they add or remove details from particular levels of abstraction to create the other levels of abstraction in the ADS.

Finally, we note that a distinction can be made between the number of levels of abstraction that workers can use for reasoning in a work domain and the number of levels of abstraction that are useful for the purpose of a WDA. As discussed by Lind (1992), a good model is not necessarily one that offers the most detailed description of a work domain but also one that is efficient for solving a particular problem. In the case of a home, it may be sufficient for the purpose of a WDA to model how the physical objects in the work domain enable the purpose-related functions of the home rather than to model how the processes of the physical objects enable the purpose-related functions of the home; therefore, analysts may choose not to model the object-related processes level of abstraction in the ADS.

Earlier in this section we highlighted that the majority of ADS models in the literature adopt Rasmussen's five levels of abstraction. It appears that analysts have found these five levels of abstraction useful for a variety of purposes in several work domains. Consequently, we base many of the following discussions in this report on Rasmussen's five levels of abstraction.

5.2 Labels for the Levels of Abstraction

Although many analysts have adopted Rasmussen's five levels of abstraction in their ADS models, they have sometimes used different labels for the levels of abstraction. The most commonly used set of labels for the five levels of abstraction includes some variation of the following terms: functional purposes, abstract functions, generalised functions, physical functions, and physical form (e.g., Amelink et al., 2003; Jamieson & Vicente, 2001; Nadimian et al., 2002; Rasmussen, 1986; Rasmussen, 1988; Rasmussen et al., 1994; Reising & Sanderson, 1996; Vicente, 1999). This set of labels was developed by Rasmussen for process control work domains and is well suited for causal systems. More recently, however, Rasmussen has suggested a new set of labels for the five levels of abstraction: functional purposes, values and priority measures, purpose-related functions, object-related processes, and physical objects (in Reising, 2000).

We describe both the old and new set of labels as generic labels because they are not specific to the work system under study. For the purposes of this report, we use Rasmussen's new set of generic labels for the five levels of abstraction because we agree with Reising (2000) that, compared with the old set of labels, the new set of labels makes more clear: the content of each level of abstraction, the relationships between the levels, and the relevance of the ADS to domains other than process control, including intentional domains. The new set of labels is therefore more helpful to analysts during the process of constructing an ADS.

In using the ADS to model military systems, however, we have found that neither set of generic labels is very meaningful to domain experts and that this may limit how readily domain experts relate to and even accept the ADS as a useful representation of their work domains. For this reason, analysts should consider using domain-specific labels that reflect the terminology of the work domain when presenting the ADS to domain experts. Sharp and Helmicki (1998), for example, developed domain-specific labels for the levels of abstraction in neonatal intensive care by studying the nomenclature used by medical experts: purpose; balance; processes; transport, storage, and control; physical form. Hajdukiewicz et al. (1998, 2001) also used similar labels for modelling the work domain of anaesthetists: purposes; balances; processes; physiology; anatomy. In addition, on one of our projects, the labels that evolved during the process of working with domain experts to refine an ADS for a military system included: purposes; capability priorities; mission functions; physical functions; and physical devices (Naikar & Sanderson, 2001).

5.3 Descriptions of the Levels of Abstraction

In this section, we present a comprehensive description of the five levels of abstraction that are commonly modelled in the ADS. We developed these descriptions by reviewing a range of publications on WDA by Rasmussen and by Vicente (e.g., Dinadis & Vicente, 1996, 1999; Hajdukiewicz et al., 1998, 2001; Hajdukiewicz & Vicente, 1999; Jamieson & Vicente, 2001; Miller & Vicente, 1998; Rasmussen, 1985, 1986, 1991, 1998, 1999; Rasmussen, Pedersen & Grønberg, 1987; Rasmussen & Pejtersen, 1995; Rasmussen et al., 1994; Rasmussen, Pejtersen & Schmidt, 1990; Vicente, 1992a; Vicente, 1999) and by various personal communications with Rasmussen and Vicente. From these sources we developed a greater appreciation of the five levels of abstraction than we were able to achieve from the two main texts on CWA (Rasmussen et al., 1994; Vicente, 1999).

As we have mentioned previously, analysts sometimes use different definitions for the five levels of abstraction in the ADS (e.g., Amelink et al., 2003; Bisantz et al., 2003; Burns, 2000a,b; Burns, Bryant et al., 2000; Dinadis & Vicente, 1996, 1999; Gualtieri et al., 2000, 2001; Linegang & Lintern, 2003; Naikar et al., 2003; Naikar & Sanderson, 1999, 2001; Rasmussen, 1998; Reising & Sanderson, 2002a,b). These variations may reflect real variations in the work systems that were studied. However, in the absence of explicit statements by analysts to confirm this, it must also be considered that the variations may reflect the lack of clear and comprehensive descriptions of the five levels of abstraction. Because we cannot be certain about the actual reasons for the variations, we do not accept or reject the definitions of different analysts but we document the variations and we discuss the relative merits of the alternatives with the aim of contributing to the development of a more coherent approach to WDA.

5.3.1 Functional Purposes

The first level of abstraction describes the purposes that a work system serves in its environment and the external constraints that the environment imposes on the work system. Many work systems have a very complex set of purposes consisting of primary and secondary objectives. The primary objectives define the reasons that a work system exists in its environment. A work system exists because the environment has certain needs and the work system can fulfil these needs. If the work system cannot fulfil these needs, or its primary objectives, it probably would not survive. For example, a primary objective of a home is to provide *shelter*; if a home cannot fulfil this objective it probably would not be occupied. Similarly, the primary objective of a commercial transport company may be to transport passengers according to schedule (Rasmussen et al., 1994); if the company cannot fulfil this objective it would probably become bankrupt.

The primary objectives of a work system generally leave many degrees of freedom for operation open which are then eliminated on the basis of the secondary objectives of the work system. The secondary objectives typically reflect the values of the people in the work system. For example, the inhabitants of a home may value a home that can promote a state of *wellbeing* in the inhabitants (where wellbeing is defined as a state characterised by health, happiness, and prosperity) rather than simply providing shelter. Similarly, whether a transport company is focussed on profit motives, safety, or passenger comfort will be influenced by the values of the work system (Rasmussen et al., 1994).

As well as the primary and secondary objectives of a work system, the functional purposes level of abstraction also describes the external constraints that the environment imposes on a work system. Generally, these constraints reflect the values of the environment or society. Sometimes these values may be formalised or legalised as laws and regulations. For instance, the external constraints on a home may include council *laws and regulations* relating to noise. Alternatively, the external constraints may reflect societal conventions and norms. For example, a society may value *environmental protection* and therefore provide recycled waste removal services for homes although there may be no laws or regulations directing that people must recycle their waste products. Similarly, the external constraints on a transport company may include laws and regulations relating to the pay and conditions of workers or to societal conventions and norms such as good customer service.

The functional purposes level of abstraction therefore describes both the values of the work system and the values of the environment or society. The values of the work system are reflected in the secondary objectives of the work system whereas the values of the environment are reflected in the external constraints on the work system.

Generally, the values of the work system and the values of the environment will be common to many work domains. For example, many different work systems value safety and profit. The values of the environment, such as concern for the natural environment and good customer service, will also be common to many work systems because they reflect general societal values.

In many work systems, the primary objectives, secondary objectives, and external constraints are often conflicting. In the case of a home, the requirement to adhere to town planning *laws and regulations* may conflict with the inhabitants' intention to add a second storey to their home to support their changing lifestyle and therefore promote a state of *wellbeing*. Similarly, in a transport company, enhancing the safety and comfort of passengers will lead to increased expenditure which may be inconsistent with the profit-making objectives of the organisation.

The information at the functional purposes level of abstraction about why a work system exists (primary objectives), the values of the work system (secondary objectives), and the values of the environment or society (external constraints) provide an explanation for the design of the work system. In essence, the design of a work system must allow it to fulfil its primary and secondary objectives and to satisfy the external constraints on its operation. Therefore, the functional purposes of a work system will determine the presence of various physical objects in the work system, the functionality that the physical objects possess, the functions that the work system performs, and the measures that the work system uses for evaluating its performance.

Finally, Rasmussen et al. (1994, p.38) state that the categories at the functional purposes level of abstraction "are in terms relating to the properties of the environment". This means that the categories of purposes (primary and secondary objectives) and external constraints at this level of abstraction are described in terms that indicate the relationship of the work system to the environment. In other words, the descriptions at this level of abstraction indicate what purposes the work system serves in the environment and what constraints the environment imposes on the work system. The functional purposes level of abstraction therefore describes the nature of the relationship or coupling between the work system and its environment.

Purposes versus Goals

Various analysts sometimes refer to the functional purposes level of abstraction as describing purposes and sometimes as describing goals (e.g., Hajdukiewicz et al., 1999; Rasmussen, 1988; Rasmussen et al., 1994; Rasmussen et al., 1990). According to Burns and Vicente (2001), goals are relevant to particular situations and are therefore dynamic. For example, the goals of the inhabitants of a home will depend on whether they are entertaining friends, cleaning the bathroom, or carrying out maintenance activities. On the other hand, purposes are relevant to a wide variety of situations and are therefore more stable over time (Burns & Vicente, 2001). For instance, one of the purposes of a home is to provide *shelter*. Given that WDA is event-independent, we suggest that it is more appropriate to describe the first level of abstraction as describing purposes rather than describing goals. Goals are more relevant to control task analysis, the second phase of CWA, which describes the constraints associated with recurring classes of situations. While we do not wish to formalise the terminology for WDA, we raise this issue because we believe that the use of the term ‘goals’ can be misleading about the concepts that are represented at the functional purposes level of abstraction.

5.3.2 Values and Priority Measures

This level of abstraction represents criteria for: (1) measuring how well a work system is progressing towards its functional purposes; and (2) comparing, prioritising, and directing resources to the various purpose-related functions so that the functional purposes of the work system are fulfilled. In the case of a home, a criterion at the values and priority measures level of abstraction may be that *total income must be greater than total expenses* by five hundred dollars per week. This criterion can be used for measuring whether the functional purpose of *wellbeing* is being achieved (where wellbeing is defined as a state characterised by health, happiness, and prosperity). In addition, this criterion can be used for comparing, prioritising, and directing resources to the purpose-related functions of *housework* and *maintenance*; the inhabitants may decide that in order to meet this criterion they can direct money to the purpose-related function of housework and hire a cleaner but that they must carry out all maintenance activities themselves.

In order to compare the effects of multiple purpose-related functions on a common set of functional purposes, and in order to prioritise and direct resources to multiple purpose-related functions, the criteria at this level of abstraction must be relevant to a wide variety of purpose-related functions. These criteria will therefore generally be independent of the particular kind of work system. For example, the criterion that expenses must not exceed a certain budget or limit is relevant to many different kinds of work systems or organisations. This is why Rasmussen et al. (1994, p.38) say that the categories at this level of abstraction will generally be “in abstract terms, referring neither to the system nor the environment”. Only the use of certain terms or phrases by analysts may hint at a particular work system.

The criteria at this level of abstraction are generally derived from fundamental principles such as the laws of nature (in causal systems) and social laws, conventions, and human values (in intentional systems). The criteria in most work systems will therefore reflect relatively stable properties that are not expected to disappear from the system in an uncontrolled fashion. In the case of a home, human values relating to pleasure or enjoyment are relatively stable properties that are not expected to disappear in an uncontrolled fashion. The concepts at this level of abstraction can therefore be assumed to follow conservation laws.

The concepts at this level of abstraction allow reasoning from first principles when workers are confronted with new or unfamiliar situations. Take, once again, the criterion *total income must be greater than total expenses* by five hundred dollars per week. In routine weeks, inhabitants can adopt general rules for ensuring that they do not exceed this criterion, for example, grocery bills must not exceed one hundred dollars per week and recreation expenses must not exceed eighty dollars per week. However, if the inhabitants are faced with unexpected expenses in a particular week, such as medical bills, they can reason about how much they will need to reduce their grocery and recreation expenses by in order to meet the criterion.

Rasmussen often describes the criteria at this level of abstraction as directing the flow of resources (e.g., money, material, mass, energy, people, information) through the system (e.g., Rasmussen et al., 1994). In the case of a home, the criterion *total income must be greater than total expenses* by five hundred dollars per week is concerned with the flow of money to the various purpose-related functions. Similarly, the criteria relating to *chore time* and *leisure time* are concerned with directing people, in particular their time, to the various purpose-related functions.

The criteria at this level of abstraction may be qualitative or quantitative. Typically, criteria relating to social laws, conventions, and values cannot be easily quantified. In the case of a home, it is difficult to quantify criteria relating to values such as pleasure or enjoyment. These criteria are therefore usually stated as properties to maximise or minimise. On the other hand, criteria relating to efficiency, reliability, economy, and probability can generally be quantified. These criteria may be formulated either as explicit or discrete quantities, or as quantities to maximise or minimise, depending on the values of the work system. In the case of a home, compare the criterion *total income must be greater than total expenses* by five hundred dollars per week with the criterion 'minimise expenses'. The former criterion allows inhabitants to allocate money to the purpose-related functions as long as an absolute saving of five hundred dollars per week is reached. The latter criterion requires that inhabitants allocate money to the purpose-related functions so as to minimise expenses and therefore reach the greatest level of savings that is possible.

In this section, we have stated that the criteria at the values and priority measures level of abstraction can reflect social laws, conventions, and values. However, we have also said that social laws, conventions, and values can be represented at the functional purposes level of abstraction[6]. The distinction is that at the functional purposes level of abstraction these properties are expressed as objectives or external constraints to achieve whereas at the values and priority measures level of abstraction the same properties are expressed in terms of criteria for measurement. In the case of a home, a value at the functional purposes level of abstraction may be expressed as an objective, such as to achieve a state of *wellbeing*. At the values and priority measures level this same value may be expressed as a criterion, such as *leisure time greater than n hours per week*. Similarly, in the case of a military system, adherence to international laws on military warfare may be expressed as an objective at the functional purposes level of abstraction whereas at the values and priority measures level of abstraction this same property may be expressed as a criterion, such as 'minimise collateral damage'.

Functional Purposes versus Values and Priority Measures

Analysts have sometimes described properties like 'safety' at the functional purposes level of abstraction (e.g., Abeloos, Mulder, van Paassen, Mulder & Pritchett, 2003; Ho & Burns, 2003; Rasmussen, 1998; Rasmussen et al., 1994; Xu, Dainoff & Mark,

[6] This is one sense in which the new set of generic labels suggested by Rasmussen (in Reising, 2000) is not ideal; values are reflected at both the functional purposes and values and priority measures levels of abstraction but the labels suggest that values are only represented at the values and priority measures level of abstraction.

1999) and sometimes at the values and priority measures level of abstraction (e.g., Benda & Sanderson, 1998; Crone, Sanderson & Naikar, 2003; Lintern & Naikar, 1998). Neither approach is necessarily wrong – depending on what the analysts intended[7]. It may be that the analysts who represented 'safety' at the functional purposes level were describing an aim or objective to achieve whereas the analysts who represented 'safety' at the values and priority measures level were describing a property for measuring performance albeit in the form of the values from which the criteria were derived rather than the actual criteria itself, such as 'minimise number of injuries'. On the basis of the descriptions of the functional purposes and values and priority measures levels of abstraction provided earlier, it can be argued that generally it is more appropriate to describe an aim or objective like 'safety' at the functional purposes level and the criteria for measuring this aim or objective, like 'minimise number of injuries', at the values and priority measures level. More importantly, however, analysts should ensure that the representations at the different levels of abstraction reflect the reasoning space of workers in a particular work domain. Therefore, if workers in a particular work domain reason about safety at the second level of abstraction, then safety should be represented at this level of abstraction. Alternatively, if workers in a particular work domain reason about safety at the fourth level of abstraction, then safety should be represented at this level of abstraction. Another, more pragmatic, perspective is that the representations should be suitable for the purposes of the WDA.

Analysts have also sometimes chosen not to restate the criteria at the values and priority measures level of abstraction in terms of aims or objectives at the functional purposes level of abstraction (e.g., Benda & Sanderson, 1998; Bisantz et al., 2003; Crone, Sanderson & Naikar, 2003; Lintern & Miller, 2003; Naikar et al., 2003; Naikar & Sanderson, 1999, 2001). Instead, they may link criteria like 'minimise number of injuries' at the values and priority measures level to objectives like 'profit making' at the functional purposes level. This representation expresses that the aim of the work system is to make a profit while keeping the number of injuries as low as possible. An alternative representation of these same constraints is to link a criterion like 'minimise number of injuries' at the values and priority measures level to an objective like 'safety' at the functional purposes level and to describe 'profit making' as another objective at the functional purposes level. Yet another format for representing these constraints is to link a criterion like 'minimise number of injuries' at the values and priority measures level to an objective like 'make a profit while operating the plant safely' at the functional purposes level (e.g., Hajdukiewicz et al., 1999; Rasmussen, 1998)[8]. All three alternatives essentially capture the same constraints but the format chosen for representation is different. Given that each level of abstraction in the ADS is supposed to represent the same work domain but from different conceptual viewpoints, it may be argued that generally the criteria at the values and priority measures level should be

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[7] Analysts may have more detailed descriptions of these constraints than the descriptions that appear in their publications. We discuss the descriptions in their publications because these can be confusing to novice analysts.

[8] The publications that we cite in this paragraph do not provide examples of the specific constraints that we mention here but they provide examples of the different formats for representing the constraints that we discuss here.

restated at the functional purposes level in terms of aims or objectives using one of the latter two formats discussed above. However, as discussed previously, it is more important that analysts ensure that the representations at each level of abstraction reflect the reasoning space of workers in a particular work domain and/or that the representations are suitable for the purposes of the WDA.

Finally, a point that we touched on earlier is that analysts sometimes do not describe criteria at the values and priority measures level of abstraction but rather the concepts from which the criteria may be derived such as laws, rules, values, and the flow of resources (Burns, Bryant et al., 2000; Hajdukiewicz et al., 1998, 2001; Ho & Burns, 2003; Kuo & Burns, 2000; Naikar et al., 2003; Naikar & Sanderson, 1999, 2001; Rasmussen, 1986; Reising et al., 2000). In the case of a home, analysts may represent 'flow of people' at the values and priority measures level rather than a criterion like *leisure time greater than n hours per week*; the criterion makes explicit the measure that is used for evaluating whether the allocation of people to the various purpose-related functions, or the 'flow of people' through the system, will achieve the functional purposes. On the basis of the descriptions of the functional purposes and values and priority measures levels of abstraction provided earlier, it can be argued that generally it is more appropriate to describe the actual criteria at the values and priority measures level of abstraction rather than the concepts from which the criteria may be derived. However, as stated previously, it is more important that analysts ensure that the representations at each level of abstraction reflect the reasoning space of workers in a particular work domain and/or that the representations are suitable for the purposes of the WDA.

5.3.3 Purpose-related Functions

This level of abstraction describes the functions that are necessary for fulfilling the functional purposes of a work system. For example, *meals and beverages*, *rest*, *recreation*, and *housework* are all necessary for achieving *wellbeing* in a work domain of a home. Generally, a variety of functions are necessary for fulfilling the functional purposes and each function makes demands on the resources of the work system. The functions must therefore be coordinated in a way that achieves the functional purposes given the available resources. In the case of a home, inhabitants are not resting while they are doing housework. Hence, in order to achieve the functional purpose of wellbeing, the inhabitants must coordinate the purpose-related functions so that they have time to do the housework as well as time to rest. More specifically, inhabitants must coordinate the purpose-related functions so that they satisfy the criteria (at the values and priority measures level) that measure whether the functional purpose of wellbeing is achieved. For instance, inhabitants must coordinate the purpose-related functions so that *chore time is less than n hours per week* and *leisure time is greater than n hours per week*.

The purpose-related functions level of abstraction describes the uses that the object-related processes and physical objects are put to in a work domain. In the case of a home (rooms and subspaces level of decomposition), *cooking* describes the uses that object-related processes like *heating* and *stirring* and physical objects like *stove* and *utensils* are put to in the work domain. Each purpose-related function typically involves several different kinds of object-related processes and physical objects. The purpose-related functions therefore involve coordinating the use of various object-related processes and physical objects to achieve the functional purposes of the work domain.

The concepts at the purpose-related functions level of abstraction are represented in general terms that can accommodate a wide variety of sub-functions or activities and that are independent of underlying object-related processes and physical objects. That is why Rasmussen et al. (1994) say that the categories at this level are represented in terms of recurrent "input-output relationships" (p.38) or "black box models of performance" (p.39). In the case of a home (rooms and subspaces level of decomposition), *cleaning* can be achieved by wetting a sponge and then wiping with the wet sponge or by dusting with a cloth.

The language at the purpose-related functions level of abstraction reflects the familiar terminology of the professional field to which a work system belongs. For example, the familiar terminology of office environments includes marketing, personnel administration, and accounting (Rasmussen et al., 1994). The familiar terminology of manufacturing plants includes design, planning, production, and maintenance (Rasmussen et al., 1994). In the case of a home (rooms and subspaces level of decomposition), *cooking* and *cleaning* are terms that are familiar to the inhabitants of many homes and not just to the inhabitants of the home that was studied for the WDA. The representations at this level of abstraction are therefore not specific to a particular work system, such as a particular commercial company, manufacturing plant, or home.

Representation of Purpose-related Functions

Contrary to the description of the third level of abstraction that is presented above, some analysts appear to represent processes relating to physical objects at this level of abstraction, rather than functions that are independent of physical objects (e.g., Bisantz & Vicente, 1994; Burns, Bryant et al., 2000; Dinadis & Vicente, 1999; Kuo & Burns, 1999, 2000; Reising & Sanderson, 2002b; Vicente, 1999). For example, analysts have represented processes like signal detection, generating signals, heat and water input, and water flow at the third level of abstraction[9]. Reising's (1999a) explanation for this is that these analyses are of engineered systems (e.g., pasteurisation plant) as opposed to analyses of the larger work domains to which the engineered systems belong (e.g., company, organisation). According to Reising, the functional purposes of engineered systems are typically related to the function of production (e.g., supply nuclear power). Objectives like ensuring safety and making a profit are generally not represented at the functional purposes level. Consequently, the values and priority measures and the purpose-related functions in these analyses are also tied to the engineering-specific process of production. Therefore, when describing the purpose-related functions that are required for achieving the functional purposes of engineered systems, analysts end up with a variety of object-related processes related to production. In contrast, if an

[9] Analysts may have more detailed (and therefore different) descriptions of these constraints than the descriptions that appear in their publications. We discuss the descriptions in their publications because these can be confusing to novice analysts.

analysis is focussed on the larger work domain to which an engineered system belongs, the purpose-related functions will not only include the function of production but also the functions required for other objectives such as ensuring safety and making a profit. An analysis of the larger work domain will therefore have a broader set of purpose-related functions than an analysis of an engineered system. Reising illustrates these distinctions with an abstraction hierarchy of a pasteurisation plant and an abstraction hierarchy of the company or organisation to which the pasteurisation plant belongs (the latter was developed by Rasmussen). Reising's explanation seems to be substantiated by the fact that some of the same analysts who appear to have reported processes relating to physical objects at the third level of abstraction in their analyses of engineered systems, do not do so when their analyses are not focussed solely on engineered systems (Benda & Sanderson, 1998, 1999; Burns & Proulx, 2002; Hajdukiewicz et al., 1999; Ho & Burns, 2003). Having said that, another reason why analysts may have represented processes relating to physical objects at the third level of abstraction is that this representation best captured the problem space of workers in the work domain under consideration and/or was best suited for the purposes of the WDA. We emphasise that if the reasoning space of workers in a particular work domain is best captured by representing processes relating to physical objects at the third level of abstraction and/or if this representation is best suited for the purposes of the WDA then analysts should represent processes relating to physical objects at this level of abstraction.

Means-Ends Relations

Another issue is the nature of the means-ends relations from the purpose-related functions level of abstraction to the values and priority measures level of abstraction. We discussed earlier in this report that links from one level of abstraction to the level above answer 'why' questions. However, in one sense, the upwards link from the purpose-related functions level to the values and priority measures level also answers a 'how' question. That is, the values and priority measures level describes how well the purpose-related functions must be performed in order to fulfil the functional purposes. This relationship is a useful way to think about the concepts that are represented at these levels of abstraction but it is not the relationship that is being referred to when the abstraction hierarchy is described as having means-ends relations between adjacent levels of abstraction. The relationship that is being referred to is that the upwards link from the purpose-related functions level to the values and priority measures level describes why the purpose-related functions are executed or present in the work system – in order to satisfy the values and priority measures of the work system. The downwards link from the values and priority measures level to the purpose-related functions level describes how the values and priority measures are achieved or satisfied – by executing the purpose-related functions of the work system (a more detailed description of the specific nature of the links between these and other levels of abstraction is provided in Section 6.3).

5.3.4 Object-related Processes

The object-related processes level of abstraction describes the functional processes or the functional capabilities and limitations of physical objects in a work system. The language at this level of abstraction therefore generally reflects physical, mechanical, electrical, or chemical processes. The categories at this level of abstraction reflect the properties of underlying physical objects in a work system. In the case of a home (contents and components level of decomposition), information about the rate of *flow of water* at the object-related processes level would reflect some of the properties of the pipes in the dishwasher, such as its diameter[10].

The object-related processes level of abstraction can represent the functional capabilities and limitations of both man-made and natural objects in a work system. For example, the object-related processes level can represent the functional capabilities and limitations of tools or equipment (man-made objects) in a work system. In addition, the object-related processes level can represent the functional capabilities and limitations, or professional abilities, of categories of personnel (natural objects) in a work system (e.g., Hajdukiewicz et al., 1999; Rasmussen, 1998).

The object-related processes of a work system are necessary for enabling the purpose-related functions of the work system. Therefore, references to the potential use of object-related processes for carrying out the purpose-related functions of a work system are usually implicit in the descriptions at the object-related processes level of abstraction. For example, *flow of water* indicates that the dishwasher can be used for the purpose-related function of *washing*.

The distinction between object-related processes and purpose-related functions is sometimes confusing. Object-related processes describe what the physical objects in a work system can do or can afford. For example, the *pipes* in a dishwasher can afford the *flow of water*. These processes are constrained by the properties of physical objects, or causal properties, and are therefore unalterable unless the properties of the physical objects are changed. In contrast, the purpose-related functions of a work system describe the uses that the object-related processes are commonly put to or enable in a work domain. For example, *flow of water* enables *washing* in a home. The purpose-related functions reflect a greater degree of choice or intentionality in how the object-related processes are used in a work domain. For example, *flow of water* can be used for *rinsing* as well as *washing*. Moreover, if necessary, the flow of water afforded by a dishwasher can also be used for drinking!

Representation of Object-related Processes

Contrary to the description of the fourth level of abstraction that is presented above, some analysts simply list the names of physical objects at this level of abstraction rather than representing the functional capabilities and limitations of the physical objects (e.g., Bisantz et al., 2003; Dinadis & Vicente, 1999; Ho & Burns, 2003;

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[10] This level of detail about object-related processes and physical objects is not included in the ADS of a home in Table 4 because of space limitations.

Vicente, 1999)[11]. One explanation for this is that the names of many physical objects are indicative of their function. In the case of a home, the name of a physical object such as 'dishwasher' indicates that this physical object affords washing. Reising (2000), however, has observed that in a nuclear power plant the object-related process of a pump during production is to circulate fluid whereas during start up the same pump can serve the object-related process of heating fluid. Simply listing the name 'pump' does not necessarily indicate this functionality. Similarly, the functionality afforded by the physical objects of many military systems can be very complex. Therefore, rather than simply listing the names of physical objects, like 'radar' and 'electronic support system', at the object-related processes level of abstraction, it may be useful to be more explicit about the functional capabilities and limitations of the physical objects. For instance, a radar 'senses the range and bearing of entities in the environment' whereas an electronic support system 'senses the bearing and identity of entities in the environment'. In addition, the range at which the radar and electronic support system can sense entities in the environment may also be represented at the object-related processes level. Having said that, another reason why analysts may have simply listed the names of physical objects at the fourth level of abstraction is that this representation best captured the problem space of workers in the work domain under consideration and/or was best suited for the purposes of the WDA. We emphasise that if the reasoning space of workers in a particular work domain is best captured by listing the names of physical objects at the fourth level of abstraction and/or if this representation is best suited for the purposes of the WDA then analysts should list the names of physical objects at this level of abstraction.

5.3.5 Physical Objects

This level of abstraction represents the physical objects in a work system that afford the processes and functions at higher levels of abstraction. The physical objects of a work system can include: tools or equipment; work premises or infrastructure (e.g., land, buildings, laboratories); personnel categories; and geography (e.g., terrain features, meteorological features). The description at this level of abstraction can include an inventory of the physical objects (e.g., names, number, types); the material characteristics of the physical objects (e.g., external form including shape, dimensions, and colour; internal configuration; material composition); and the topography or organisation of the physical objects (e.g., layout or location of physical objects in relation to each other). These descriptions can take many forms, such as textual formats (e.g., inventory lists, design specifications); photographs (e.g., of equipment or premises); drawings (e.g., architectural drawings, engineering blueprints, circuit diagrams); and maps (e.g., site maps, weather maps, elevation maps). Several types of formats may be used in combination; for example, text labels can be used to identify physical objects on a site map.

[11] Analysts may have more detailed descriptions at this level of abstraction than the descriptions that appear in their publications. We discuss the descriptions in their publications because these can be confusing to novice analysts.

The physical objects level of abstraction can be thought of as representing the physical world or physical reality that is available for visual inspection when visiting a work site. During work, the representations at this level of abstraction are necessary for navigating in the work domain and for searching for and identifying objects from their external appearance, such as their colour, shape, and size. We mentioned earlier that the names or verbal labels of physical objects typically refer to the processes or functions that the objects serve at higher levels of abstraction. In this sense, the verbal labels indicate the reason that the physical objects are present in the work domain.

Representation of Physical Objects

Sometimes analysts simply name the physical objects at this level of abstraction rather than including descriptions of their appearance and location (e.g., Benda & Sanderson, 1998, 1999; Lintern, Miller & Baker, 2002; Naikar et al., 2003; Naikar & Sanderson, 1999, 2001; Rasmussen et al., 1994). One reason for this may be that information about the appearance and location of physical objects was not available when the WDA was performed. For example, when we used WDA to evaluate alternative proposals for the design of a military system, details about the appearance and location of physical objects were not available at that stage of the project (Naikar & Sanderson, 2001). Another reason that analysts only name the physical objects at this level of abstraction may be that information about the appearance and location of physical objects was not relevant to the purpose of the WDA. For instance, when we used WDA to design a team for a military system during the early stages of system development, information about the appearance and location of physical objects in the aircraft was not essential (Naikar et al., 2003).[12] Although the names of physical objects are usually indicative of their function rather than their form, on both of the projects discussed above, the names of the physical objects were entered at this level of abstraction to indicate the presence or availability of these objects in the work system.

5.4 Analysing the Abstraction Dimension

To help analysts to model the abstraction dimension of a work domain, we have developed a set of generic prompts and keywords for the five levels of abstraction that are commonly included in the ADS. These prompts and keywords, which are shown in Table 5, provide a guide to the kinds of properties that analysts should search for, or uncover, about a work system in order to develop the abstraction dimension of an ADS. To illustrate, the prompts for the functional purposes level of abstraction indicate that analysts should search for information about the services that a work system provides to the environment (purposes) and the laws and regulations that the environment imposes on a work system (external constraints). The keywords at this level of abstraction indicate the different guises in which the purposes and external constraints may be revealed in a work system. For example, documents or domain

[12] We did not explicitly note these reasons in our publications. Hence, the descriptions at the physical objects level of abstraction in our publications may be confusing to novice analysts, which is why we raise this issue here.

experts may refer to aims, objectives, desires, and ambitions (purposes) or to policies, conventions, customs, and values (external constraints).

The terminology that is used in a work system will usually be domain specific. In other words, documents or domain experts will tend to identify domain-specific aims and objectives or laws and regulations. For example, the inhabitants of a home may refer to a desire for financial prosperity or they may refer to noise regulations. Moreover, documents and domain experts will tend to describe particular instances or examples of constraints. In the case of a home, the inhabitants may discuss their goal or desire to reduce their grocery bills by fifty dollars per week or they may discuss lodging a complaint with the city council about a neighbour who frequently holds noisy parties. Consequently, as discussed in Section 5.1, analysts will need to group the work-domain properties into the categories of constraints that will be represented in the ADS. Furthermore, if analysts are actually identifying the levels of abstraction in a work domain from scratch, as opposed to relying on the five levels of abstraction that are commonly included in the ADS, analysts will also have to sort the categories into similar and dissimilar concepts and organise the concepts into a hierarchy of means-ends relations (Section 5.1).

Several readers may have noticed the duplication of keywords at some of the levels of abstraction in Table 5. For instance, at the functional purposes level of abstraction, some of the keywords for purposes are the same as some of the keywords for external constraints. This is because the purposes (secondary objectives) of a work system can be derived from the values of the people within the work system and the external constraints on a work system can be derived from the values of society. The keywords do not distinguish between the values of people within the work system and the values of society. Similarly, some of the keywords at the functional purposes level of abstraction are the same as some of the keywords at the values and priority measures level of abstraction. This is because values are expressed as aims or objectives at the functional purposes level of abstraction and as criteria for measurement at the values and priority measures level of abstraction. The keywords do not distinguish between the expression of values as aims or objectives and the expression of values as criteria for measurement.

Finally, we note that the generic prompts and keywords in Table 5 can be used with a variety of data-collection techniques. For example, the prompts and keywords can be used for document analysis or for conducting interviews, walkthroughs, and table-top analysis with domain experts. We will discuss these and other techniques in greater detail in Section 12 of this report.

Table 5. Generic prompts and keywords for analysing the abstraction dimension.

	Prompts	Keywords
Functional Purposes	Purposes: • For what reasons does the work system exist? • What are the highest-level objectives or ultimate purposes of the work system? • What services does the work system provide to the environment? • What needs of the environment does the work system satisfy? • What role does the work system play in the environment? • What has the work system been designed to achieve? • What are the values of the people in the work system? External Constraints: • What kinds of constraints does the environment impose on the work system? • What values does the environment impose on the work system? • What laws and regulations does the environment impose on the work system? • What societal laws and conventions does the environment impose on the work system?	Purposes: reasons, goals, objectives, aims, intentions, mission, ambitions, plans, services, products, roles, targets, aspirations, desires, motives, values, beliefs, views, rationale, philosophy, policies, norms, conventions, attitudes, customs, ethics, morals, principles. External constraints: laws, regulations, guidance, standards, directives, requirements, rules, limits, public opinion, policies, values, beliefs, views, rationale, philosophy, norms, conventions, attitudes, customs, ethics, morals, principles.
Values and Priority Measures	• What criteria can be used to judge whether the work system is achieving its purposes? • What criteria can be used to judge whether the work system is satisfying its external constraints? • What criteria can be used to compare the results or effects of the purpose-related functions on the functional purposes? What are the performance requirements of various functions in the work system? How is the performance of various functions in the work system measured or evaluated and compared? • What criteria can be used to assign priorities to the purpose-related functions? What are the priorities of the work system? How are priorities assigned to the various functions in the work system? • What criteria can be used to allocate resources (e.g., material, energy, information, people, money) to the purpose-related functions? What resources are allocated to the various functions of the work system? How are resources allocated to the various functions of the work system?	Criteria, measures, benchmarks, tests, assessments, appraisals, calculations, evaluations, estimations, judgements, scales, yardsticks, budgets, schedules, outcomes, results, targets, figures, limits. Measures of: effectiveness, efficiency, reliability, risk, resources, time, quality, quantity, probability, economy, consistency, frequency, success. Values: laws, regulations, guidance, standards, directives, requirements, rules, limits, public opinion, policies, values, beliefs, views, rationale, philosophy, norms, conventions, attitudes, customs, ethics, morals, principles.

Purpose-related Functions	• What functions are required to achieve the purposes of the work system? • What functions are required to satisfy the external constraints on the work system? • What functions are performed in the work system? • What are the functions of individuals, teams, and departments in the work system? • What functions are performed with the physical resources in the work system? • What functions coordinate the use of the physical resources in the work system?	Functions, roles, responsibilities, purposes, tasks, jobs, duties, occupations, positions, activities, operations.
Object-related Processes	• What can the physical objects in the work system do or afford? • What processes are the physical objects in the work system used for? • What are the functional capabilities and limitations of physical objects in the work system? • What physical, mechanical, electrical, or chemical processes are afforded by the physical objects in the work system? • What functionality is required in the work system to enable the purpose-related functions?	Processes, functions, purposes, utility, role, uses, applications, functionality, characteristics, capabilities, limitations, capacity, physical processes, mechanical processes, electrical processes, chemical processes.
Physical Objects	• What are the physical objects or physical resources in the work system – both man-made and natural? • What physical objects or physical resources are necessary to enable the processes and functions of the work system? • What is the inventory (e.g., names, number, types) of physical objects or physical resources in the work system? • What are the material characteristics (e.g., external form including shape, dimensions, colour; internal configuration; material composition) of physical objects or physical resources in the work system? • What is the topography or organisation (e.g., layout or location of physical objects in relation to each other) of physical objects or physical resources in the work system?	Man-made and natural objects: tools, equipment, devices, apparatus, machinery, items, instruments, accessories, appliances, implements, technology, supplies, kit, gear, buildings, facilities, premises, infrastructure, fixtures, fittings, assets, resources, staff, people, personnel, terrain, land, meteorological features. Inventory: names of physical objects, number, quantities, brands, models, types. Material characteristics: appearance, shape, dimensions, colour, attributes, configuration, arrangement, layout, structure, construction, make up, design. Topography: organisation, location, layout, spacing, placing, positions, orientations, ordering, arrangement.

6. Means-Ends Relations

6.1 Alternatives and Combinations of Means-Ends Relations

An issue that has not been discussed explicitly in previous publications on WDA is whether the means-ends relations in an ADS should represent the alternative means to achieve an end or the combinations of means to achieve an end. For example, either a chair or a bench can be used for sitting. This represents the alternative means to achieve an end or an OR relationship. On the other hand, both pen and paper are necessary for writing. This represents the combination of means that are necessary to achieve an end or an AND relationship. Similarly, both chalk and blackboard are necessary for writing. This too represents the combination of means that are necessary to achieve an end or an AND relationship. However, either combination – the pen AND paper OR the chalk AND blackboard – can be used for writing. This represents the alternative combinations (Rasmussen et al., 1994) of means that can be used to achieve an end[13]. Given that the aim of WDA is to identify all of the possibilities for action in a work domain, it is necessary to capture all of these types of means-ends relations in an ADS.

6.2 Instantiations of Means-Ends Relations

Many analysts have explicitly shown the means-ends relations between different levels of abstraction in an ADS by drawing links between the nodes or entries at different levels (e.g., Bisantz et al., 2003; Gualtieri et al. 2000; Lintern, 2002; Naikar & Sanderson, 1999, 2001; Rasmussen et al., 1994; Thompson, Hickson & Burns, 2003; Vicente, 1999). Generally, these links do not illustrate all of the means-ends relations that are possible in a work domain but rather particular instantiations of means-ends relations. Different ADS models may illustrate different instantiations of means-ends relations in a work domain, and sometimes analysts are not explicit about what the instantiations are, so readers must devote some attention to understanding what the links actually represent. For example, in some ADS models the links illustrate all of the means-ends relations that have been designed or engineered into a work system whereas in other ADS models the links illustrate the trajectories of workers' problem-solving activities in particular situations or set of situations. Generally, neither of these instantiations will capture all of the means-ends relations that are possible in a work domain. Workers are flexible and adaptive so they will usually adjust their work patterns to local contingencies. Moreover, workers may invent new ways of working to deal with novel situations that were not anticipated by designers (Vicente, 1999). Workers can therefore 'create' means-ends links that were not active in particular situations or that were not present at the time of design, either in the course of performing their daily work activities or in the course of dealing with unanticipated situations.

[13] We note that a single object or property can belong to many different combinations of means-ends relations. For example, paper may also be used in combination with paint and a paintbrush for writing.

6.3 Analysing Means-Ends Relations

To assist analysts with establishing means-ends relations along the abstraction dimension of an ADS, in Figure 1 we describe the specific nature of the means-ends relations or 'how-why' relations between adjacent levels of abstraction. Figure 1 shows, for instance, that the nature of the means or 'how' relations from the functional purposes to the values and priority measures level of abstraction is: *How are the purposes of the work system achieved and how are the external constraints satisfied? By adhering to the criteria or measures of the work system*. Conversely, the nature of the ends or 'why' relations from the values and priority measures to the functional purposes level of abstraction is: *Why should the criteria or measures of the work system be respected? To achieve the purposes of the work system and to satisfy the external constraints*. While the descriptions of means-ends relations in Figure 1 may seem obvious to some analysts, especially to expert analysts, we have found that the specific nature of means-ends relations between adjacent levels of abstraction is not always clear to novice analysts. For example, as we discussed in Section 5.3.3, the nature of the means-ends relations between the purpose-related functions and the values and priority measures levels of abstraction can be confusing. Moreover, like Vicente (1999), we have found that it is quite easy for analysts to drift from identifying means-ends relations to other kinds of relations that do not belong in an abstraction hierarchy but that characterise other types of hierarchies.

Vicente (1999) provides a nice illustration of the distinctions between the nature of relations in an abstraction hierarchy compared with other kinds of hierarchies such as authority, classification, and decomposition hierarchies. In constructing an abstraction hierarchy, it is important to ensure that the relationships between the different levels of abstraction are means-ends relations. Moreover, as we have discussed in Sections 4.1.1 and 5.1, the nature of the means-ends relations in an abstraction hierarchy must be structural means-ends relations and not action means-ends relations.

7. Decomposition Dimension and Part-Whole Relations

7.1 Number of Levels of Decomposition

Like the abstraction dimension, there is currently no explicit process for identifying the number of levels of decomposition to include in an ADS. While this too is a topic that can benefit from further research, we believe that there is merit in beginning to outline such a process here. The process for identifying the number of levels of decomposition to include in an ADS is similar to the process for identifying the number of levels of abstraction to include in an ADS. The decomposition dimension structures the problem space of workers in terms of the different levels of resolution

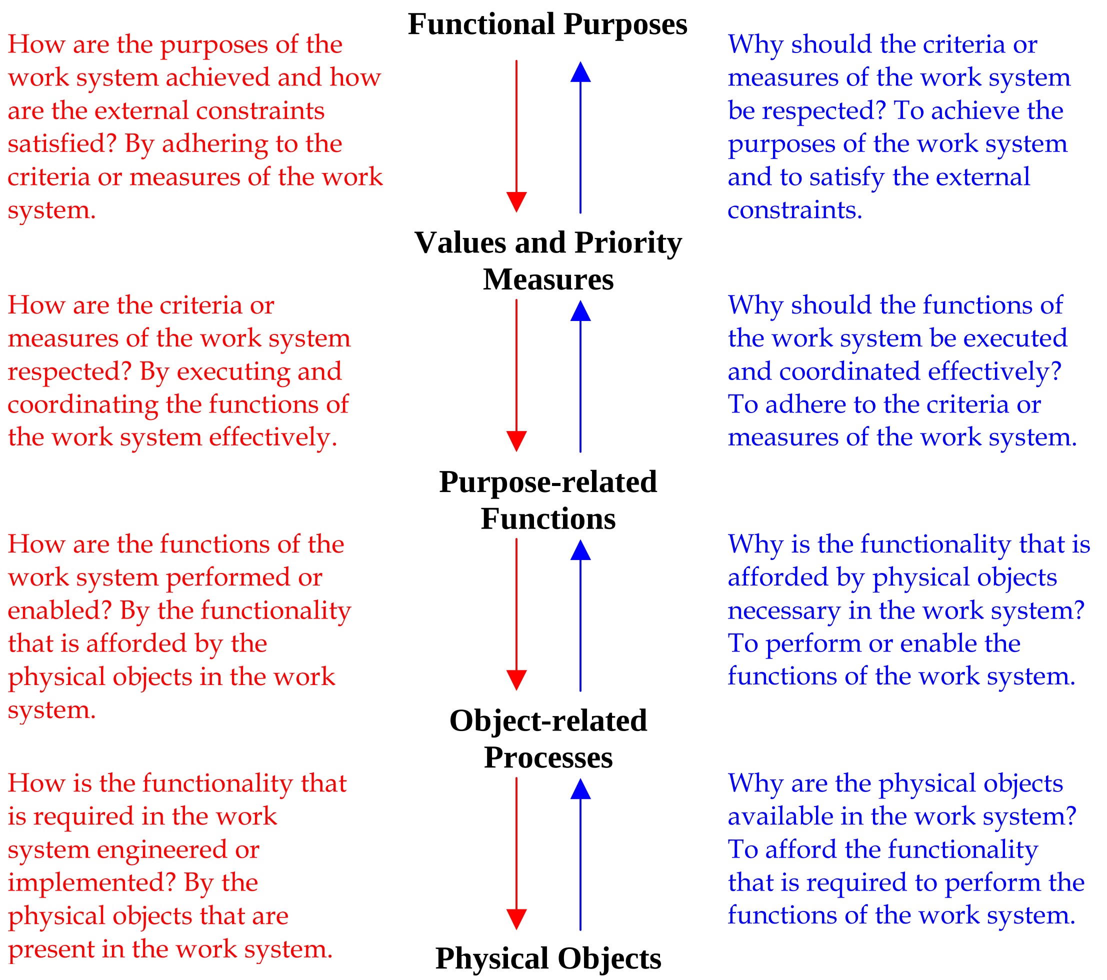

Figure 1. The specific nature of the means-ends relations between adjacent levels of abstraction. Means or 'how' relations are shown in red and ends or 'why' relations are shown in blue.

that workers can use for reasoning in a work system, from the whole system to its individual components. The number of levels of decomposition to include in an ADS can therefore be determined by studying the number of levels of resolution in the reasoning space of workers. Like the abstraction dimension, a variety of techniques can be used to study the number of levels of resolution that workers can use for reasoning in a work system. These techniques, which we will discuss in greater detail in Section 12, include document analysis, interviews, and table-top analysis.

As we will illustrate shortly, the data that are obtained with these techniques can be studied for references to the parts of a work system in the reasoning space of workers. Several sets of data collection exercises will generally be necessary with analysts using the parts that have already been identified, together with 'part of' and 'composed of' questions, as a basis for identifying additional parts in the work system. Once a comprehensive set of parts has been identified, the process for identifying the number of levels of resolution that workers can use for reasoning in the work system includes sorting the parts into similar and dissimilar levels of resolution and organising the levels of resolution into a hierarchy of part-whole relations.

To illustrate, in the course of carrying out observations of a home, analysts may find that inhabitants make various statements like: 'I just got home', 'the telephone is in the hallway', and 'I sat on the lounge-room couch'. From this data, analysts can identify the various parts of the work system such as 'home', 'telephone', 'hallway', 'lounge room', and 'couch'. Analysts can use these parts as a basis for identifying other parts in the work system, for example, by asking 'is the hallway a part of a home' and 'what are the other parts of a home'. Analysts can then start organising the parts into similar and dissimilar levels of resolution. For example, analysts can identify that 'telephone' and 'couch' are at similar levels of resolution because they both refer to the contents of a home and that 'hallway' and 'lounge room' are at similar levels of resolution because they both refer to the rooms or subspaces of a home. Moreover, analysts can identify that 'home', which refers to the whole house, is at a different level of resolution to either the contents and components of a home or to the rooms and subspaces of a home. Finally, analysts can order the different levels of resolution into a hierarchy of part-whole relations. In the example discussed here, the hierarchy that is evident is: whole house – rooms and subspaces – contents and components.

Like the abstraction dimension, we note that a distinction can be made between the number of levels of resolution that workers can use for reasoning in a work domain and the number of levels of decomposition that an analyst chooses to include in an ADS. Analysts may find that only some of the levels of resolution that workers use for reasoning in a work domain are useful for the purpose of the WDA. In addition, what is defined as the whole system or components in an ADS will also depend on the purpose of the WDA. For example, in a work domain of a home, a television may be defined as a component if the focus of the analysis is on the inhabitants of a home whereas a television may be defined as the whole system if the focus of the analysis is on the television-repair person.

Finally, the levels of decomposition or resolution that workers can use for reasoning in a work system can take many different forms. In some work systems the decomposition dimension is defined by physical structures. In a work domain of a home, for instance, inhabitants can reason along a dimension of physical structures relating to the whole house, rooms and subspaces, and contents and components. Similarly, in the work domain of computer repair, technicians can reason along a dimension of physical structures relating to the parts of a computer system: whole system, subsystem, functional circuit, circuit-stage, component (Rasmussen, 1985). In addition, in the work domain of the human body, medical personnel can reason along a dimension of physical structures relating to the parts of the human body: whole body, system, organ, tissue, cell (Hajdukiewicz et al., 1998). Alternatively, the decomposition dimension can be defined by organisational structures: company/organisation, division/reporting area, section, position (Reising, 2000) or by conceptual structures: national levels, theatre of engagement, active force, mission, platoon/component/ UAV team (Rasmussen, 1998).

7.2 Labels for the Levels of Decomposition

Many of the ADS models in the literature adopt labels for the levels of decomposition that are only slight variations of the nomenclature used by Rasmussen et al. (1994); that is, total system, sub-system, function unit, sub-assembly, and component. For example, analysts may use the label 'whole system' rather than 'total system' or 'units' instead of 'function units' but otherwise the labels are the same. We describe these labels as generic labels because they are not specific to any particular work system. As we pointed out in Section 5.2, when discussing labels for the abstraction dimension, generic labels are usually not very meaningful to domain experts and may limit how readily domain experts relate to, and even accept, an ADS model as a useful representation of their work domain. Therefore, as for the abstraction dimension, we suggest that analysts consider adopting domain-specific labels for the levels of decomposition when presenting an ADS to domain experts.

Domain-specific labels can usually be derived from the terminology that experts use in the work domain. In the case of a home, inhabitants frequently use terms such as 'rooms' and 'contents' which we have used to label some of the levels of decomposition in the ADS of a home (Table 4). Some other examples of domain-specific labels for the levels of decomposition have been reported for an ADS of the human body: whole body, system, organ, tissue, cell (Hajdukiewicz et al., 1998, 2001); an ADS of a military system: national level, theatre of engagement, active force, mission, platoon (Rasmussen, 1998); an ADS of a production company: company/organisation, division/reporting area, section, position (Reising, 2000); and an ADS for emergency management: national overview and patterns, emergency classes, companies and installations, specific production plants and equipment, and processes, substances and components (Rasmussen, 1986).

7.3 What to Decompose?

One approach that analysts have sometimes taken to develop the decomposition dimension of an ADS is to decompose the nodes or entries in the cells of the ADS into parts in order to obtain entries for the cells at the next level of decomposition. Figure 2 illustrates the case where the entries in *every* cell of the ADS have been decomposed into parts in order to obtain entries for the cells at the next level of decomposition. However, sometimes analysts may only decompose the entries in *some* of the cells of the ADS into parts in order to obtain entries for the cells at the next level of decomposition; for instance, analysts may only decompose the entries in cells that fall along the diagonal of the ADS.

In the case of a home, developing the decomposition dimension using this approach would involve decomposing entries like *shelter* or *cooking* into parts in order to obtain entries for cells at the next level of decomposition. However, we have found a number of problems with this approach (e.g., Naikar & Sanderson, 1999). First, apart from the cells at the physical objects level of abstraction, it is usually difficult to decompose the entries in the cells at the other levels of abstraction into parts. For example, in the case of a home, it is difficult to decompose entries like *shelter* and

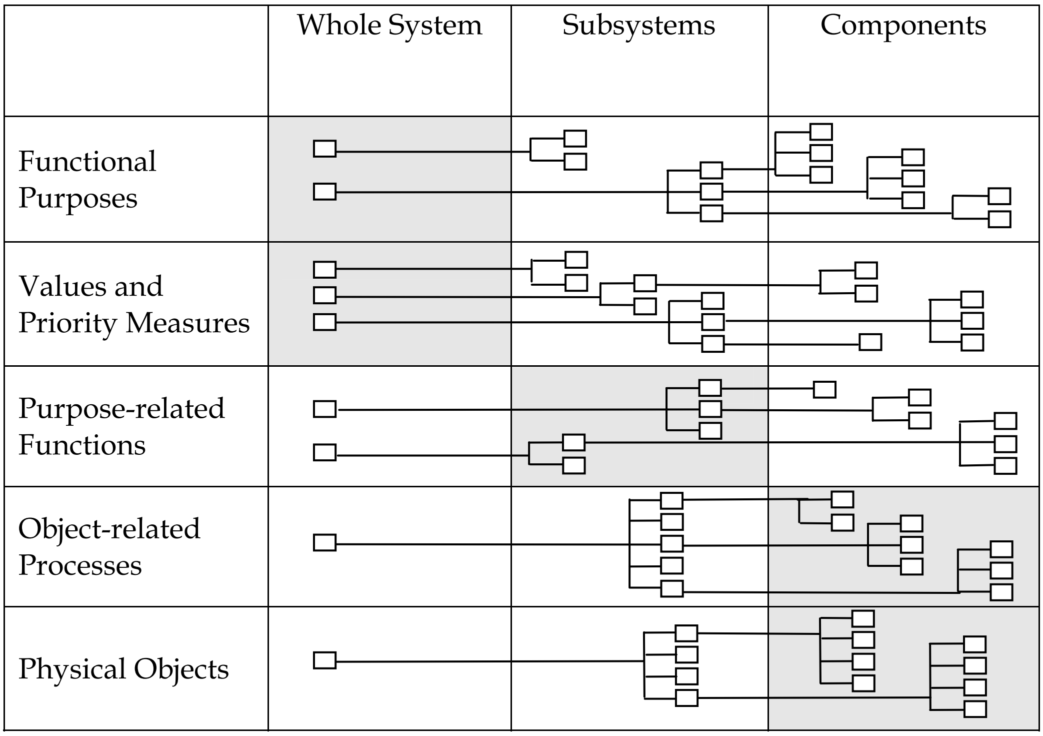

Figure 2. An illustration of an ADS in which the decomposition dimension was developed by decomposing the nodes or entries in the cells of the ADS into parts in order to obtain entries for the cells at the next level of decomposition.

cooking into parts. Consequently, most attempts at doing this will usually result in relations that are not part-whole relations. Hence, analysts may end up decomposing cooking into 'kind-of' relations by identifying the different kinds of cooking such as boiling or frying; or analysts may end up decomposing cooking into action means-ends relations by identifying the tasks or action sequences for cooking; or analysts may end up decomposing cooking into structural means-ends relations by identifying the objects that can be used to achieve cooking such as pots and pans.

Second, developing the decomposition dimension using this approach may not produce a coherent abstraction hierarchy at every level of decomposition. To illustrate, in Figure 2, decomposing the entries in the cells at the whole system level of decomposition into parts in order to obtain entries for the cells at the subsystems level of decomposition may not produce a coherent abstraction hierarchy at the subsystems level of decomposition.

Another approach for developing the decomposition dimension of an ADS is to decompose the work system itself into parts. As illustrated at the top of Figure 3, this approach involves decomposing the whole system into its subsystems and

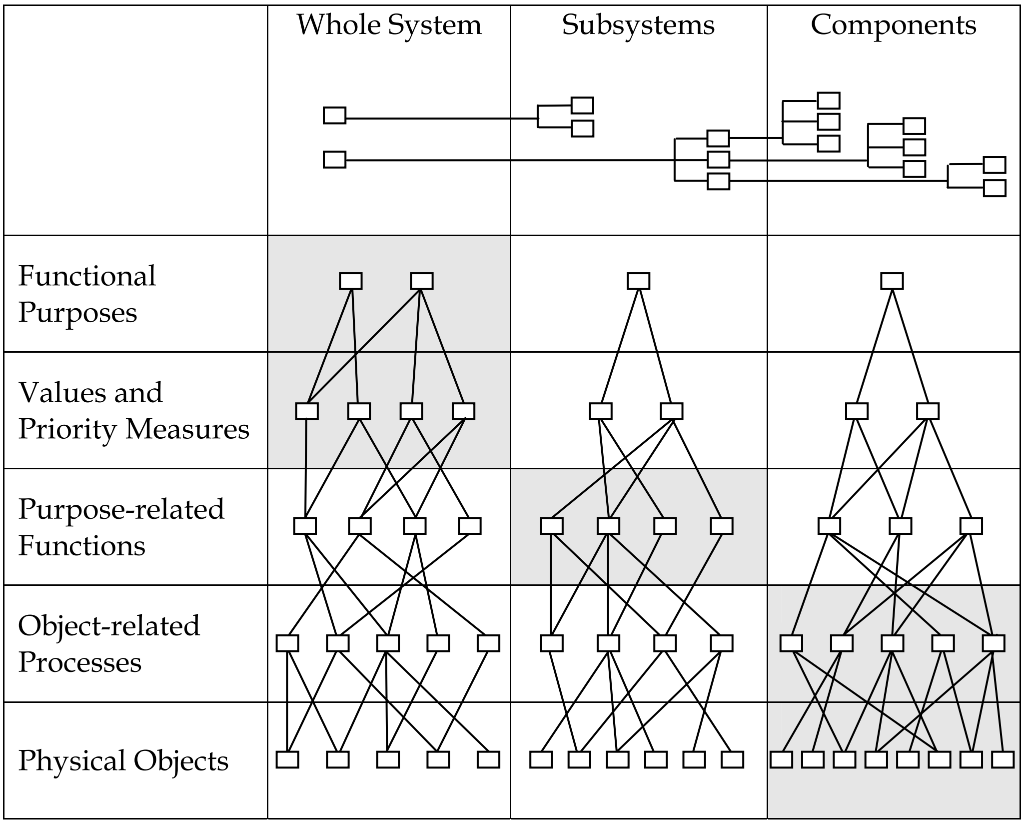

Figure 3. An illustration of an ADS where the decomposition dimension was developed by decomposing the work system itself into its parts, as shown in the top row of the figure. Separate abstraction hierarchies can then be constructed for the parts at each level of decomposition.

components. Once the work system has been decomposed into its parts, separate abstraction hierarchies can be constructed for the parts at each level of decomposition. In the case of a home, the whole house can be decomposed into its rooms and subspaces and contents and components. Following that, separate abstraction hierarchies can be constructed for each of the rooms and subspaces and for each of the contents and components. In addition to the ADS of a home (Table 4), Rasmussen (1998) provides another example of an ADS model where the decomposition dimension was developed using this approach. This approach does not suffer from the problems that we identified with the first approach.

Finally, although it is theoretically possible to populate all of the cells in the ADS by constructing full abstraction hierarchies for the parts at each level of decomposition (as illustrated in Figure 3), it may not be very meaningful or useful to do so. Miller and Vicente (1998) have observed that populating all of the cells in the ADS is rarely productive or efficient. Instead they recommend that analysts evaluate the unique value or the unique information that will be provided by each cell, in order to decide which cells of the ADS to populate. Previously we discussed that cells that fall along the diagonal of the ADS are usually meaningful in the work domain because workers tend to adopt purposive models when working at coarse levels of resolution and physical models when working at fine-grained levels of resolution (Section 4.3). Therefore, we suggest that it is generally worthwhile populating the cells that fall along the diagonal of the ADS. To evaluate the value of populating the remaining cells in the ADS, we recommend that analysts examine these cells, first, in terms of the unique information that each cell contributes relative to cells that fall along the diagonal of the ADS and, second, in terms of the relevance or usefulness of this information for the purpose of the WDA[14].

7.4 Why Decompose?

Many papers on WDA do not report modelling the decomposition dimension of the work domains that were studied, presumably because the decomposition dimension was not necessary for the purposes of the WDA. These papers focus on the abstraction dimension or the abstraction hierarchy as it is illustrated in Figure 4. A point that is generally not acknowledged though is that all of the nodes in the abstraction hierarchy are actually at some level of decomposition although this is not evident in the format shown in Figure 4.

Figure 5 maps the abstraction hierarchy onto the ADS to illustrate one possibility for the levels of decomposition at which the nodes in the abstraction hierarchy can occur. However, there are many other possibilities. Figure 6 shows that the nodes in the abstraction hierarchy can be at different levels of decomposition rather than all at

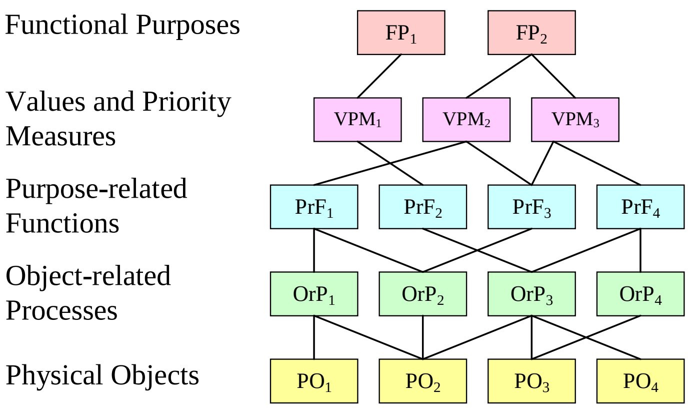

Figure 4. A generic abstraction hierarchy illustrating the format in which the results of a WDA are often reported.

[14] In Section 12.6.4 we discuss how to use a sketch of the ADS to evaluate which cells of the ADS to populate.

the same level of decomposition. Unless analysts make an explicit statement, we cannot be sure about the levels of decomposition at which the nodes in an abstraction hierarchy occur.

Figures 5 and 6 illustrate well-formed abstraction hierarchies because the nodes at any particular level of abstraction are within a level of decomposition. However, Figure 7 shows the kind of model that analysts may unintentionally end up with if they develop an abstraction hierarchy without modelling the decomposition dimension of a work domain explicitly or without at least producing a 'sketch' of the ADS. In Figure 7, each level of abstraction contains nodes or entries from different levels of decomposition. In this case, it would not be true to say that each level of the abstraction hierarchy provides a complete representation of the work domain. In fact, each level of the abstraction hierarchy represents only some of the properties of different parts of the work domain. For instance, the representation in Figure 7 mixes the values and priority measures of the whole system and of the components so that the model may not provide a complete representation of either the values and priority measures of the whole system or of the components. These kinds of mistakes in developing an abstraction hierarchy are relatively easy to make in complex work domains if analysts do not at least produce a sketch of the ADS before developing the abstraction hierarchy.

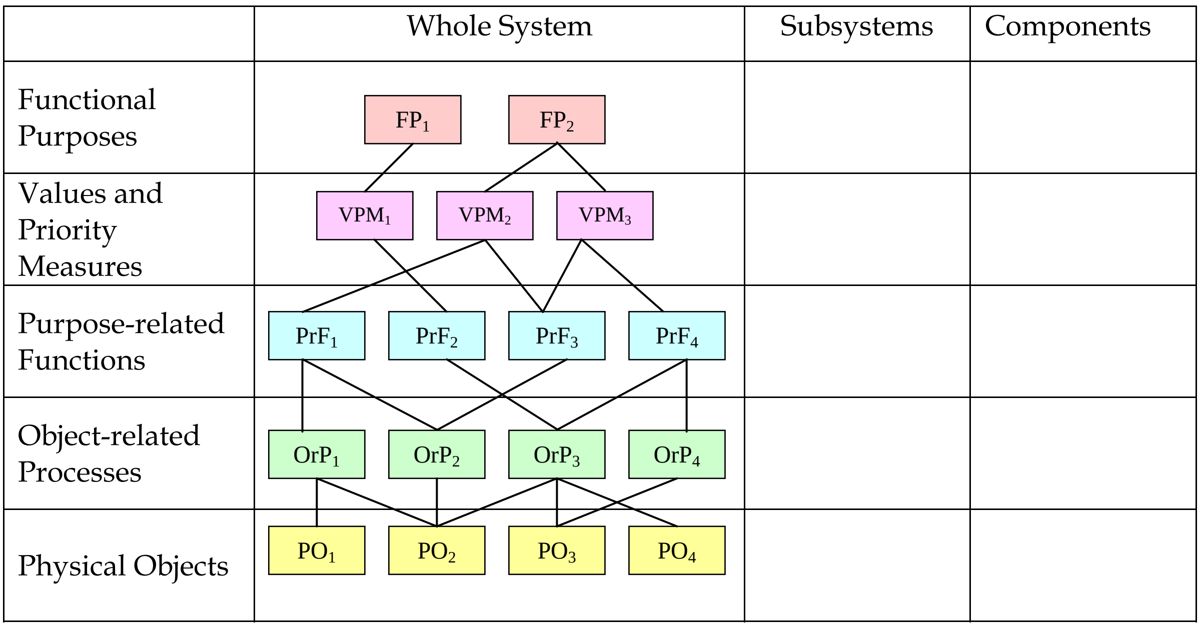

Figure 5. One possibility for the levels of decomposition at which the nodes in the abstraction hierarchy in Figure 4 can occur.

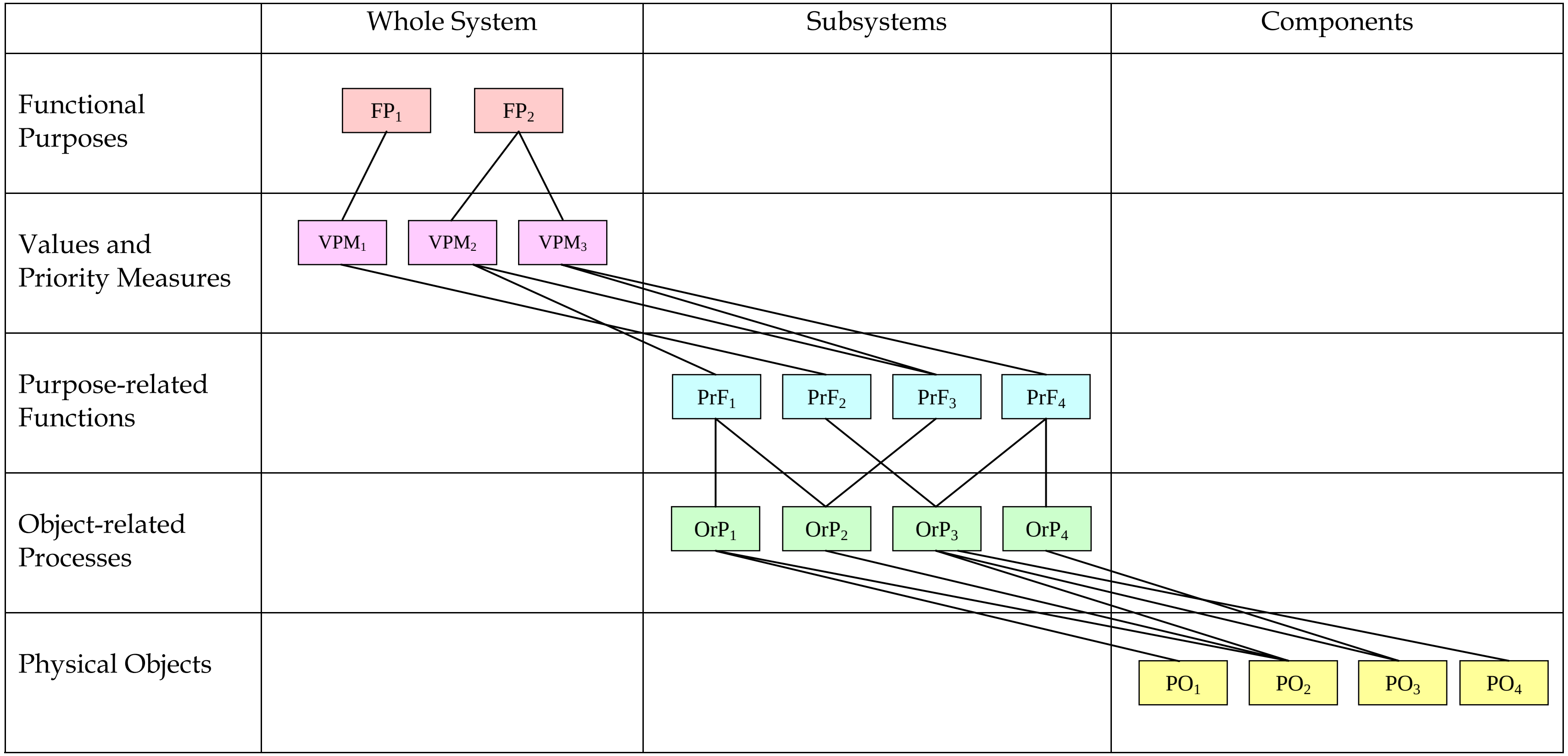

Figure 6. Another possibility for the levels of decomposition at which the nodes in the abstraction hierarchy in Figure 4 can occur.

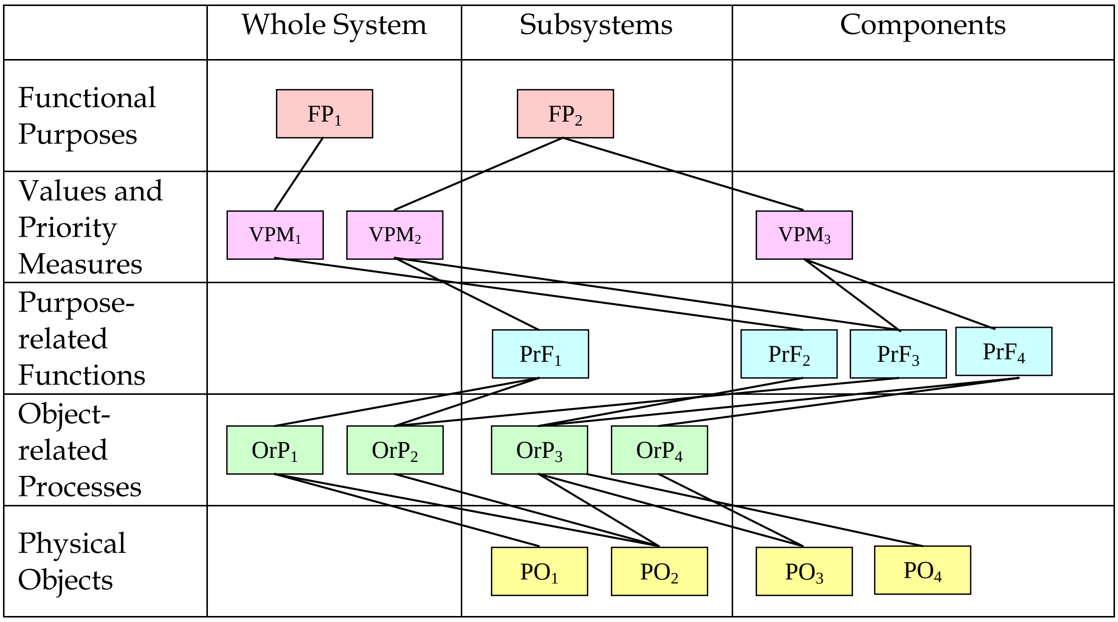

Figure 7. An illustration of the kind of model that analysts may unintentionally end up with if they develop an abstraction hierarchy without modelling the decomposition dimension explicitly or without at least producing a sketch of the ADS.

A sketch of the ADS organises the levels of abstraction and decomposition in a work domain into a matrix and therefore provides an indication of the potential content of each cell in the matrix. For example, a sketch of an ADS of a home that organises the five levels of abstraction and three levels of decomposition in this work domain into a matrix will indicate that the three cells in the middle row of the matrix will contain information about the purpose-related functions of the whole house, rooms and subspaces, and contents and components of a home. By appreciating the potential content of each cell in the ADS, even at this very general level, analysts will be more likely to maintain the distinctions between the different cells of the ADS when developing the abstraction hierarchy.

In summary, then, even if the decomposition dimension is not necessary for the purposes of a WDA, modelling the decomposition dimension explicitly or at least producing a sketch of the ADS may be important for ensuring accuracy and consistency in the abstraction hierarchy. Furthermore, by indicating the potential content of each cell in the ADS, a sketch of the ADS also provides a basis for examining which cells in the ADS will provide the most useful information for the purposes of a WDA and that therefore should constitute the abstraction hierarchy. For example, the cells that constitute an abstraction hierarchy can either be the five cells that fall along the whole system level of decomposition (Figure 5) or the five cells that fall along the diagonal of the ADS (Figure 6).

7.5 Analysing the Decomposition Dimension

In Table 6 we present a set of generic prompts and keywords that we have developed to help analysts define the levels of decomposition and part-whole relations in an ADS. These prompts and keywords provide a guide to the kinds of properties that analysts must search for or uncover about a work system in order to develop the decomposition dimension of an ADS. To illustrate, the prompts for the levels of decomposition indicate that analysts should search for information about what is viewed as the whole system in the work domain and the parts around which work is organised in the work domain. The keywords indicate the different guises in which the wholes and parts of work systems may be revealed to analysts. For example, documents or domain experts may refer to the names of wholes or parts of organisations, physical structures, or conceptual structures. The terminology that is used in a work system, however, will usually be domain specific; so the inhabitants of a home may refer to the house, kitchen, hallway, table, or couch rather than to the term 'physical structures'. Once a comprehensive set of parts has been identified, analysts will need to sort the parts into similar and dissimilar levels of resolution and then organise the levels of resolution into a hierarchy of part-whole relations. This process is illustrated in Section 7.1. Table 6 also presents some prompts to help analysts to check that the relationships between the different levels of resolution or decomposition are in fact part-whole relations and not other kinds of relations that do not belong in a decomposition hierarchy.

As we discussed in Section 6.3, Vicente (1999) provides a nice illustration of the different types of hierarchies, such as authority, classification, decomposition, and abstraction hierarchies, and the kinds of relations that characterise these hierarchies. Analysts must be careful not to confuse the different hierarchy types and to ensure that the relations between the different levels of a decomposition hierarchy are part-whole relations. The prompts in Table 6 indicate that analysts should check whether the entities at higher levels of decomposition are composed of the entities at lower levels of decomposition and whether the entities at lower levels of decomposition are parts of the entities at higher levels of decomposition.

As with the abstraction dimension, the generic prompts and keywords for the decomposition dimension can be used with a variety of data-collection techniques. For example, the prompts and keywords can be used for document analysis or for conducting interviews, walkthroughs, and table-top analysis with domain experts. We will discuss these and other techniques in greater detail in Section 12 of this report.

Table 6. Generic prompts and keywords for analysing the decomposition dimension.

Prompts	**Keywords**
Levels of decomposition: • What is viewed as the whole system in the work domain? • What is the coarsest level at which workers view the work system? • What is the whole system around which work is organised in the work domain? • What do workers view as the parts of the work system? • What is the most detailed level at which workers view the work system? • What are the different levels of detail at which workers view the work system? • What are the parts around which work is organised in the work system? Part-whole relations: • Are the entities at higher levels of decomposition composed of the entities at lower levels of decomposition? • Are the entities at lower levels of decomposition parts of the entities at higher levels of decomposition?	Names of wholes or parts of: organisations, physical structures, physical spaces, conceptual structures, groups, teams, functions, positions, arrangements, aggregations, formations, assemblies, segments, pieces, units, components, systems, subsystems, divisions, branches, sectors, departments

8. Modelling Activity and Control Systems in WDA

8.1 Should Activity be represented in the ADS?

One area in which Rasmussen et al. (1994) and Vicente (1999) appear to contradict each other is with respect to whether activity should be modelled in the ADS. Rasmussen et al. make various statements that imply that activity can be modelled in the ADS. For example, Rasmussen et al. state that a description at the purpose-related functions level of abstraction "… comprises the properties necessary and sufficient to identify the functions and activities to be coordinated" (p.39). In addition, they state that WDA produces an "… inventory of objectives, functions, activities, and resources…." (p.35). Vicente, on the other hand, discusses that the ADS should not represent actions and action means-ends relations but rather the objects of action and structural means-ends relations. Therefore, the ADS should represent objects like 'fireplace' and 'furnace' and structural means-ends relations like a 'fireplace affords warmth' but it should not represent actions and action means-ends relations like 'going down to the basement' and 'lighting the fireplace', which are activities for achieving warmth. Moreover, using the famous ant and beach analogy (Simon, 1981), Vicente emphasises that WDA describes the constraints or properties of the beach and that activity is not a property of the beach but rather a property of the ant. He discusses that it is not that the properties of the ant are not important but that these properties are described in the other phases of CWA and not in WDA.

At first glance, the approaches of Rasmussen et al. (1994) and Vicente (1999) appear to be contradictory. However, we believe that they are not. Like Vicente, Rasmussen et al. do not include actions and action means-ends relations in their ADS models. Rather, Rasmussen et al. represent the categories of activities or functions that are afforded by the work domain in their ADS models. For example, using the ant and the beach analogy, we believe that Rasmussen et al. would include categories of functions or activities that are afforded by the beach in an ADS model. Therefore, they might represent that the beach affords 'walking' and 'sleeping'. Their intention in representing these categories is not to describe the trajectories of activity or properties of the ant. Instead, their intention is to represent the affordances of the beach. Notably, Vicente and other analysts also include what appear to be categories of functions or activities in some of their ADS models (e.g., Burns, Bryant & Chalmers, 2001; Burns & Proulx, 2002; Hajdukiewicz et al., 1999).

8.2 Use of Verbs versus Nouns in the ADS

Another, related, area in which Rasmussen et al. (1994) and Vicente (1999) appear to contradict each other is with respect to the use of verbs versus nouns in the ADS. Rasmussen et al. often use verbs in their ADS models whereas Vicente encourages the use of nouns. In an ADS of a home, Rasmussen et al. may represent that a clock affords the ability to 'tell time' whereas Vicente may represent that a clock affords 'time'. Similarly, Rasmussen et al. may represent that one of the purposes of the inhabitants of a home is to 'save money' whereas Vicente may represent this same purpose as 'financial savings'.

The main reason that Vicente (1999) encourages analysts to use nouns in the ADS is to emphasise that WDA does not model actions and action means-ends relations but rather the objects of action and structural means-ends relations. He argues that this is important for distinguishing the ADS from other forms of work or task analysis that describe actions and action means-ends relations. While we agree with Vicente that it is important to distinguish WDA from other forms of work or task analysis that describe actions and action means-ends relations, there are a number of problems with always using nouns in the ADS. First, it often seems more natural to describe many of the categories of constraints in a work system using verbs rather than nouns. For example, at the values and priority measures level of abstraction, it seems more natural to say that a criterion of the inhabitants is to 'maximise leisure time' rather than 'maximisation of leisure time'. Here, the verb form is not meant to represent activity but rather a rule or a criterion for behaviour. The noun form can often appear contrived or 'foreign' to domain experts compared with the language or terminology that they commonly use in a work system. In addition, given that verbs can be more natural for describing many of the categories of constraints in a work system, analysts may find that thinking about reasonable noun forms for describing these same constraints is time consuming. Second, many words in the English language can be either nouns or verbs depending on the context. For example, 'sleeping' and 'cooking' can be either nouns or verbs. Thus, using these words in the ADS in itself will not distinguish the ADS from other forms of work or task analysis that describe actions and action means-ends relations. These may be some reasons why Vicente and other analysts do not always use nouns in their ADS models (e.g., Burns & Proulx, 2002; Dinadis & Vicente, 1999).

Finally, it is also important to appreciate that the debate about nouns and verbs becomes irrelevant if we consider that we are discussing the grammatical form of the single words or short phrases that analysts typically enter into their ADS models. The use of single words and short phrases is largely a result of the space limitations of the two main formats for representing the ADS, that is, the table and the graphical formats (Section 11). Often we have found that the categories of constraints in a work system are best described using whole sentences or even entire paragraphs. Therefore, in our methodology for WDA we discuss the use of a glossary to record more detailed information about the entries in the ADS regardless of whether they are nouns or verbs (Section 12.6.5).

In summary, because we agree with Vicente (1999) that many people have difficulty distinguishing the ADS from other forms of work or task analysis that describe actions and action means-ends relations, we recommend that where possible or where appropriate analysts should consider using nouns to represent the categories of constraints in their ADS models. However, if the use of nouns seems less natural, contrived, or 'foreign', and if it is difficult or time consuming to come up with reasonable noun forms for describing the categories of constraints in a work system, analysts should not hesitate to use verbs. More importantly, analysts should consider supplementing their ADS models with a glossary that describes the categories of constraints in greater detail than the entries in their ADS models, regardless of whether the entries are nouns or verbs.

8.3 Distinction between WDA and Control Task Analysis

Another related area of confusion is the distinction between WDA and control task analysis, the second phase of CWA. Amongst other types of constraints, WDA models the categories of functions or activity that are *afforded* by the physical resources in a work system. On the other hand, as well as other types of constraints, control task analysis models the categories of functions or activity that are *carried out* in a work system. As a result, there may appear to be some overlap between the constraints that are modelled in WDA and the constraints that are modelled in control task analysis, especially if verbs are used to represent the categories of functions or activity in WDA. In particular, the overlap appears to occur between the representation of purpose-related functions in WDA and the representation of work functions in control task analysis (Naikar, Moylan, & Pearce, in press). This overlap, however, does not mean that the two phases of analysis are describing the same constraints. Rather, the overlap indicates a logical relationship between WDA and control task analysis. This logical relationship exists because the categories of functions or activity that are afforded by the physical resources in a work system are necessary for fulfilling the functional purposes of the work system. It therefore follows that the categories of functions or activity that are carried out in a work system will be related to the categories of functions or activity that are necessary for fulfilling the functional purposes of the work system and, hence, the categories of functions and activity that are afforded by the physical resources in the work system.

8.4 Should Control Systems be represented in the ADS?

Finally, another area of controversy about WDA is whether control systems, such as people and automation, should be modelled in the ADS. Lind (2003) points out that Rasmussen is not explicit about whether control systems should be represented in the ADS. However, Rasmussen includes categories of staff or people in some of his ADS models (e.g., Rasmussen, 1998; Rasmussen et al. 1994) which indicates that he does not preclude the modelling of categories of control systems in the ADS. Vicente (1999), on the other hand, discusses that WDA models the structure of the system being controlled independently of any particular worker, automation, event, task, goal, or interface. Consequently, Vicente has sometimes been interpreted as advocating that control systems should not be modelled in the ADS (e.g., Bisantz, Burns & Roth, 2002; Miller & Sanderson, 2000). However, like Rasmussen, Vicente and other analysts have also included categories of staff or people in some of their ADS models (e.g., Burns & Proulx, 2002; Hajdukiewicz et al., 1999). It can therefore be argued that it was not Vicente's intention to preclude the modelling of categories of control systems in the ADS per se but rather to preclude the modelling of the trajectories of activity or the behaviour of control systems in the ADS. Indeed, neither Rasmussen (e.g., Rasmussen, 1998; Rasmussen et al., 1994) nor Vicente and other analysts (e.g., Burns & Proulx, 2002; Hajdukiewicz et al., 1999) represent the trajectories of activity or the behaviour of control systems in their ADS models. Rather, they model the functional capabilities and limitations of the categories of control systems in the work domain.

The justification for modelling categories of control systems in the ADS can be made on two other bases. First, control systems not only afford the control of activity in a work domain but they are also often the objects of control. For example, staff are typically under the control of other human workers, such as supervisors or managers, and automation is typically under the control of human workers. Therefore, it can be argued that control systems that are under the control of human workers should be included in the ADS, given that WDA models the objects of control in a work domain (Vicente, 1999). Bisantz et al. (2002) make a similar observation in comparing two ADS models of shipboard command and control. Second, given that the ADS models the reasoning space or problem space of workers, it can be argued that control systems should be included in the ADS if they are in the reasoning space of workers. For example, in pursuing the objectives of a work system, workers may have to reason about the availability of particular control systems in the work domain as well as the functional capabilities and limitations of the control systems. If so, the control systems should be represented in the ADS, while keeping in mind that the ADS should not model the trajectories of activity or the behaviour of the control systems but rather their availability and functionality. Other characteristics of control systems, such as their activity or behaviour, may be modelled in the other phases of CWA[15].

9. Topological Relations

So far in this report we have not discussed the modelling of topological relations in the ADS. Few analysts include topological relations in their ADS models and there is relatively little information about topological relations in the literature on WDA. The aim of this section is to review the information that is currently available about topological relations and, on this basis, draw some inferences about the modelling of topological relations in the ADS.

Topological relations show how the nodes or entries *within* cells of the ADS are linked or connected (Figure 8). Topological relations can therefore be contrasted with means-ends and part-whole relations, which show the connections *between* cells in the ADS; means-end relations show the connections between cells along the abstraction dimension of the ADS and part-whole relations show the connections between cells along the decomposition dimension of the ADS. The specific nature of topological relations within the cells of the ADS appears to vary as a function of the level of abstraction and the type of work system.

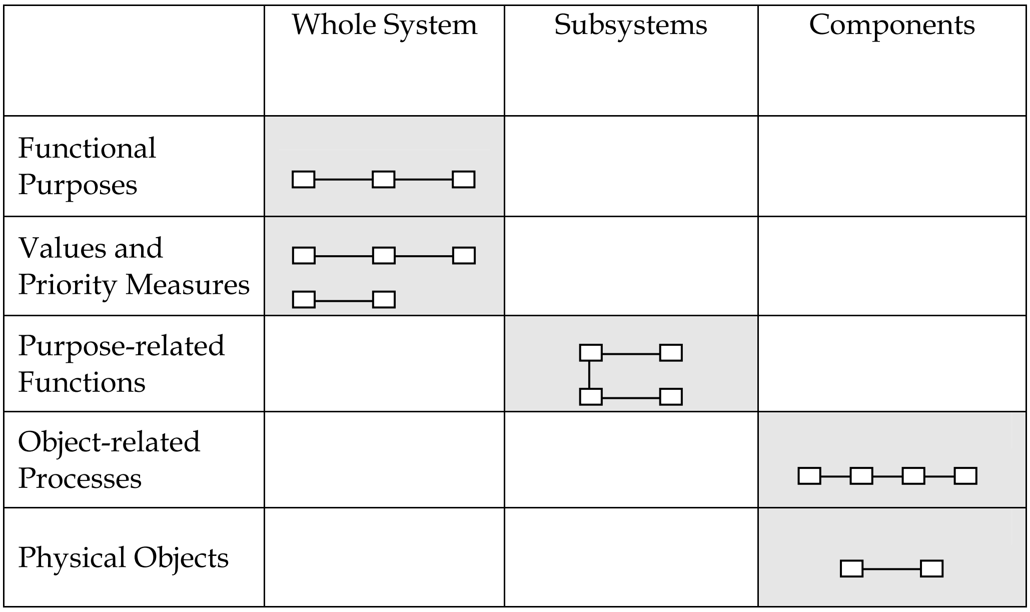

Figure 8. Topological relations connect nodes or entries within the cells of the ADS.

Perhaps the most comprehensive description of topological relations in an ADS is provided by Vicente (1999). Vicente describes the nature of the topological relations at

[15] The representation of control systems in WDA deserves further research which is beyond the scope of this report. Our motivation for including a small section on this topic here was mainly to document this as an issue relating to WDA and to provide a starting point for further research in this area.

each level of abstraction in an ADS model of DURESS, a process control microworld. At the abstract function (values and priority measures) level of abstraction, the topological relations indicate the flows of mass and energy through the subsystems of DURESS. At the generalized function (purpose-related functions) level of abstraction, the topological relations indicate the flows of water and heat through the components of the DURESS system. At the physical function (object-related processes) level of abstraction, the topological relations indicate the physical connections between the components of the DURESS system. Finally, at the physical form (physical objects) level of abstraction, the topological relations indicate the spatial relationships between the components of the DURESS system. The topological relations at the second and third levels of abstraction therefore indicate causal relationships or causal flows whereas the topological relations at the fourth and fifth levels of abstraction indicate physical and spatial relationships, respectively. Vicente does not identify any topological relations at the functional purposes level of abstraction. In addition, not all of the nodes or entries within a cell in Vicente's ADS model of DURESS are connected by one topological flow; some of the nodes are part of one topological flow whereas other nodes are part of another topological flow; this is illustrated in Figure 8 in the cell at the values and priority measures level of abstraction and the whole system level of decomposition.

There are only a few other examples in the literature of models with topological relations in process control work domains like DURESS. These examples include ADS models of: a simulated nuclear power plant (Burns, 1998); a fossil-fuel plant feedwater subsystem (Dinadis & Vicente, 1996); a petrochemical plant (Jamieson & Vicente, 1998, 2001); and a simulated pasteurisation plant (Reising & Sanderson, 2002b). All of these ADS models appear to represent the same kinds of topological relations as the ADS model for DURESS. In some other analyses of nuclear power plants, the nature of the topological relations in the ADS models is not discussed (Gualtieri et al., 2000; Itoh, Sakuma & Monta, 1995; Roth, Lin, Kerch, Kenney & Sugibayashi, 2001).

Although there are some examples of models with topological relations in causal systems other than process control, there is relatively little information about the nature of the topological relations in these work systems. In one ADS model of a terrain collision and avoidance system in the aviation domain, the nature of the topological relations is not discussed explicitly (Ho & Burns, 2003). In another ADS model of the human body for diabetes management, the topological relations at the abstract function (values and priority measures) level of abstraction are described as modelling flows of energy (Thompson et al., 2003). Finally, in an ADS model of network performance management, the topological relations at the abstract function (values and priority measures) level of abstraction are described as modelling information and data flows (Burns, Kuo, et al., 2003; Kuo & Burns, 1999, 2000).

Even fewer studies in the literature discuss models of topological relations in intentional work domains. Perhaps the only comprehensive discussion of the nature of topological relations in an intentional system is provided by Kinsley, Sharit, and Vicente (1994). Kinsley et al. observe some key differences in the nature of topological relations in highly causal systems, such as continuous process control, compared with work systems with a greater degree of intentionality, such as discrete manufacturing systems. In highly causal systems, the topological relations or flows are determined by physical laws and are hardwired into the system. Human operators have little discretion in determining the topological flows in these systems. In contrast, in work systems with a greater degree of intentionality, there are multiple possibilities for topological relations or flows and there is considerably greater scope for human operators to choose the topological relations or flows in the system. In discrete manufacturing systems, for example, human operators can choose the order in which a machine should process jobs or choose which of several routes a part that is to be manufactured should take through the system.

In light of the discussion by Kinsley et al. (1994), we can consider the nature of topological flows in a work domain of a home, which is a highly intentional system. It seems that in an ADS of a home (Table 4), there are likely to be multiple, if not infinite, possibilities for topological relations in at least some of the cells of the ADS. In the cell at the physical objects level of abstraction and rooms and subspaces level of decomposition, there are likely to be infinite possibilities for the spatial relationships between the physical objects of a kitchen given that the location of cutlery, for instance, can change multiple times in the course of preparing a single meal. Similarly, there are many possibilities for the flow of functions in the cell at the purpose-related functions level of abstraction and the whole house level of decomposition. For example, inhabitants can have a *meal* and then a *rest* before doing the *housework* or inhabitants can do the housework and then have a rest before eating a meal. Conversely, in the cell at the physical objects level of abstraction and the contents and components level of decomposition, the spatial relationships between the components of a dishwasher are likely to be finite and unalterable[16].

On the basis of this review of the nature of topological relations in various ADS models in the literature, we can make some observations about the modelling of topological relations in causal versus intentional systems. It seems that we can distinguish between identifying the general nature of topological relations within cells in an ADS and modelling the specific connections between nodes or entries within cells in an ADS. The first step is to identify the general nature of the topological relations within cells in an ADS; for example, whether the topological relations reflect spatial relationships or sequential flows. This step should be possible for both causal and intentional systems. Having identified the general nature of the topological relations within the cells of an ADS, the second step is to identify the specific connections between the nodes or entries in the cells of the ADS. On the basis of our review, it seems that this step should be possible for causal systems. For intentional systems, however, this step may not be feasible or useful for cells in the ADS with multiple, if not infinite, possibilities for topological flows, except in the context of specific situations or problems[17].

[16] In providing these examples from the work domain of a home, we have made some assumptions about the nature of the topological relations in an ADS of a home; we have not analysed these relations systematically.

[17] The representation of topological relations in WDA deserves further research which is beyond the scope of this report. Our motivation for including a small section on this topic here was mainly to document this as an issue relating to WDA and to provide a starting point for further research in this area.

10. Object Worlds and Stakeholders

Another topic that we have not discussed so far in this report is the modelling of object worlds and stakeholders in WDA. These terms have not been well defined or discussed in detail in the WDA literature so it is not readily apparent whether analysts have used the terms consistently and whether the terms can be used interchangeably. Moreover, analysts typically model object worlds or stakeholders along the horizontal axis of a matrix which, like the ADS, represents the abstraction dimension along the vertical axis of the matrix (Table 7). Consequently, without a clear definition of what the terms object worlds and stakeholders mean, it can be difficult to distinguish models of object worlds or stakeholders from decomposition models, especially for novice analysts. In this section, we explore how various analysts have used the terms object worlds and stakeholders and we discuss how to distinguish models of object worlds and stakeholders from decomposition models.

The first analyst to use the term object worlds in the context of WDA appears to be Rasmussen (e.g., Rasmussen et al., 1990). However, Rasmussen identified Bucciarelli (1988) as the original source of the term. Bucciarelli coined the term object worlds in the context of engineering design to describe his observation that the same object or artifact in a design project can be construed differently by the various participants involved in the design problem. Specifically, Bucciarelli found that a mechanical engineer, an electrical engineer, and a marketing manager on a design project had different object worlds or different views of the artifact under design. The participants' views of the design artifact depended largely on their technical specialisation, which focused their attention on different subsets of attributes of the design artifact.

One instance in which Rasmussen used the term object worlds was in discussing a WDA of a health care system (Rasmussen et al., 1990). In this analysis, Rasmussen et al. (1990) modelled the patients and the various professional groups in a hospital (e.g., medical practitioners, administrative officers) as having different object worlds. The model therefore showed the different views that the patients and the various professional groups had of the same work domain of health care. Rasmussen et al. (1994) observed that the object worlds of the patients and the various professional groups were coupled to each other, to varying degrees, at different levels of abstraction. Changes or effects in one object world could therefore propagate to other object worlds. According to Rasmussen et al. (1994), it is this coupling between object worlds that makes it necessary to model the different object worlds in WDA. Otherwise, changes in one object world, such as the introduction of new technologies, may have unintended side effects in other object worlds.

Table 7. A matrix that has stakeholders or object worlds along its horizontal axis and the abstraction dimension along its vertical axis.

	Stakeholder / Object World	Stakeholder / Object World	Stakeholder / Object World
Functional Purposes			
Values and Priority Measures			
Purpose-related Functions			
Object-related Processes			
Physical Objects			

While it appears that Rasmussen has not used the term stakeholders in any of his publications, other analysts have used this term more recently. Burns and Vicente (2000) used the term stakeholders to describe groups of people with different goals and perspectives of the same design problem. They identified the stakeholders in the design of a control room for a nuclear power plant as including ergonomics designers, structural engineers, implementers, customers, and management. The stakeholders had different perspectives of the same design problem; so whereas an ergonomist might view a console as a workspace that must be comfortable and useable, a structural console engineer might view the same console as a piece of furniture that must have a certain strength, rigidity, and lifetime of use. Burns and Vicente found that all of the views of the different stakeholders were correct but only partial views of the design problem. In addition, they found that at the highest level of abstraction (which they labelled objectives) vast differences were seen between the goals of the different stakeholders whereas at the lowest level of abstraction (which they labelled physical components) many elements were shared. Finally, Burns and Vicente also observed that changes in the domain of one stakeholder forced reactionary design activities to occur in the domains of the other stakeholders.

Chow and Vicente (2001) also used the term stakeholders within the domain of network management. In their analysis, Chow and Vicente made a distinction between stakeholders that were within versus outside a network management company. Stakeholders within the company included network managers, technical experts, field staff, and change managers. Stakeholders outside the company included service providers and equipment suppliers. Chow and Vicente observed that the stakeholders had different but overlapping views of the networks.

Benda and Sanderson (1998) also discussed the term stakeholders in the context of an elevator firm. In this study, they described the stakeholders in the elevator firm as having overlapping and interacting work domains. The work domains overlapped because the stakeholders shared elements of their affordance structure – whether this was at the level of physical objects or at higher levels of abstraction. As a result of these shared elements, changes in one stakeholder domain could lead to changes in other stakeholder domains. Benda and Sanderson identified the stakeholders in the elevator firm as including: the public, maintenance, operations research, engineering, designers, builders, client/owner, and architect. They observed that for all of these stakeholders, the elevator system played a role at the physical objects level of abstraction.

From this review, it seems that we can use the term stakeholders to refer to groups or organisations with different but overlapping views of the same work domain or problem. In contrast, the term object worlds can be more accurately used to refer to the stakeholders' views of that work domain or problem (Table 8). In Rasmussen's analysis of the work domain of health care, the patients and the various professional groups in a hospital are stakeholders whereas the views that the patients and the various professional groups in a hospital have of the work domain of health care are their object worlds. The object worlds of different stakeholders can overlap at any level of abstraction or at multiple levels of abstraction; although we note that in all of the studies we reviewed the overlap occurred at the physical objects level of abstraction. The overlap or coupling between different stakeholders means that changes or effects in one stakeholder domain can propagate to other stakeholder domains.

Table 8. A matrix that shows the distinction between stakeholders and their object worlds.

	Stakeholder 1	Stakeholder 2	Stakeholder 3
Functional Purposes			
Values and Priority Measures			
Purpose-related Functions	Object world 1	Object world 2	Object world 3
Object-related Processes			
Physical Objects			

We should mention, however, that we did find one instance of the use of the term object worlds that may be inconsistent with the concept of object worlds that is proposed above. Hajdukiewicz et al. (1999) used the term object worlds to describe an abstraction hierarchy for emergency ambulance dispatch management which they adapted from Rasmussen et al. (1987). Hajdukiewicz et al. identified the two object worlds in this work domain as the "… domain of potential risk associated with identifying, assessing, and prioritising emergencies…." and the "… domain of mitigating resources associated with the capabilities and limitations of the response resources…." (p.334). In addition, they discussed that "Dividing the work environment into two "object worlds" provides a way of distinguishing the risks in the environment (i.e., emergencies) and resources available to manage those risks (i.e., response resources)" (p.334). Unlike the view of object worlds presented in this report, the object worlds identified by Hajdukiewicz et al. do not appear to be associated with different stakeholders or different groups or organisations within the domain of emergency ambulance dispatch management. The term object worlds was not used by Rasmussen et al. in their original analysis of emergency ambulance dispatch management. Rasmussen et al. only state that the problem space of emergency management consists of two independent parts; the two parts consist of separate sets of items from which only a subset is selected for consideration in particular situations.[18]

Earlier we mentioned that distinguishing stakeholders from decomposition models can be difficult given that both stakeholders and decomposition models are typically represented along the horizontal dimension of a matrix with the different levels of abstraction along the vertical dimension of the matrix. Moreover, given that stakeholders are different groups or organisations in a work domain, distinguishing stakeholders from decomposition models can be particularly difficult when the decomposition dimension represents different groups or organisations that are parts of the work system under study. In light of the view of stakeholders presented in this report, stakeholder models can be distinguished from decomposition models by studying the nature of the relationships between the entities along the horizontal dimension of the matrix. In the case of decomposition, entities at lower levels of the dimension will be parts of the entities at higher levels of the dimension and entities at higher levels of the dimension will be composed of entities at lower levels of the dimension. In the case of stakeholders, entities along the horizontal dimension will be groups or organisations that do not have part-whole relationships with each other. In the case of a home, the decomposition dimension of the ADS models the whole house, rooms and subspaces, and contents and components of a home (Table 4). These entities have part-whole relationships with each other. In contrast, the various stakeholders in the work domain of a home can include the inhabitants of a home, the visitors to a home, and the various tradespeople that service the home. The ADS of a home in Table 4 models the work domain from the perspective of the inhabitants of a home.

Finally, we note that a matrix that represents stakeholders along the horizontal axis and the abstraction dimension along the vertical axis, as shown in Table 8, can be referred to as an abstraction-stakeholder space (Benda & Sanderson, 1998). This does not mean, however, that using the horizontal axis to model stakeholders precludes the

[18] To justify modelling the problem space of emergency management as two separate parts, Rasmussen et al. (1987) observed that in this domain the faults or disturbances that must be controlled do not originate from the same system that does the controlling. In contrast, in process control work domains, the resources for dealing with disturbances are from the same system in which the faults originate.

modelling of the decomposition dimension of a work domain. Table 9 shows how separate ADS models can be constructed for the different stakeholders in a work domain.

Table 9. A matrix with separate ADS models for each stakeholder. The ADS models represent the object worlds of each stakeholder. WS refers to whole system, Ss refers to Subsystems, and Co refers to Components.

	Stakeholder 1			Stakeholder 2			Stakeholder 3		
	WS	Ss	Co	WS	Ss	Co	WS	Ss	Co
Functional Purposes									
Values and Priority Measures									
Purpose-related Functions		Object world 1			Object world 2			Object world 3	
Object-related Processes									
Physical Objects									

11. Formats for Representing the ADS

In this section, we discuss two formats that are commonly used to represent the ADS. One format, which is the format that we have used for the ADS of a home, represents the ADS as a table (Table 10). The other format represents the ADS as a graphical network of nodes (Figure 9)[19]. In our experience, novice analysts are usually confused about how the table format maps onto the graphical format and vice versa. We therefore discuss the overlap or mapping between the two formats as well as the relative advantages of the table and graphical formats for representing the ADS.

Much of the confusion about the overlap between the table and graphical formats for modeling the ADS is caused by the fact that it appears as though the table format (Table 10) models both the abstraction and decomposition dimensions of a work domain whereas the graphical format (Figure 9) only models the abstraction dimension of a work domain. However, as we have discussed in Section 7.4, the graphical format also models both the abstraction and decomposition dimensions of a work domain; it's just that the decomposition dimension is not made explicit in this format. Figures 10 and 11 map the graphical format onto the table format to illustrate two possibilities for the levels of decomposition at which the nodes in the graphical format can occur. As a result of not understanding the overlap between the graphical (Figure 9) and table (Table 10) formats of the ADS, novice analysts tend to be confused by the claim that each cell in the table format offers a complete representation of the work domain.

[19] Figures 9, 10, 11, and 12 in this section have appeared earlier in this report. We repeat them here for the sake of convenience.

Table 10. The table format for representing the ADS.

	Whole System	Subsystems	Components
Functional Purposes (FP)	FP_1, FP_2		
Values and Priority Measures (VPM)	VPM_1, VPM_2, VPM_3		
Purpose-related Functions (PrF)	PrF_1, PrF_2, PrF_3, PrF_4		
Object-related Processes (OrP)	OrP_1, OrP_2, OrP_3, OrP_4		
Physical Objects (PO)	PO_1, PO_2, PO_3, PO_4		

Novice analysts can usually see how each level of abstraction in the graphical format (Figure 9) offers a complete representation of the work domain (and how the different levels of abstraction offer different representations of the same work domain). However, novice analysts often do not realise that a cell in the table format contains all of the nodes at a particular level of abstraction in the graphical format. For instance, the cell at the purpose-related functions level of abstraction and the whole system level of decomposition in Table 10 contains all of the nodes at the purpose-related functions level of abstraction in the graphical format (Figure 9); this mapping is illustrated in Figure 10. The purpose-related functions cell at the whole system level of decomposition in Table 10 therefore offers a complete representation of the work domain as does the purpose-related functions level of abstraction in the graphical format (Figure 9).

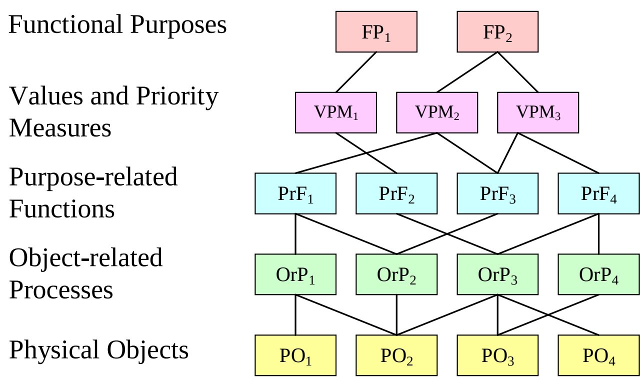

Figure 9. The graphical format for representing the ADS.

One disadvantage of the graphical format (Figure 9), then, is that it does not make clear at what level of decomposition the nodes at the different levels of abstraction belong. Figures 10 and 11 illustrate only two of the many possibilities for the levels of decomposition at which the nodes in the graphical format (Figure 9) can occur. However, there are many other possibilities. Unless an explicit statement is made by analysts, viewers of the graphical format cannot be sure about the level of decomposition to which the nodes in the abstraction hierarchy belong. One variation of the table format (Table 10) that suffers from the same disadvantage as the graphical format (Figure 9) is illustrated in Table 11. As with the graphical format, we cannot be certain about the level of decomposition of the entries in the table unless analysts state this explicitly[20].

One advantage of the table format (Table 10) for viewers of the ADS, therefore, is that it makes explicit the level of decomposition at which entries in the table occur. In addition, this format offers some advantages to analysts in constructing the ADS. First, a sketch of the ADS based on the table format (Table 10) is useful for systematically evaluating which cells of the ADS it is most meaningful or useful to populate; we discussed in Section 7.3 that although it is theoretically possible to populate all of the cells in the ADS it is usually not very meaningful or useful to do so. Second, having selected which cells of the ADS to populate, a sketch of the ADS based on the table format (Table 10) is useful for ensuring accuracy and consistency in populating the cells of the ADS. Moreover, a sketch of the ADS based on the table format (Table 10) is useful for ensuring accuracy and consistency in developing an abstraction hierarchy (if analysts are only modelling the abstraction dimension of a work domain); Figure 12 shows the kind of model that analysts may unintentionally end up with if they develop an abstraction hierarchy without at least producing a sketch of the ADS.

Conversely, one advantage of the graphical format (Figure 9) compared with the table format (Table 10) is that the graphical format allows the means-ends relations between nodes at different levels of abstraction to be shown explicitly. This is useful for two main reasons. The first has to do with the process of constructing the ADS. Drawing links between the nodes at the different levels of abstraction helps analysts to check that the relationships between the different levels of abstraction are structural means-ends relations; we discussed in Sections 5.1 and 6.3 that it is easy for analysts to drift from identifying structural means-ends relations to other kinds of relations that do not belong in an abstraction hierarchy. The second reason has to do with the application of the ADS. Specifically, the graphical format (Figure 9) is useful for applications that involve tracing the impact of nodes at lower levels of abstraction on nodes at higher levels of abstraction or vice versa (e.g., Naikar & Sanderson, 2001; Crone et al., 2003). The means-ends links allow analysts to systematically and efficiently trace the propagation of effects throughout the work domain, including the propagation of unintended side effects.

A format for representing the ADS that combines the advantages of the table (Table 10) and graphical (Figure 9) formats is illustrated by Figures 10 and 11. This format

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[20] In this sense, the advantages and disadvantages of the table and graphical formats that we discuss here are not inherent to table and graphical formats in general but rather to the particular formats illustrated in Table 10 and Figure 9. We cannot discuss the advantages and disadvantages of all of the variations of the table (Table 10) and graphical (Figure 9) formats in this report. However, we believe that we have provided sufficient information to allow readers to generalise the observations that we make here to variations of these formats.

shows the means-ends relations between the nodes at different levels of abstraction and it also models the decomposition dimension explicitly. However, the problem with this format, and possibly with any other format that combines the advantages of the table (Table 10) and graphical (Figure 9) formats, is that the representations will probably be very large and cumbersome when modeling large-scale, complex systems like many of the military systems we have analysed.

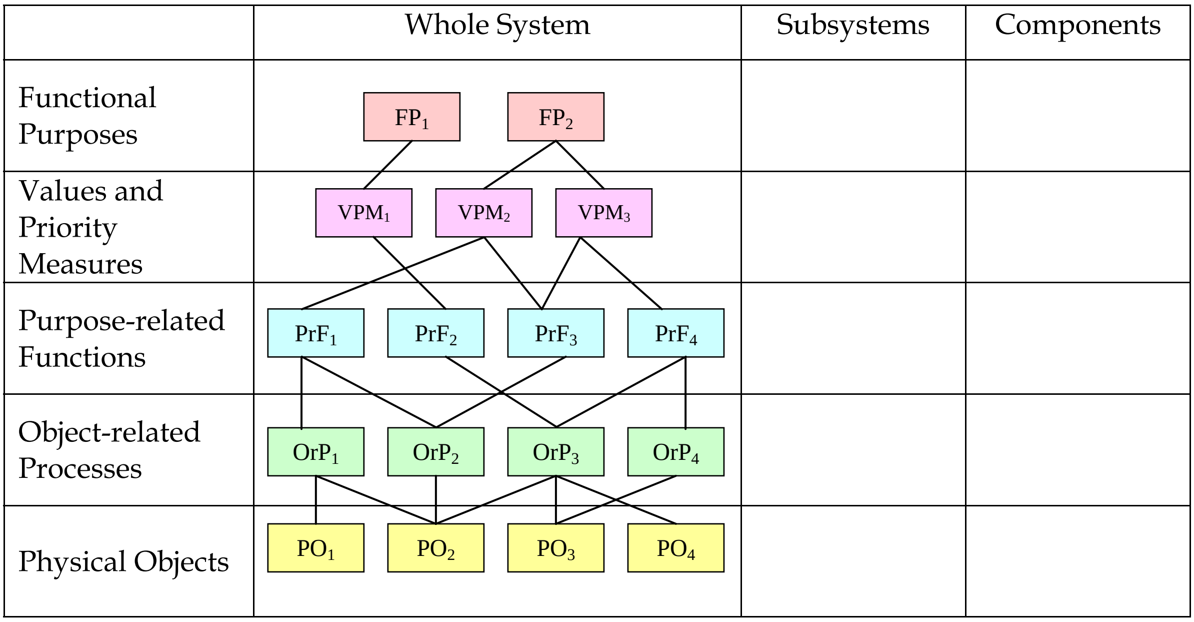

Figure 10. One possibility for the levels of decomposition at which the nodes in the graphical format in Figure 9 can occur.

To take advantage of both the table (Table 10) and graphical (Figure 9) formats without having to combine the two formats, we recommend that analysts use the two formats alternatively at different stages of constructing the ADS. Analysts can use the table format (Table 10) at the early stages of an analysis to develop a sketch of the ADS that defines the levels of abstraction and decomposition in a work domain and therefore the potential content of each cell in the ADS. Analysts can then use this sketch or, in other words, the table format to evaluate which cells of the ADS it would be most meaningful or useful to populate, and to ensure accuracy and consistency in populating the cells of the ADS or in developing an abstraction hierarchy. Following that, analysts can switch to the graphical format (Figure 9) so that they can draw means-ends links between the entries or nodes at different levels of abstraction to check that the relationships between the different levels of abstraction are structural means-ends relations. The first switch should occur reasonably early in the construction process so

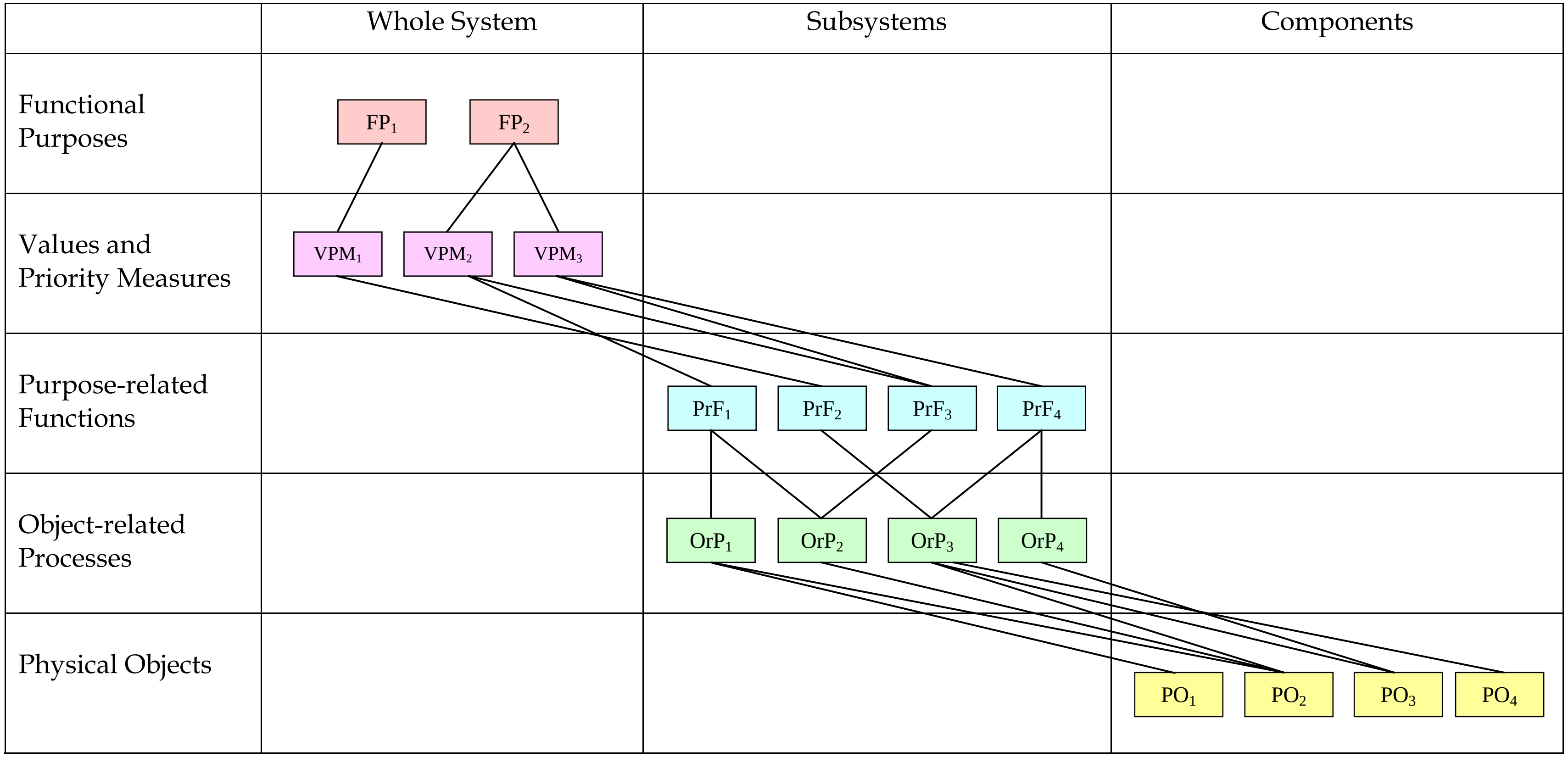

Figure 11. Another possibility for the levels of decomposition at which the nodes in the graphical format in Figure 9 can occur.

Table 11. A variation of the table format (Table 10) that does not make explicit the level of decomposition at which the entries in the table belong.

Functional Purposes	FP_1, FP_2
Values and Priority Measures	VPM_1, VPM_2, VPM_3
Purpose-related Functions	PrF_1, PrF_2, PrF_3, PrF_4
Object-related Processes	OrP_1, OrP_2, OrP_3, OrP_4
Physical Objects	PO_1, PO_2, PO_3, PO_4

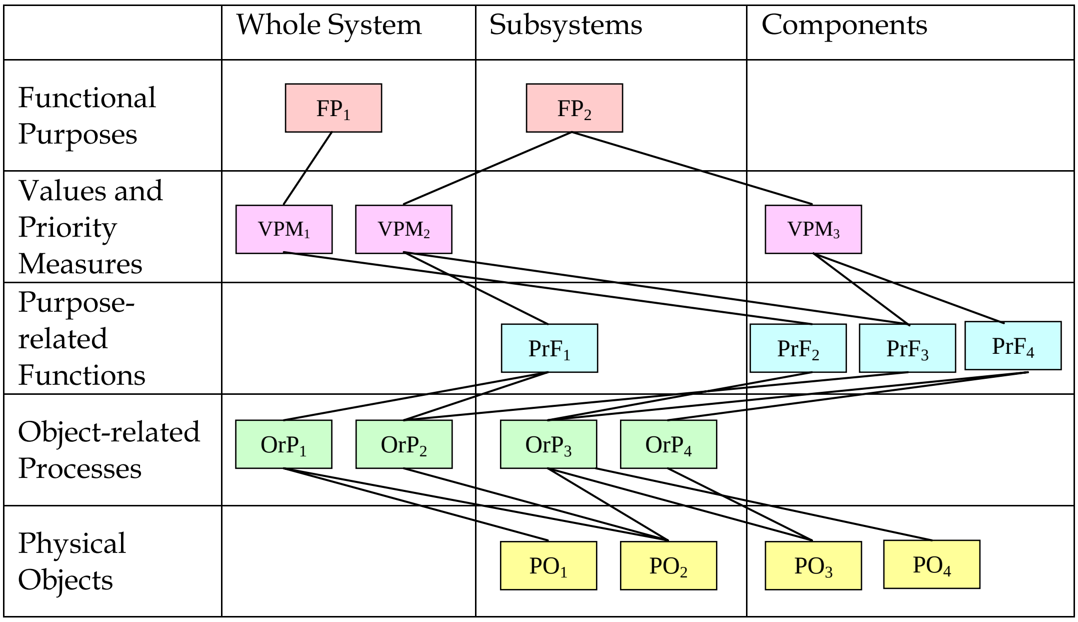

Figure 12. An illustration of the kind of model that analysts may unintentionally end up with if they develop an abstraction hierarchy without producing at least a sketch of the ADS.

that any problems with the analysis can be addressed before vast amounts of time or resources are spent on developing the ADS. Analysts should then continue to switch between the two formats during the remainder of the construction process until they are confident that they have a well-formed ADS. The final format of the ADS should be the one that is best suited for the intended application.

12. Methodology

Having discussed a number of conceptual issues relating to WDA, in this section we propose a methodology for performing WDA. This methodology consists of nine main steps. Steps 1-5 describe several decisions that must be considered prior to constructing the ADS including: establishing the purpose of the analysis (step 1), identifying the project constraints (step 2), identifying the boundaries of the analysis (step 3), identifying the nature of the constraints in the work domain (step 4), and identifying the sources of information for the analysis (step 5). Following that, the process for constructing the ADS is described in steps 6 to 8 as involving three main iterations. The first iteration (step 6) involves constructing the ADS with readily available sources of information. The second iteration (step 7) involves constructing the ADS by conducting special data collection exercises. The third iteration (step 8) involves reviewing the ADS with domain experts. Finally, step 9 involves validating the ADS.[21]

The methodology for WDA is informed by the theoretical concepts that we presented earlier in this report. Therefore, in describing the methodology for WDA we often draw upon or refer to the earlier discussions. For example, step 6 of the methodology involves defining the levels of abstraction and decomposition in a work domain. A process for defining the levels of abstraction and decomposition in a work domain, together with examples from the work domain of a home, was provided in Sections 5.1 and 7.1. Hence, this information is not redescribed in step 6 of the methodology; instead the reader is guided to the relevant sections of the report. Other steps of the methodology also draw on previous discussions in a similar way. As a result, the methodology for WDA places the theoretical concepts that we presented earlier in this report into a logical sequence or context.

The methodology for WDA is also informed by our experience in conducting WDA for complex, military systems. In particular, we have used WDA to define the training needs and training-system requirements for the acquisition of a training system for F/A-18 fighter aircraft (Naikar & Sanderson, 1999); to evaluate competing design proposals for the provision of an Airborne Early Warning and Control system to the Australian Government (Naikar & Sanderson, 2001); and to develop a team design for the Airborne Early Warning and Control system (Naikar et al., 2003). As a result of our experience on these industry projects, the methodology for WDA includes a number of practical considerations such as the need to take into account project constraints, for example, time constraints and budget constraints (step 2). Our approach to WDA on these large-scale, industry projects has led to feasible and useful applications of WDA.

Our intention in developing this methodology for WDA was not to be prescriptive. Instead our intention was to save time and resources on projects. On previous projects, we have had to invent the process for performing WDA alongside using WDA to

[21] Vicente (1999) provides a glossary of terms that are commonly used in CWA which may be a useful complement to the methodology for WDA that we describe in this report.

address the particular problem at hand. Needless to say, inventing the process for performing WDA consumed valuable time and resources on projects. A methodology for WDA that has been developed a priori will free up project time and resources so that it is feasible to carry out more of the steps of the methodology or carry out some of the steps of the methodology in greater detail compared with what would have been possible otherwise. The full methodology for WDA is best suited for long-term projects in which the ADS will be used throughout a system's lifecycle. For example, we have used an ADS model of an Airborne Early Warning and Control system to evaluate alternative design proposals (Naikar & Sanderson, 1999), to design a team (Naikar et al., 2003), and to develop a test and evaluation program for this system.

Finally, although we present the steps of this methodology in a logical sequence, the process for performing WDA is largely iterative. For instance, constructing the ADS in steps 6 to 8 may lead analysts to reconsider some of the decisions that they made earlier in the methodology, such as, decisions about the purposes and boundaries of the WDA. For this reason, it may be useful for analysts to perform a 'trial' that involves brainstorming steps 1 to 5, which precede the construction of the ADS, and then attempting the next step or the first iteration of the ADS but only in sufficient detail to enable analysts to judge whether the resulting product will be suitable or useful for the project in question. If the resulting product is judged to be unsuitable, then analysts can revisit steps 1 to 5 to revise, for example, their decisions about the purposes or boundaries of the WDA. If the resulting product is judged to be suitable, then analysts can revisit steps 1 to 5 to state their decisions more clearly and comprehensively, and with greater confidence, before resuming the construction of the ADS.

12.1 Step 1: Establish the Purpose of the WDA

The first step of the methodology for WDA is to establish the purpose of the analysis. There are really two parts to this problem. First, analysts must define the problem that they want to address or resolve with WDA. Second, analysts must define how they will use WDA to address that problem. Establishing the purpose of the WDA is an important step because there are actually many different ways to model a work domain and how analysts choose to model a work domain will depend largely on the purpose of the analysis. In particular, many of the decisions that analysts must make in subsequent steps of this methodology, such as decisions about the boundaries of the analysis and about which cells of the ADS to populate, can only be addressed in light of the purpose or intent of the WDA.

To illustrate, in modelling the work domain of a home, analysts might define the problem they want to address with WDA as: to determine what internal renovations to make to a home. Given this problem, analysts might decide that the boundaries of the WDA should include the inside of the house but not the external surroundings of the house such as its garden, garage, and driveway. In addition, analysts might define that they will use WDA to explore how well the requirements of the inhabitants are supported by the current design of the home and to pinpoint what changes to the design of their home would better support their requirements. Therefore, analysts might establish that the requirements of the inhabitants can be defined in terms of the top three levels of abstraction in the ADS, that is, the functional purposes, values and priority measures, and purpose-related functions, and that the current design of the home can be defined in terms of the bottom two levels of abstraction in the ADS, that is, the object-related processes and physical objects. The ADS can then be used to trace the impact of the current design of the home on the higher-level requirements of the inhabitants. In addition, the ADS can be used to trace the impact of changes or alterations to the current design of the home on the higher-level requirements of the inhabitants. Naikar and Sanderson (2001) discuss a similar application of WDA for evaluating alternative design proposals for a new military aircraft.

In order to establish the purpose of a WDA, and also to make some of the other decisions in steps 2 to 5, analysts will generally need some level of familiarity with the work system in question. Rasmussen et al. (1990) suggest that at the early stages of an analysis it is useful to understand in general terms: (1) what the work system is; that is, whether it is a private company, a government agency, or a research institute; (2) what the work system does; for example, whether it does engineering design, power production, public administration, or mathematical research; (3) what the general objectives of the work system are; for example, whether it is to make a profit or to provide a public service; (4) what its technical resources are and the layout and distribution of its technical resources; for example, whether the work system has laboratories at multiple geographical sites or whether the work system has a single customer service centre; (5) who the work system services; for example, whether the work system serves the general public or whether it has a particular customer or clientele; and finally (6) what constraints are placed by the external environment on the operations of the work system; for example, whether the work system is constrained by government laws and regulations or by customer requirements for quality products. For the early stages of WDA, this type of information can be readily ascertained by browsing through documents, having conversations with domain experts, and by conducting work site inspections. In step 6 of this methodology we discuss in more detail the sources of information that are useful for a WDA.

12.2 Step 2: Identify the Project Constraints

As well as establishing the purpose of the WDA, it is important to identify any project constraints that may affect how the WDA is conducted. Project constraints are typically related to schedule and budget. If the schedule and budget are tight, then the problem to be addressed with WDA may need to be redefined and the scope of the WDA reduced. Continuing with the home example, the owner of a home may only have sufficient funds to make renovations to one or two rooms in the house – this is an example of a financial budget constraint. On the other hand, there may be insufficient analysts to perform the WDA – this is an example of a staff budget constraint. Alternatively, there may be insufficient time to complete the WDA before the renovations of the house are scheduled to begin – this is an example of a schedule constraint. To deal with these constraints, analysts may decide to redefine the purpose of the WDA from determining what internal renovations to make to the whole house to determining what internal renovations to make to only some of the rooms in the house.

On the other hand, analysts may decide to conduct only some of the steps of the methodology for WDA. For example, analysts may decide to only conduct the first iteration of the ADS (step 6) and not the second and third iterations of the ADS (steps 7 and 8); this, and other such decisions, may be justified if analysts judge that conducting the first iteration of the ADS will be beneficial compared with not conducting a WDA at all.

12.3 Step 3: Determine the Boundaries of the WDA

Determining the boundaries of a WDA involves defining the work system, or the part of the work system, that will be the focus of the study. Rasmussen et al. (1990) refer to the work system or part of the work system that is defined as the focus of a study as the focus system. The boundaries of a WDA therefore separate what becomes the focus system from its environment. The environment of the focus system can include the larger work system to which the focus system belongs.

The decision about where to draw the boundaries that separate the focus system from its environment is largely a pragmatic one. There are no correct or actual boundaries in the sense that there will usually be elements outside the focus system that are coupled to elements within the focus system (Rasmussen et al., 1994). Hence, changes or effects to elements within the focus system will propagate to elements outside the focus system and vice versa. The boundaries of a WDA are therefore essentially artificial divisions that are necessary for keeping the WDA within a useful scope (Burns, Bryant & Chalmers, in press).

In choosing the boundaries of a WDA, there are two main considerations that analysts must take into account. First, analysts must take into account practical considerations such as the purpose of the WDA and the project constraints. Some examples of how the purpose of a WDA and the project constraints can influence the boundaries of the WDA were provided in steps 1 and 2. Second, analysts must take into account any natural delineations that exist in the work system of interest so that the focus system is as well bounded as possible. For instance, Rasmussen et al. (1990) recommend that analysts draw the boundaries for a WDA so that elements within the focus system are tightly coupled to each other but in comparison are loosely coupled to elements outside the focus system. This means that changes or effects to elements within the focus system are more likely to propagate to other elements within the focus system compared with elements outside the focus system. For example, changing the location of a bed in a bedroom is more likely to change the location of other furniture in the bedroom compared with the location of furniture in other parts of a house. Rasmussen et al. also recommend that analysts draw the boundaries for a WDA so that information traffic between elements in the focus system is high relative to the information traffic between the focus system and its environment. For instance, the information traffic within a home is likely to be high compared with the information traffic between a home and other houses in the neighbourhood. According to Rasmussen et al., elements with tight coupling to each other or with high information traffic are usually labelled by proper names, for example, the names of companies or institutions or, in the case of a home, the names of subspaces or rooms.

Finally, in conducting a WDA of a naval system Burns et al. (in press) observed that unlike a nuclear power plant, which is almost a closed system, a naval system is very open and has boundaries that are very difficult if not impossible to define. Burns et al. therefore recommended that for these types of systems the WDA should ideally be as broad as possible. We add that what is possible will be determined by practical considerations. For all open systems, regardless of where the boundaries are drawn, there will always be elements outside the focus system that influence elements within the focus system. For these types of systems it is rarely possible to produce a total or complete work domain model (also see Flach, Mulder, and van Paassen, in press). Inevitably, the WDA will have to be bounded and the boundaries will have to take into account practical considerations such as the purpose of the WDA and the project constraints.

12.4 Step 4: Identify the Nature of Constraints

Having established the focus system for the WDA, the next step is to identify where on the causal-intentional continuum the focus system falls. Defining the location of the focus system along this continuum gives some insight into the nature of the constraints that should be modelled in the ADS (Hajdukiewicz et al., 1999). Rasmussen et al. (1994) describe five categories of work systems, ranging from highly causal to highly intentional, which can be used as a basis for considering where on the causal-intentional continuum a focus system falls. A brief description of these five categories of work systems is provided in Table 12.

Table 12 describes the categories of work systems in terms of: examples of work systems that fall in that category; the nature of the functionality that enables production in that category; the nature of the intentional structures in that category; and the nature of the constraints that are the source of regularity of work systems in that category. This table therefore highlights that there are two key characteristics that determine the nature of constraints that are the source of regularity of a work system's behaviour: (1) whether production in a work system is based on the processes of the technical equipment, on the organisation and activities of the staff, or on the individual users' personal objectives; and (2) whether the intentional structures in a work system are embedded in the technical system, in the organisational policies, plans, and legislation, or in the goals, values, and preferences of individual users. The constraints that are the source of regularity of a work system's behaviour can be used for planning and predicting the work system's behaviour.

To illustrate, work systems to the left of Table 12 are tightly coupled systems with highly structured environments such as industrial process plants. Production in these work systems is based on physical processes that are constrained by technical equipment. Intentionality in these work systems is embedded in automatic control systems and in formal operating procedures, and reflects the designers' operational objectives. Hence, workers' activities are paced by the system and the workers 'serve'

Table 12. The five categories of work systems, ranging from highly causal to highly intentional, that are described by Rasmussen et al. (1994).

Categories of work systems	Automated systems governed by laws of nature	Mechanised systems governed by rules of conduct	Systems governed by actors' intentions	Systems governed by actors' personal objectives	Systems for the autonomous, casual user
Examples	Industrial process plants e.g., nuclear power plants, chemical production plants.	Manufacturing systems based on mechanised work.	Hospitals, offices, and manufacturing systems based on manual work.	Public service systems e.g., research institutes, universities.	Information systems for the general public e.g., websites.
Production	Functionality is based on physical processes that are constrained by technical equipment.	Functionality is based on mechanised processes that are constrained by technical equipment.	Functionality is based on the organisation, work practices, and accepted rules of conduct of the staff, and on the resources supplied.	Functionality is based on individual actors' personal objectives and work practices and on the resources supplied.	Functionality is based on users' personal objectives and work practices and on the tools supplied.
Intentionality	Intentionality is embedded in automatic control systems and in formal operating procedures and represents the designers' operational objectives. The task of the staff is to ensure that the functioning of the automatic control system is consistent with the designers' operational objectives. The personal goals and preferences of the staff are of little significance.	Centrally planned and scheduled manufacturing systems: intentionality is embedded in rules of conduct. Flexible and discretionary manufacturing systems: intentionality is defined by high-level management objectives and by staff who make daily operational decisions to fulfil those objectives.	Intentionality originates from the interpretation of environmental conditions and constraints by high-level management which then becomes implemented in more detailed policies and practices by staff at intermediate levels. Staff at intermediate levels still have many degrees of freedom that are resolved in light of situational factors and subjective criteria.	Intentionality is defined by individual actors within the space determined by institutional constraints such as high-level institutional objectives and resources.	Intentionality is defined by individual users and their goals, values, and preferences at the time of use within the constraints of the tools supplied.
Sources of regularity	Causal constraints based on the laws of nature.	Causal constraints based on the laws of nature, which govern the operation of the technical equipment, and intentional constraints based either on pre-planned schedules and formal or informal rules of conduct, which govern the staff's decisions, or on management objectives.	Intentional constraints based on organisational policies, plans, legislation, and other forms of regulation; social laws and conventions; and actors' intentions or motives.	Intentional constraints based on high-level institutional objectives; social laws and conventions; and actors' personal objectives.	Intentional constraints based on individual users' goals, values, and preferences.

the system. The behaviour of the work system is therefore largely regulated or determined by causal constraints such as the laws of nature. Accordingly, bottom-up reasoning based on causal structures can be used for planning and predicting the behaviour of work systems in this category.

Work systems to the right of Table 12 are characterised by individual users' own work environments. Examples of work systems in this category include information systems for the general public such as websites. Production in these work systems is based on individual users' personal objectives and work practices and on the tools that are supplied to users. Intentionality in these work systems is almost entirely defined by individual users' goals, values, and preferences; the users define the problem at the time of use. The system therefore 'serves' the users. According to Rasmussen et al. (1994), it is generally very difficult to define a universally relevant intentional structure for autonomous, casual users. Consequently, it is very difficult, if not impossible, to construct an ADS for work systems in this category except in very general terms.

Work systems to the middle of Table 12, such as hospitals and offices, are loosely coupled systems consisting of man-made objects and tools. Production in these work systems is based on the organisation, work practices, and accepted rules of conduct of the staff, and on the resources supplied. Intentionality in these work systems is defined by policies, plans, legislation, and other forms of regulation in the organisation, social laws and conventions, and individual actors' intentions and motives. The workers and the system can therefore be seen as sharing control. Although work systems in this category have causal constraints associated with the man-made objects and tools, it is usually not possible to predict the behaviour of these work systems on the basis of these causal constraints alone. Instead, the behaviour of these work systems is largely determined by intentional constraints and can therefore be predicted using top-down reasoning based on intentional structures.

Finally, the nature of the constraints that are modelled in an ADS may depend on the purpose of a WDA. If the purpose of a WDA of a home requires modelling the home as a technical system that provides shelter, the nature of the constraints in the ADS will be primarily causal. On the other hand, if the purpose of a WDA of a home requires modelling the home as a social system that promotes the wellbeing of the inhabitants, the nature of the constraints in the ADS will be primarily intentional.

12.5 Step 5: Identify the Potential Sources of Information

Having established the nature of the constraints in the focus system, the next step is to identify the potential sources of information for constructing the ADS. Generally, the information or data for constructing the ADS can be obtained from a variety of sources. One major source of information is documents relating to the work system. Documents can include engineering and technical manuals, company reports, textbooks, commercial brochures, newspaper items, operating procedures, policy documents, training manuals, accident and incident reports, site maps, and architectural drawings (Rasmussen et al., 1994). For future systems or for systems under development, documents may prove to be the main source of information for a WDA (Naikar et al., 2003; Naikar & Sanderson, 2001). The kinds of documents that are particularly relevant for future systems or for systems under development include concept papers, feasibility studies, and engineering documents such as documents of system requirements and specifications.

A second source of information for constructing the ADS is the work setting itself. Analysts should identify what observations of the work setting are possible. Can analysts conduct inspections of the work sites to observe the tools that workers use and the interactions amongst workers? Can analysts attend planning meetings or observe training sessions? Generally, it is best to carry out field observations after analysts have already developed some level of familiarity with the work system (e.g., by reviewing documents) so that analysts can make sense of what they see and hear with minimal interruption to the activities under observation. Analysts may choose to carry out multiple field observations with the early sessions focussed on developing a general understanding of the work system and later sessions focussed on developing a more detailed understanding of particular aspects of the work system. Hajdukiewicz et al. (1998), for example, distinguished between exploratory and focused observations in analysing a medical work domain. Exploratory observations centred on understanding the work environment from a global perspective whereas focussed observations concentrated on particular aspects of a chosen system, such as the cardiovascular system.

A third source of information for constructing the ADS is domain experts whom analysts can, for instance, interview or involve in walkthroughs, talkthroughs, or table-top analyses (Kirwan & Ainsworth, 1992). Analysts should therefore identify the domain experts who would be useful sources of information for the WDA. Workers are often the main domain experts who are considered by analysts. However, Rasmussen et al. (1994) caution that, in well-established systems, work may have evolved into familiar routines so that the constraints that control behaviour are no longer considered explicitly by workers. Workers may even develop rationalisations and explanations of their activities that do not reflect the actual reasons or intentions behind the design of the work system. In addition, workers may focus on the functionality of tools and technologies that they typically use in their daily work activities as opposed to the full range of functionality afforded by the tools and technologies in the work system. It is therefore important for analysts to include a variety of domain experts in a WDA. For example, analysts can include domain experts who can shed light on the reasons for the policies, rules, and regulations in a work system such as high-level managers, executive officers, policy makers, and strategists. In addition, analysts can include domain experts who can shed light on the full range of functionality afforded by the tools and technologies in a work system such as engineers, systems developers, and technicians. Flach, Eggleston, Kuperman, and Dominguez (1998) recommend that where possible analysts should include more than one domain expert in a knowledge-elicitation session because the arguments and discussions between domain experts can often provide important insights about the work domain.

While all of the sources of information that we have outlined above are generally useful for a WDA, Table 13 shows that different kinds of documents, work settings, and domain experts may be particularly relevant for analysing the different levels of abstraction in a work system. For instance, Table 13 shows that strategic, policy, and planning documents may be useful for analysing the functional purposes and values and priority measures levels of abstraction; operational and training documents may be useful for analysing the purpose-related functions level of abstraction; and engineering and technical manuals may be useful for analysing the object-related processes and physical objects levels of abstraction. Table 13 also provides examples from the military domain of the different types of documents, work settings, and domain experts that are useful for analysing the different levels of abstraction in a work system.

Finally, regardless of which sources of information are used for a WDA, it is important to bear in mind that the constraints that shape behaviour in a work domain will rarely be explicit. Documents will tend to describe how a system works or should work rather than the constraints that shape how the system actually works. In addition, in well-established systems, workers may no longer be aware of the constraints that control their behaviour in the work system. Analysts must therefore use the sources of information to 'reverse engineer' or uncover the 'hidden' constraints that govern system operation (Rasmussen et al., 1994).

Table 13. The different types of documents, work settings, and domain experts that are useful for analysing particular levels of abstraction in a work system.

<table>
<tr><th></th><th>Documents</th><th>Work Settings</th><th>Domain Experts</th></tr>
<tr><td>Functional Purposes</td><td rowspan="2">Strategic, policy, planning, reporting, and operational documents (e.g., doctrine, concept of operations, budget reports, staff reports)</td><td rowspan="2">Planning meetings for priority setting and allocation of resources, and performance reviews (e.g., mission planning, mission debrief, training debrief)</td><td rowspan="2">Executives and company managers (e.g., chief of air force/army/ navy, force element group commanders, wing and squadron commanders)</td></tr>
<tr><td>Values and Priority Measures</td></tr>
<tr><td>Purpose-related Functions</td><td>Operational and training documents (e.g., concept of operations, tactical manuals, training manuals, standard operating procedures)</td><td>Work stations and training sessions (e.g., cockpits, consoles, offices, simulators)</td><td>Team leaders, heads of department, project managers, and workers (e.g., wing and squadron commanders, pilots, navigators, fighter controllers)</td></tr>
<tr><td>Object-related Processes</td><td rowspan="2">Engineering documents and technical manuals (e.g., requirements, specifications, flight manuals)</td><td rowspan="2">Work stations, training sessions, and maintenance planning and reviews</td><td rowspan="2">Workers, technicians, maintenance personnel, and engineers</td></tr>
<tr><td>Physical Objects</td></tr>
</table>

12.6 Step 6: Construct ADS – First Iteration

The first attempt at constructing an ADS should be based on existing or readily available sources of information, such as information from documents and general observations of work settings. Other sources of information, such as information from domain experts, require special preparation and activities and are therefore more resource intensive. For example, to conduct interviews with domain experts, analysts will have to develop an interview format and domain experts will have to participate in activities that are not within the scope of their normal work duties. These additional sources of information should therefore only be considered after existing or readily available sources of information have been exploited. In a WDA of a home, for instance, analysts should first analyse the information that can be obtained from architectural drawings and from observations of inhabitants carrying out their daily activities before holding interviews with the inhabitants.

12.6.1 Identify Work-Domain Properties

Analysing documents and conducting general field observations involves searching for and making notes about the properties of a work domain that workers can use for reasoning in a work system. In a WDA of a home, analysts can explore: the different objects that are available in the home; the layout or location of the objects; the uses that the objects are put to in the home; the kinds of activities that inhabitants carry out; the kinds of concerns that inhabitants refer to when making decisions in various situations; and the different areas or rooms in which particular activities occur. Similarly, in a WDA of a commercial company, analysts can explore: the various activities that are performed by people in the company; how work is organised around different individuals, teams, or departments; and the figures that are contained in annual reports such as profit levels, amount of sick leave taken, number of personnel, and maintenance expenses.

Some guidelines about the kinds of work-domain properties that are relevant for constructing the ADS are provided in previous sections of this report. Sections that are particularly applicable include the descriptions of the five levels of abstraction in Section 5.3, the generic prompts and keywords for analysing the abstraction dimension in Section 5.4, the discussion of the means-ends relations between adjacent levels of abstraction in Section 6.3, and the generic prompts and keywords for analysing the levels of decomposition and part-whole relations in Section 7.5.

To illustrate, the description of the functional purposes level of abstraction in Section 5.3.1 suggests that analysts should search for information about the primary and secondary objectives of the work system and the constraints that the environment places on the work system. The prompts and keywords for the functional purposes level of abstraction in Table 5 (Section 5.4) indicate that analysts should explore what services the work system provides to the environment and the laws and regulations that the environment imposes on the work system. The prompts for the decomposition dimension in Table 6 (Section 7.5) suggest that analysts should search for information about the coarsest level of the system and the most detailed level of the system that is referred to in documents or by domain experts. In addition, the keywords for the decomposition dimension in Table 6 (Section 7.5) provide an indication of the different wholes and parts that may be relevant in a work system, such as different groups or physical spaces.

While the information in Sections 5.3 and 5.4 is limited to the five levels of abstraction that were developed by Rasmussen (e.g., Rasmussen et al., 1994), it is highly likely that at least some of these levels of abstraction will be relevant to the work system under analysis. For example, most work systems will have *physical objects* such as tools and other resources for achieving the ultimate objectives or *functional purposes* of the work system. The information about Rasmussen's five levels of abstraction therefore provides a basis for identifying a preliminary set of work-domain properties by allowing analysts to explore whether or not the same properties are present in the work system under analysis.

To uncover additional properties of the work domain from a preliminary set of work-domain properties, analysts should ask 'how' and 'why' questions of the properties they have identified (Sections 5.1 and 6.3). For example, by asking 'why' certain physical objects are present in a work domain, analysts will be prompted to investigate how the physical objects are used and therefore to uncover information about the functionality of the physical objects. In addition, analysts should also ask 'part of' and 'composed of' questions of the properties that they have identified to uncover further relevant work-domain properties (Sections 7.1 and 7.5). For example, by asking whether a particular group is 'part of' a larger organisation or whether the group forms the entire organisation and is 'composed of' various subgroups, analysts will be prompted to search for other groups that are present in the work system. Analysts should make notes about the specific means-ends and part-whole relations that they identify or observe in the work system.

12.6.2 Define the Levels of Abstraction and Decomposition

Once analysts have identified as many work-domain properties as possible from the initial sources of information for the WDA, the next major activity is to define the levels of abstraction and decomposition that workers can use for reasoning in the work system. Most of the work-domain properties that analysts have identified are likely to be in the form of examples or instances. Hence, to define the levels of abstraction in the ADS, analysts will need to group the work-domain properties into categories, sort the categories into similar and dissimilar concepts, and then organise the concepts into a hierarchy of means-ends relations. An illustration of this process was provided in Section 5.1 (also see Section 5.4). As we discussed in Sections 5.1 and 6.3, it is important to ensure that the relations between the levels of abstraction are structural means-ends relations. To define the levels of decomposition in the ADS, analysts will need to identify the parts of the work domain, sort the parts into similar and dissimilar levels of resolution, and then organise the levels of resolution into a hierarchy of part-whole relations. An illustration of this process was provided in Section 7.1 (also see Section 7.5). As we discussed in Section 7.5, it is important to ensure that the relations between the levels of decomposition are part-whole relations[22]. If analysts have insufficient information about work-domain properties to begin defining the levels of abstraction

[22] We acknowledged in Sections 5.1 and 7.1 that the processes for defining the levels of abstraction and decomposition in the ADS require further development. We are reluctant to provide greater definition of these processes than what we have provided in this report until we have completed our research in this area.

and decomposition in the ADS, they will need to move on to Step 7 which involves analysing additional sources of information for the WDA (Section 12.7).

12.6.3 Develop a Sketch of the ADS

Once analysts have defined the levels of abstraction and decomposition in the work domain, the levels can be organised into a matrix (e.g., Table 2). This matrix will highlight all of the cells that can be populated to develop an ADS model of the work domain. To complete this sketch of the ADS, analysts should develop a working summary that describes the potential content of each cell in the matrix; amongst other things, this working summary will be useful later on in the analysis for evaluating which cells of the ADS it is worthwhile populating.

The working summary should describe the conceptual view of the work domain that is offered by each cell in the ADS, as defined by the level of abstraction at which the cells occur. In addition, the working summary should describe the level of resolution for viewing the work domain that is offered by each cell in the ADS, as defined by the level of decomposition at which the cells occur. In the ADS of a home in Table 4, the conceptual view of the work domain that is offered by the three cells at the purpose-related functions level of abstraction is that of the functions of the home. The three cells offer different resolutions for viewing the functions of the home: the first cell offers a view of the functions of the whole house, the second cell offers a view of the functions of rooms and subspaces, and the third cell offers a view of the functions of contents and components.

The working summary should also contain examples of the categories of constraints that will occur in each cell of the ADS. In the ADS of a home, examples of the categories of constraints that will occur in the cell at the purpose-related functions level of abstraction and the rooms and subspaces level of decomposition include *cooking* and *cleaning*. These categories of constraints relate to the kitchen which is one of the parts of the work domain at the rooms and subspaces level of decomposition. However, this cell will also contain categories of constraints that relate to other parts of the work domain at the rooms and subspaces level of decomposition, such as the bathroom and hallway. The working summary for this cell should therefore also contain examples of the categories of constraints for the bathroom and hallway. In general terms, the working summary should contain examples of the categories of constraints for all of the parts of the work domain that are relevant to the level of decomposition at which a cell occurs[23]. The examples of the categories of constraints and parts of the work domain to include in the working summary will be available to analysts from their analysis of work-domain properties to define the levels of abstraction and decomposition in the ADS (Section 12.6.2).

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[23] Analysts might decide to model only some of the parts of the work domain that are relevant to a particular level of decomposition. For example, analysts might decide to model the kitchen and bathroom but not the other rooms and subspaces of a home. In this case, the working summary should only contain examples of categories of constraints for those parts of the work domain that analysts have chosen to model.

12.6.4 Evaluate which Cells of the ADS to Populate

In Section 7.3 we discussed that although it is theoretically possible to populate all of the cells in the ADS, it is generally not very useful or meaningful to do so. Instead, analysts should evaluate which cells of the ADS it is worthwhile populating by assessing the value of each cell. The working summary of the ADS that was prepared in the previous step is helpful for examining the potential content of each cell in the ADS and for deciding which cells are meaningful or useful to populate.

In Section 7.3 we also discussed that cells that fall along the diagonal of the ADS are usually meaningful in the work domain because workers tend to adopt purposive models when working at coarse levels of resolution and physical models when working at fine-grained levels of resolution. Therefore, it is generally worthwhile populating the cells that fall along the diagonal of the ADS. To evaluate the value of populating the remaining cells in the ADS, we recommend that analysts examine these cells, first, in terms of the unique information that each cell contributes relative to cells that fall along the diagonal of the ADS and, second, in terms of whether this information is relevant or useful for the purpose of the WDA.

12.6.5 Populate the Selected Cells of the ADS

Once analysts have determined which cells of the ADS to populate, they can begin filling in these cells with all of the relevant categories of constraints that they identified in the process of defining the levels of abstraction for the ADS (Section 12.6.2). The categories of constraints in each cell of the ADS must be defined in relation to the parts of the work domain that are relevant to the level of decomposition at which the cell occurs (as was done for the working summary in Section 12.6.3). The parts of the work domain that are relevant to each level of decomposition would have been identified in the process of defining the levels of decomposition for the ADS (Section 12.6.2).

The working summary that was developed earlier (Section 12.6.3) is also useful at this stage of the analysis for ensuring accuracy and consistency of the entries in the ADS model. Specifically, the working summary can help analysts to check that they do not place information that rightfully belongs in one cell of the ADS into another cell of the ADS and that they do not mix entries that rightfully belong in different cells of the ADS.

Once analysts have started populating the cells of the ADS, it is useful to develop a glossary for the entries in the ADS. Previously we discussed that the various formats for representing the ADS, such as the table and the graphical formats, force analysts to use single words or short phrases to represent information in the ADS (Sections 8.2 and 11). Many of these entries are not self-explanatory and can be open to misinterpretation. A glossary is useful for providing a more detailed description of the categories of constraints in the work domain. Moreover, a glossary can be used to reference the original data records from which the entries in the ADS were derived and also to document analysts' justifications for the placement of entries in particular cells of the ADS.

12.6.6 Revisit the Data for the ADS

After populating the cells of the ADS, analysts should consider revisiting the original data records, such as documents or their notes from field observations, to examine them further in light of the context provided by the ADS. There are two main reasons for revisiting the original data records. First, analysts should check the data records for work-domain properties that disconfirm the sketch of the ADS or, in other words, for work-domain properties that do not belong at any of the levels of abstraction or decomposition that they have identified. If the ADS is disconfirmed by returning to the original data records, analysts must update or revise the levels of abstraction and decomposition in the ADS taking into account the new work-domain properties that have been uncovered. In addition, analysts will have to adjust the working summaries of the cells in the ADS, re-evaluate which cells of the ADS to populate, repopulate the selected cells of the ADS, and update the glossary of the entries in the ADS. These are not necessarily difficult tasks especially if analysts have good documentation of the ADS, including the working summary and glossary, that can be easily adjusted with the new information. If analysts have insufficient information about the new work-domain properties to redefine the levels of abstraction and decomposition in the ADS, then analysts will need to conduct further general field observations or proceed to the next step (Section 12.7) to analyse additional sources of information before they can revise the ADS.

Second, if the ADS is not disconfirmed by returning to the original data records, analysts can use the context provided by the ADS to examine the data records for work-domain properties that they may have missed during their initial analysis. Specifically, analysts can examine the data records for: work-domain properties that belong to existing categories of constraints; work-domain properties that lead to new categories of constraints at existing levels of abstraction; work-domain properties that relate to the parts of the work domain that have already been identified at existing levels of decomposition; and work-domain properties that highlight new parts of the work domain at existing levels of decomposition. Given that conducting data collection exercises consumes resources, it is cost-effective to exploit existing data records as fully as possible before moving on to new sources of information for the WDA.

12.7 Step 7: Construct ADS – Second Iteration

The second iteration of the ADS involves analysing additional sources of information to further develop the ADS. The sources of information that are particularly relevant for this stage of the analysis include information from focussed observations of work settings and information from domain experts. Some of the techniques that are useful for eliciting information from domain experts include walkthroughs, talkthroughs, interviews, and table-top analysis (Kirwan & Ainsworth, 1992). As we have mentioned previously, these techniques are relatively resource intensive and should only be considered after existing or readily available sources of information have been exploited.

For the second iteration of the ADS, it is useful to focus the data collection exercises on one or two cells of the ADS at a time, mainly to manage the complexity of the analysis. In the case of a home, interviews with domain experts may be targeted at the physical objects in particular rooms and subspaces or at the functions of particular contents and components. Analysts may choose to focus on cells that were relatively undeveloped after the first iteration of the ADS or they may systematically work their way through all of the cells in the ADS, perhaps depending on the project constraints and the purpose of the WDA. Despite focusing on particular cells of the ADS, analysts are likely to find that their data collection exercises will reveal many work-domain properties that are useful for other cells of the ADS.

To plan what areas of the work setting to observe or what topics should be the focus of knowledge-elicitation sessions with domain experts, analysts can use the working summary of the cells in the ADS (Section 12.6.3) as a guide to the type of information that is required for populating each cell of the ADS. In addition, as with the first iteration of the ADS (Section 12.6.1), previous sections of this report are useful for pinpointing the kinds of work-domain properties that are relevant for constructing the ADS. These sections include: the descriptions of the five levels of abstraction in Section 5.3, the prompts and keywords for analysing the abstraction dimension in Section 5.4, the discussion of the means-ends relations between adjacent levels of abstraction in Section 6.3, and the prompts and keywords for analysing the levels of decomposition and part-whole relations in Section 7.5.

These sections of the report are also useful for developing questions or queries for the knowledge-elicitation sessions with domain experts. Consider the prompts and keywords for analysing the abstraction dimension in Section 5.4. To populate a cell at the functional purposes level of abstraction, the prompts and keywords indicate that analysts can ask domain experts about 'what services their organisation provides'. On the other hand, to populate a cell at the values and priority measures level of abstraction, the prompts and keywords indicate that analysts can ask domain experts about 'what benchmarks they use for evaluating their performance'. When using the prompts and keywords for either the abstraction or decomposition dimensions (Sections 5.4, 7.5) to develop questions for the knowledge-elicitation sessions with domain experts, analysts should consider rephrasing the prompts and keywords in the 'language' of the work domain so that the questions are more meaningful for domain experts. Finally, analysts can also ask domain experts 'how' and 'why' and 'part of' and 'composed of' questions about preliminary work-domain properties to uncover further relevant work-domain properties (Sections 5.1, 6.3, 7.1, 7.5).

Once analysts have conducted focussed field observations or walkthroughs, talkthroughs, interviews, or table-top analyses with domain experts, they will have a set of data records to analyse. These data records may be in the form of notes, transcripts, or audio and video recordings. The process for analysing these data records is almost the same as the process that we outlined for analysing the data records for the first iteration of the ADS (Section 12.6). To recap, analysts should search the data records for work-domain properties that are relevant for constructing the ADS, using the previous sections of this report as a guide (Sections 5.3, 5.4, 6.3, 7.5). In addition, analysts can ask 'how' and 'why' and 'part-of' and 'composed-of' questions about work-domain properties in the data records to uncover further relevant work-domain properties (Sections 5.1, 6.3, 7.1, 7.5). Once analysts have identified as many work-domain properties as possible, they can group the properties into categories, sort the categories into similar and dissimilar concepts, and organise the concepts into a hierarchy of means-ends relations (Sections 5.1 and 5.4). In addition, analysts can identify the parts of the work domain, sort the parts into similar and dissimilar levels of resolution, and organise the levels of resolution into a hierarchy of part-whole relations (Sections 7.1 and 7.5).

Analysts can then check whether the resulting levels of abstraction and decomposition disconfirm the ADS that was developed in the first iteration of the ADS (Section 12.6). If the resulting levels of abstraction and decomposition are not the same as those in the ADS, so that the ADS is disconfirmed, analysts will have to revise the ADS (Section 12.6.6). In addition, analysts will have to adjust the working summary of the cells in the ADS, re-evaluate which cells of the ADS to populate, repopulate the selected cells with relevant categories of constraints and parts of the work domain, including the categories of constraints and parts of the work domain from the second iteration of the ADS, and update the glossary of entries in the ADS. If, on the other hand, the resulting levels of abstraction and decomposition do not disconfirm the ADS, analysts can proceed with populating the ADS with the additional categories of constraints and the parts of the work domain that were identified in the second iteration of the ADS. Analysts should also update the glossary with the new entries in the ADS. Finally, given the context provided by the updated ADS, analysts should consider returning to the data records from both the first and second iterations of the ADS to check for additional work-domain properties that they may have missed during their previous analyses of this data.

In the remainder of this section, we discuss the relative merits of focussed field observations, walkthroughs, talkthroughs, interviews, and table-top analysis for the second iteration of the ADS[24]. Before we begin we make two general points about these techniques. First, many of the techniques are typically used to study workers' tasks or action sequences or their decision-making processes. In using these techniques for WDA, however, the aim is not to analyse how work is done in a work system but rather to uncover the constraints that *shape* how the work is done. For instance, in observing the use of a particular tool in a work domain, the aim is not to analyse the sequences of tasks or activities that are carried out with the tool but rather to analyse the functionality of the tool that allows those tasks or activities to be performed. Similarly, in interviewing domain experts about their experiences in challenging situations, the aim is not to analyse their decision-making processes in those situations but rather to uncover the factors that influenced their decisions. Second, many of the techniques are typically used to elicit information from workers, and our discussion in this section also tends to focus on workers. However, these techniques are also suitable for eliciting information from a variety of other domain experts. For example, although we describe walkthroughs as involving workers explaining and demonstrating their

[24] There are many other techniques that can be used for the second iteration of the ADS. Although we cannot discuss all of these techniques in this report, many of the benefits and limitations of the techniques that we present in this section can be extended to other techniques.

tasks or activities, walkthroughs can also be conducted with engineers to study the range of functionality that is afforded by the tools in a work system. In Section 12.5, we discussed why it is important to involve a variety of domain experts in WDA and we also provided some examples of the kinds of domain experts that are useful for WDA.

12.7.1 Focussed Field Observations

In contrast to general observations of work settings, which are useful for the first iteration of the ADS, focussed field observations are useful for the second iteration of the ADS because they involve targeted observations of a work system. For example, focussed field observations can be conducted of the way certain tools are used in a work system or of the activities that are performed by specific teams or departments in a work system. Hence, focussed field observations can be targeted at particular cells of the ADS. Focussed field observations are generally useful when analysts still have relatively little knowledge of a work system. In contrast, knowledge-elicitation techniques such as interviews require that analysts have sufficient knowledge of a work system to develop interview questions and to participate in discussions with domain experts without seeking too much clarification during the interview process.

12.7.2 Walkthroughs and Talkthroughs

Like focussed field observations, walkthroughs and talkthroughs are useful when analysts have relatively little knowledge of a work system. In a walkthrough, workers explain and demonstrate their work activities at their actual work location, perhaps by pointing to displays and controls but without necessarily carrying out the tasks. In contrast, in a talkthrough, workers explain their work activities away from their actual work location, perhaps by describing how they perform certain tasks or deal with various problems in the work system. In both walkthroughs and talkthroughs, analysts can either allow workers to proceed with minimal interruption, which is more appropriate when analysts still have relatively little knowledge of a work system, or analysts can prompt workers for information relating to particular aspects of the ADS.

Both walkthroughs and talkthroughs can be used to elicit information about how workers will deal with novel or unfamiliar events, for example, by asking workers to describe how they will use various tools or approach particular tasks or problems in these situations. In contrast, in conducting focussed field observations, analysts are limited to events that occur at the time of observation, which are more likely to be events that are routine or familiar to workers. Analysing novel or unfamiliar events is useful because work-domain constraints are more likely to be considered explicitly by workers in these situations (Rasmussen et al., 1994). For both walkthroughs and talkthroughs, however, workers must have sufficient knowledge of how the system will operate and how work will be performed in these conditions. Otherwise, as we will discuss later, table-top analysis may be a more suitable technique for knowledge elicitation.

One advantage of talkthroughs, compared with both walkthroughs and focussed field observations, is that talkthroughs can be used to elicit information about future systems. Unlike walkthroughs and focussed field observations, talkthroughs do not require access to particular work settings or tools. However, workers must have sufficient knowledge of how the future system will operate or how work will be performed in the future system. The future system must therefore be relatively similar to existing systems. As we will discuss later, when future systems are dissimilar to existing systems, table-top analysis may be a more suitable technique for knowledge elicitation. Finally, another advantage of talkthroughs compared with walkthroughs and focussed field observations, is that talkthroughs can be used when it is not appropriate for analysts to be present at a work site or for demonstrations to occur at a work site for safety or inefficiency reasons.

12.7.3 Interviews

Another technique that is useful for the second iteration of the ADS is interviews with domain experts. As we mentioned earlier, this technique is appropriate when analysts have sufficient knowledge of a work system to develop interview questions and to participate in discussions with domain experts without requiring extensive clarification of information. According to Rasmussen et al. (1994), a useful interview format for getting an overview of the total work domain is to ask workers to name all of the functions in which they are involved and then to ask them about what is done, why it is done, and how it is done. We add that this interview format can also be targeted at particular cells of the ADS. For example, workers can be asked to describe all of the functions they perform with particular components or physical objects in a work system. The prompts and the keywords for the abstraction and decomposition dimensions (Sections 5.4 and 7.5) can be adapted into questions for this interview format. Moreover, in addition to the 'how' and 'why' questions that are described by Rasmussen et al. (also see Sections 5.1 and 6.3), analysts can also ask 'part of' and 'composed of' questions (Sections 7.1 and 7.5).

Another format that we have found useful for interviews is based on the critical decision method (Hoffman, Crandall & Shadbolt, 1998; Klein, Calderwood & MacGregor, 1989). The critical decision method relies on workers' accounts of critical incidents in which they were involved. Using this technique, analysts take workers through several 'sweeps' of a critical incident; the first sweep focuses on eliciting an operational description of the incident, the second sweep focuses on identifying the critical decision points in the incident, and the third sweep focuses on exploring the cognitive strategies of workers at each decision point. This technique is typically used for studying the decision-making strategies of experts in time critical, high workload situations. To use the critical decision method for WDA, the third sweep of the technique can be amended to explore the work-domain properties that are relevant at each decision point, for example, the values and priority measures that influenced experts' decisions at each decision point and the physical objects that were useful at each decision point. The prompts and keywords for the abstraction and decomposition dimensions (Sections 5.4 and 7.5) can be adapted into questions for the third sweep of this interview format. In addition, analysts can ask 'how' and 'why' (Sections 5.1 and 6.3) and 'part of' and 'composed of' (Sections 7.1 and 7.5) questions. As the critical decision method involves interviewing workers about challenging situations, rather than routine or familiar situations, this technique is well suited for WDA because workers are more likely to consider work-domain constraints explicitly in these situations.

While we have found this type of semi-structured format useful for interviews, we should mention that Rasmussen et al. (1994) argue that unstructured interviews are the only suitable format for WDA because structured formats "repeatedly cause interruptions in the interviewees' train of thought" (p.55). Although this claim has some validity, we have found that unstructured interviews are time consuming, resource intensive, and generally not feasible within the time and budget constraints of industry projects. Unstructured interviews are inefficient not only because of the large number of interviews that are required to gather sufficient data about relevant work-domain properties for the ADS but also because of the effort required to transform the data from unstructured interviews into structured models like the ADS.

So far, our discussion of interviews has focussed on well-established or existing work systems; the interview format suggested by Rasmussen et al. (1994) asks workers to describe the functions that they perform in existing work systems and the interview format based on the critical decision method asks workers to recount critical incidents that they have experienced in existing work systems. Bisantz et al. (2003), however, describe a semi-structured interview format that they used to conduct a WDA of a future military ship. The probes or questions that they used for the interviews were based on "abstraction hierarchy concepts" (p.184). For example, the probes asked interviewees to describe: the goals of undersea warfare missions; the higher level guidelines or constraints on achieving those goals; what functions, such as sensing, can be used to achieve those goals and how those functions are linked; the different kinds of systems that are available on and off the ship and how they are used to achieve the ship's tasks; and how the ship's ability to achieve its mission would be affected if some of the systems were disabled and whether there are other systems that could be used as substitutes for the disabled systems. These kinds of probes may be supplemented with questions derived from the prompts and keywords for the abstraction and decomposition dimensions in Sections 5.4 and 7.5. In addition, analysts can also ask 'how' and 'why' (Sections 5.1 and 6.3) and 'part of' and 'composed of' (Sections 7.1 and 7.5) questions. This interview format, however, assumes that domain experts have sufficient knowledge of how the future system will operate and how work will be performed in the future system. The future system must therefore be relatively similar to existing systems.

12.7.4 Table-top Analysis

Finally, another technique that is useful for the second iteration of the ADS is table-top analysis. This technique involves a group of domain experts examining, in a problem-solving and exploratory way, various aspects of a system's operation (Kirwan & Ainsworth, 1992). Domain experts can discuss, for example, the range of functionality that is afforded by the tools in a work system or the kinds of factors that are important to take into account when making decisions in various situations. The role of the analyst in these sessions is to guide and facilitate the discussions between domain experts. To structure the table-top sessions, analysts can use the prompts and keywords for the abstraction and decomposition dimensions in Sections 5.4 and 7.5. In addition, analysts can ask 'how' and 'why' (Sections 5.1 and 6.3) and 'part of' and 'composed of' (Sections 7.1 and 7.5) questions to facilitate discussions. Analysts can also adapt the interview format described by Rasmussen et al. (1994), the interview format based on the critical decision method, or the probes described by Bisantz et al. (2003) to guide the table-top discussions.

Unlike talkthroughs and interviews, table-top analysis can be used for studying future systems even when the future system is dissimilar to existing systems. Because of its exploratory format, table-top analysis does not require that domain experts already have knowledge of how the future system will operate or how work will be performed in the future system but in fact allows domain experts to explore these issues (Naikar et al., in press; Naikar et al., 2003). In addition, table-top analysis allows a variety of domain experts, such as workers, engineers, and policy-makers to participate in a single table-top session, which is useful because the domain experts can bring different perspectives to the problem under discussion. For these reasons, table-top analysis is also useful for exploring how workers might deal with novel or unfamiliar situations even when the future system is dissimilar to existing systems.

12.8 Step 8: Construct ADS – Third Iteration

The third iteration of the ADS involves reviewing the ADS with domain experts. The aim of the review is first to check whether the domain experts agree with the various elements of the ADS model that analysts have developed and second to check whether the domain experts can think of other aspects of the work domain that analysts have not represented in the ADS. In particular, the review should cover: the levels of abstraction and means-ends relations in the ADS, the levels of decomposition and part-whole relations in the ADS, and the categories of constraints in each cell of the ADS including the parts of the work domain to which the constraints relate. The review can be conducted with individual domain experts or with a group of domain experts. As with previous iterations of the ADS, the review should involve a variety of domain experts such as workers, engineers, and policy makers. Different kinds of domain experts may be appropriate for reviewing different aspects of the ADS. For example, engineers may be more suitable for reviewing cells at the bottom two levels of abstraction whereas policy makers may be more suitable for reviewing cells at the top two levels of abstraction (see Table 13 in Section 12.5).

In reviewing the ADS with domain experts, analysts should focus on one aspect of the ADS at a time. The review should start with analysts giving an overview or explanation of the chosen aspect of the ADS. In a WDA of a home, analysts may choose to review the decomposition dimension (including part-whole relations) of the ADS. The analysts should show the decomposition dimension to the domain experts and explain what the different levels of decomposition mean in the context of that work domain. For example, analysts may explain that they are trying to describe or represent the different parts of a home and that the parts they have identified so far are the whole house, the rooms and subspaces, and the contents and components of a home. Analysts can then check whether the domain experts agree with the different levels of decomposition by asking ‘would you say that rooms and subspaces are part of a house’ or ‘would you say that a house is composed of rooms and subspaces’. Similarly, analysts can ask ‘would you say that rooms and subspaces are composed of contents and components’ or ‘would you say that contents and components are parts of rooms or subspaces’. Analysts can then check whether the domain experts agree with the specific parts of a home that have been identified at each level of decomposition. For example, analysts can ask ‘would you say that a kitchen is a room or subspace of a home’ or ‘would you say that a dishwasher is one of the contents or components of a kitchen’. After checking whether the domain experts agree with the representations that are already in the ADS, analysts can check whether the domain experts can think of any other parts of the work domain that they may have missed. For instance, analysts can ask ‘are these all of the rooms or subspaces of a home or can you think of any other rooms or subspaces’ and ‘are these all of the contents and components of a kitchen or can you think of any other contents and components’.

To give a second example, analysts may choose to review the categories of constraints in each cell of the ADS, including the parts of the work domain to which the constraints relate. If analysts choose the cell at the purpose-related functions levels of abstraction and the rooms and subspaces level of decomposition in an ADS of a home, analysts can show this cell to domain experts and explain that they are trying to represent the functions of particular rooms and subspaces of a home. Analysts can then select a particular room or subspace, such as the kitchen, and check whether domain experts agree with the categories of constraints that relate to this part of the work domain by asking ‘would you say that these are the functions of a kitchen’ or ‘would you say that these functions occur in a kitchen’. After checking whether the domain experts agree with the categories of constraints that relate to the kitchen, analysts can check whether the domain experts can think of any other categories of constraints related to this part of the work domain that they may have missed. For example, analysts can ask ‘are these all of the functions of a kitchen or can you think of any other functions’.

The final example relates to checking the means-ends relations between cells at different levels of abstraction in the ADS. To do this, analysts will need to focus on two cells of the ADS at a time. In the case of a home, analysts may choose to focus on the cells at the purpose-related functions and the values and priority measures level of abstraction, where both cells are from the rooms and subspaces level of decomposition. Specifically, analysts may choose to review the ‘why’ relations from the purpose-related functions level to the values and priority measures level. Analysts can explain that they are trying to describe the factors or concerns that are taken into account in performing the functions of particular rooms and subspaces in a home. Analysts can then select a particular room or subspace, such as the kitchen, and check whether the domain experts agree with the current representations by asking ‘would you say that these are the concerns that are taken into account in performing the functions of the kitchen’. Following that, analysts can check whether domain experts can think of any other concerns that they have missed by asking ‘are these all of the concerns that are taken into account in performing the functions of the kitchen or can you think of any other concerns'.

To formulate questions for the review with domain experts, analysts can use the prompts and keywords for the abstraction and decomposition dimensions in Sections 5.4 and 7.5 as well as the information about 'how' and 'why' (Sections 5.1 and 6.3) and 'part of' and 'composed of' (Sections 7.1 and 7.5) relations in the ADS. The prompts and keywords for the decomposition dimension and the information about 'part of' and 'composed of' relations were used to formulate the questions for the first example in this section, the prompts and keywords for the abstraction dimension were used to formulate the questions for the second example in this section, and the prompts and keywords for the abstraction dimension and the information about 'why' relations were used to formulate the questions for the third example in this section. As with the knowledge-elicitation sessions in the second iteration of the ADS, analysts will need to rephrase the prompts and keywords for the abstraction and decomposition dimensions and the 'how' and 'why' and 'part of' and 'composed of' questions in the 'language' of the work domain so that the questions are more meaningful to domain experts.

The working summary and glossary that were prepared during the first and second iterations of the ADS are useful resources for this stage of WDA. By providing descriptions of the cells and entries in the ADS, the working summary and glossary can help analysts to conduct a systematic and thorough review of all of the representations in the ADS. The working summary and glossary can also help analysts to formulate questions in the 'language' of the work domain for the review. Finally, the working summary and glossary can help analysts to check whether any additional information or work-domain properties suggested by domain experts during the review are already represented in the ADS or whether this information must be incorporated into the ADS.

If the review with domain experts disconfirms the ADS, by calling into question the levels of abstraction and decomposition in the ADS, analysts will need to re-examine the data that they used for the first and second iterations of the ADS (e.g., documents, transcripts of interviews, video recordings of walkthroughs) for evidence of the new information from domain experts[25]. If analysts find that they can agree with the domain experts, for instance, by discovering information that they had previously overlooked in the data, analysts will need to revise the ADS. This will involve redefining the levels of abstraction and/or decomposition, adjusting the working summary of the cells in the ADS, re-evaluating which cells of the ADS to populate, re-populating the cells with the data from the first, second, and third iterations of the ADS, and updating the glossary of entries in the ADS (see Section 12.6.6 for a more detailed description of this process).

If analysts do not find that they can agree with the domain experts on the basis of the data that they used for the first and second iterations of the ADS, analysts may decide to conduct focussed field observations or knowledge-elicitation sessions that address the queries raised by the domain experts. The domain experts who participate in these additional data collection exercises should not be the same as the domain

[25] It is unlikely that the ADS will be disconfirmed at this stage of the WDA, however, we discuss this possibility here for the sake of completeness.

experts who participated in the review. If analysts find evidence for the new information that was suggested by the domain experts who participated in the review, then analysts will need to revise the ADS as described above. However, if analysts do not find evidence to confirm the suggestions made at the review, they will need to revisit the issue with domain experts and show them the data that supports the existing version of the ADS.

If, on the other hand, the review with domain experts does not call into question the ADS, analysts can proceed with adding any further categories of constraints and parts of the work domain that were identified during the review with domain experts. Analysts will also need to update the glossary with the new entries in the ADS. Finally, analysts should consider revisiting the data records from the first and second iterations of the ADS to examine them further in light of the context provided by the third iteration of the ADS (Section 12.6.6).

12.9 Step 9: Validate the ADS

The aim of the final step of WDA is to determine whether the ADS that has been developed is as accurate and complete as possible. Given that the ADS is a model of the reasoning space of workers, one way of validating the ADS is to examine whether workers' reasoning patterns in a variety of situations can be accommodated by the ADS. The information that is used to validate the ADS should not be the same as the information that was used to create the ADS. Therefore, analysts may have to collect additional information about workers' reasoning patterns in various situations for the validation exercise.

To gather data for the validation exercise, it is possible to use the same sources of information (i.e., documents, work settings, domain experts) and data-collection techniques (i.e., focussed field observations, walkthroughs, talkthroughs, interviews, table-top analysis) that are useful for creating the ADS. However, the nature of the information that is relevant for creating the ADS may not be useful for validating the ADS. For example, engineering documents of requirements and specifications that are relevant for creating the ADS may not be useful for the validation exercise. Instead, the types of documents that may be relevant for validating the ADS are those that contain information about workers' reasoning patterns in various situations, such as, reports of particular incidents and accidents that describe what went wrong and how the workers attempted to deal with the problem, as well as training documents that describe case studies of workers' experiences in novel or challenging situations including the problems or difficulties that they encountered and the decisions and actions that they took. Similarly, whereas interviews that are conducted for creating the ADS may focus on asking workers to describe the services that the work system offers or the functions of a particular team or department, interviews that are conducted for the validation exercise should focus on asking workers to recount their reasoning processes in dealing with various situations.

To adequately reconstruct workers' reasoning patterns in various situations, it may be necessary to include a variety of domain experts in the validation exercise. For example, it may be necessary to include engineers to understand the state of the physical components that characterised a situation or to understand the impact of workers' actions and decisions on the state of the physical components. Similarly, it may be useful to involve executives and policy makers to define the nature of the objectives, laws, and regulations that characterised a situation and to understand the effects of workers' actions or decisions on these high-level constraints. In addition, it may be necessary to include teams of workers in the validation exercise, including supervisors and managers, if teams of workers were responsible for dealing with a situation. Consequently, multiple knowledge-elicitation sessions with a variety of domain experts may be required to reconstruct the reasoning space of workers for a single situation.

Once analysts have collected sufficient information about workers' reasoning patterns in various situations, analysts can examine the data records for work-domain properties that characterised workers' reasoning patterns in those situations. To determine whether the ADS can accommodate these reasoning patterns, analysts will have to map the work-domain properties in the data records onto the ADS model. Once again, the work-domain properties in the data records will typically be in the form of particular examples or instances. Therefore, the process of mapping the work-domain properties onto the ADS model will involve examining whether the instances in the data records are captured by the categories of constraints and the parts of the work domain that are represented in the ADS. The working summary and glossary that were developed earlier (Sections 12.6.3 and 12.6.5) are useful at this stage of WDA for checking whether the representations in the ADS model can accommodate the work-domain properties in the data records.

One example of a validation exercise is provided by Burns et al. (2001). In their validation exercise, which was for an ADS model of shipboard command and control, operational experts participated in a walkthrough of a pre-developed training scenario and mapped their action patterns against the ADS. The analysts had developed the ADS a priori and without knowledge of the training scenario that was used in the validation exercise. The operational experts, who were familiar with the training scenario, first worked individually to identify the aspects of the ADS that were in use at each step of the scenario. Then, at the end of the walkthrough, the operational experts participated in a group discussion to compare opinions and to extract further information about the mapping of action patterns to the ADS. The analysts found that in no case did the operational experts "mention constraints that were not in some way handled in the existing work domain models" (Burns et al., 2001, p. 427). The analysts also found that certain areas of the ADS were visited more often than other areas and some of the areas not at all. On checking the training scenario, the analysts found that the areas of the ADS that were not visited by the operational experts were not covered in the training scenario.

Whereas Burns et al. (2001) validated their ADS against a scenario that was familiar to domain experts, Miller and Vicente (1998) checked whether their ADS of a petrochemical plant could explain an incident that was novel at the time of its occurrence. The incident was novel in the sense that it was not familiar to operators and it had not been anticipated by domain experts. Although the incident had occurred sometime prior to the WDA, the incident was not part of the normal operating procedures or part of the system documentation that the analysts had used to construct the ADS. To validate the ADS, the analysts checked whether the ADS could be used to trace the causes and structural states produced in the plant during the incident, the motivations of operators as they attempted to address the incident, and the effects of operators' actions. The analysts found that their ADS model could satisfactorily explain the incident that had occurred, although the validation exercise also revealed several potential improvements to the ADS model.

One criticism of a validation approach that is based on checking whether the ADS accommodates the reasoning patterns of workers in particular situations is that the ADS may only be valid for those situations that were part of the validation exercise. However, there seems to be no better alternative. To enhance the rigour of the validation exercise, analysts should use a variety of situations to validate the ADS including both routine and novel events. Finding records of novel events (i.e., events that were unfamiliar to workers or that were not anticipated by domain experts at the time of occurrence) within the constraints of a particular project will generally be difficult – unless the project is a long-term one in which the ADS will be regularly upgraded and validated as new incidents or events come to light. Flach et al. (in press) discuss the concept of "living abstraction hierarchies" where the ADS is maintained over the operational life of a system rather than being abandoned once the purpose for which the ADS was initially developed is achieved. Although maintaining the ADS over a period of time will consume time and resources, Sanderson, Naikar, Lintern, and Goss (1999) discuss how an ADS model can be used throughout a system's lifecycle for making decisions about interface design, training, team design, and maintenance and technology upgrades, amongst other things. The benefits of WDA can therefore potentially far outweigh its costs.

13. Conclusion

In this report we have addressed a number of conceptual issues relating to WDA and we have proposed a methodology for performing WDA. In addition, we have illustrated the theoretical concepts and methodology for WDA with a case study of a home, a 'system' that will be highly familiar to everyone. By contributing to the development of a coherent theoretical and methodological approach for WDA, this report will help to: make WDA more accessible to researchers and practitioners who were not involved in the development of WDA or who cannot be apprenticed to experts in the area; reduce the time and effort it takes to perform WDA, even for experts in the area; and facilitate the application of WDA to large-scale industry projects. From a DSTO perspective, this report will help to facilitate the application of WDA to a greater variety of Defence projects in the land, maritime, air, and joint environments.

A methodology for performing WDA can never be completely specified. For example, it is difficult to develop prompts and keywords for analysing all of the levels of abstraction that could possibly be relevant in any kind of work system. It is therefore important to have a sound understanding of the theoretical foundations of WDA, and CWA in general, so that WDA is not performed in a way that is inconsistent with its theoretical underpinnings. The most comprehensive resources for the theory of WDA and CWA are the texts by Rasmussen et al. (1994) and Vicente (1999)[26].

The methodology for WDA that we have proposed is based on the theoretical concepts that we presented earlier in the report and on our experience with conducting WDA for complex, military systems. As we mentioned previously, using this methodology has led to feasible and useful outcomes on a number of major Defence projects (Naikar et al., 2003; Naikar & Sanderson, 1999, 2001). One limitation of this report, though, is that we do not know the extent to which the methodology for WDA generalises to domains other than the military. By documenting the methodology for WDA, however, this report will allow other researchers and practitioners to trial the application of this methodology to additional domains.

Another limitation of this report is that we do not have any empirical evidence for the validity and reliability of the methodology for WDA. In other words, we do not know whether the methodology for WDA will result in valid and reliable ADS models of complex work systems. This is a key area for further research and one that we plan to address as part of our program at DSTO. This program will involve case studies that trial the application of the methodology for WDA to complex, military systems, which may lead to refinements of the methodology, followed by empirical studies to test the reliability and validity of the methodology for WDA. This report is an essential first step in this line of research. Specifically, by making the methodology for WDA more explicit, this report will allow the methodology, or at least parts of the methodology, to be tested empirically. Given that WDA is becoming widely used at DSTO as a basis for making system design and development decisions for real, military systems, the need for empirical verification of the methodology for WDA is critical.

Finally, while this report has focussed on WDA, the remaining phases of CWA model other powerful constraints on workers' behaviour. The theoretical concepts and methodology for these phases of CWA are generally less well developed and understood than WDA. Despite this, we have found some of the other phases of CWA useful in a Defence context. For example, we have found control task analysis, the second phase of CWA, useful for team design (Naikar et al., 2003) and for developing training strategies to manage human error (Naikar & Saunders, 2003). It therefore seems that there may be considerable benefits to be gained from developing a coherent theoretical and methodological approach for the other phases of CWA as well. Naikar et al. (in press) have made a start in this direction for control task analysis.

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[26] John Flach (personal communication, November, 2004) has observed that it may be useful to read an earlier text by Rasmussen (1986) as an introduction to the text by Rasmussen et al. (1994).

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19. ABSTRACT

This report contributes to the development of a coherent theoretical and methodological approach for work domain analysis (WDA), the first phase of cognitive work analysis. The report: (1) addresses a number of conceptual issues relating to WDA, including differences in the approaches of Rasmussen, Pejtersen, and Goodstein (1994) and Vicente (1999); (2) proposes a methodology for performing WDA; and (3) illustrates the theoretical concepts and methodology for WDA with a work domain of a home – a 'system' that will be highly familiar to everyone. This research will help to: make WDA more accessible to researchers and practitioners who were not involved in the development of WDA or who cannot be apprenticed to experts in WDA; reduce the amount of time and effort it takes to perform WDA even for experts in WDA; and facilitate the application of WDA to large-scale industry projects. In addition, by making the methodology for WDA more explicit, this research will allow the methodology, or at least parts of the methodology, to be tested empirically.

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