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Designing safe and effective future systems: A new approach for modelling decisions in future systems with Cognitive Work Analysis

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Introduction

Designing safe and effective future systems requires knowledge of their work demands. Without this information, interfaces, crew concepts, training programs, and workspace layouts cannot be tailored to the work that will occur in these systems. Analysing the work demands of systems that do not exist poses special challenges for work analysis. This paper contributes to the emerging body of evidence that Cognitive Work Analysis (Rasmussen, Pejtersen & Goodstein, 1994; Vicente, 1999) offers an approach for analysing the work demands of future systems.

Standard techniques for work analysis may be categorised as descriptive or normative (Vicente, 1999). Descriptive techniques focus on analysing how work is currently done in a system. These techniques cannot readily be applied to future systems because such systems cannot be observed. Normative techniques focus on prescribing how work should be done in a system by specifying the set of tasks or task sequences that workers should perform to achieve various goals. It is difficult, however, to specify the full set of tasks or task sequences for future systems because workers often develop novel ways of working as they gain experience with a new system. Furthermore, it is difficult to specify the tasks or task sequences that workers should perform in novel or unanticipated situations because the goals in these situations are unknown.

Cognitive Work Analysis offers an approach for analysing the work demands of future systems by modelling how work can be done rather than how work is currently done or how work should be done. This framework recognizes that workers in complex sociotechnical systems usually have a great variety of options with respect to what to do, when, and how, and that not all of these work patterns can be observed or specified prior to design. Therefore, rather than analysing how work is currently done or how work should be done in particular situations or under certain conditions, Cognitive Work Analysis focuses on analysing the constraints that shape work in the first place. The analysis of constraints can take place in the absence of an existing or observable system. In addition, the set of constraints that are identified by Cognitive Work Analysis can accommodate many different tasks or task sequences, including those that are difficult to prescribe or specify upfront.

Cognitive Work Analysis consists of five separate phases of analysis, which focus on analysing different kinds of constraints. This paper is concerned with Activity Analysis, the second phase of Cognitive Work Analysis, which models the work that needs to be done in a system in order to fulfil its purposes with a given set of physical resources. Activity Analysis models the work that is required in a system in two main ways (Naikar, Moylan & Pearce, 2006). First, Activity Analysis identifies the work situations that actors will need to participate in and/or the work functions that actors will need to perform. The main product of this step is a contextual activity template. Second, Activity Analysis identifies the decisions that actors will need to make for each work situation or work function. The main product of this step is a set of decision ladders.

Activity Analysis has previously been used to model the work demands of future systems. Specifically, Activity Analysis was used to model the work situations, work functions, and decisions of a future Airborne Early Warning and Control (AEW&C) system for the Australian Defence Organisation (Naikar et al., 2006). This analysis resulted in a contextual activity template and a set of decision ladders for AEW&C. While this analysis has been useful for various applications, one limitation of this work relates to the development of decision ladders for AEW&C.

Prior to the analysis of the AEW&C system, decision ladders had mainly been used for modelling activity in existing systems (e.g., Rasmussen, 1980; Vicente, 1999). Thus a strategy for developing decision ladders for future systems had not been defined. As the decision ladder comprises a set of generic information-processes and states of knowledge, Naikar et al. (2006) considered whether decisions in the future AEW&C system might be modelled in these terms. One option was to model decisions in terms of the information-processes that are required to make them. However, the processes for decision making are more suitably considered within Strategies Analysis, the third phase of Cognitive Work Analysis. Another option was to model decisions in terms of the states of knowledge that result from them. For any particular decision, though, the states of knowledge that are possible are highly-situation dependent and infinite.

Naikar et al. (2006) recognized that a different strategy for capturing the decisions in the future AEW&C system was required. In the absence of a well-defined approach, however, the resulting decision ladders that they developed for AEW&C reflected a variety of strategies. For instance, some decisions were expressed in terms of the sources of information required for a decision whereas others were expressed in terms of the tasks that result from a decision. Consequently, many decisions in the future AEW&C system were not represented explicitly but, instead, had to be inferred.

This paper presents an approach for modelling decisions in future systems that is explicit and consistent. As will be demonstrated shortly, this approach employs a 'question' strategy. The questions reflect the recurring concerns or decisions of actors in future systems. The answers to these questions, which are formulated by actors in specific situations, reflect their states of knowledge. It should be acknowledged that some of the decisions in the AEW&C system were modelled in this form.

In this paper, the question strategy for developing decision ladders is illustrated by its application to a future uninhabited aerial system (UAS) for maritime surveillance operations in Australia. First, the Activity Analysis of the future UAS is presented. Following that, the question strategy is described and illustrated with examples from the preceding analysis. Finally, the paper considers how the decision ladder question strategy differs from more conventional forms of analysis as well as issues relating to the validation of this new approach.

Activity Analysis of a Future Unmanned Aerial System

This description of the Activity Analysis of a future UAS for maritime surveillance focuses solely on the results of the analysis. The process by which this analysis was performed is reported in Elix and Naikar (2008).

The result of the first step of the Activity Analysis, which is a contextual activity template, is presented in Figure 1. This representation shows that the work situations in which the future UAS will be required to participate are the different phases of a mission (e.g., *In Hanger, On Runway, Enroute to Specified Area*). These mission phases, which are depicted along the horizontal axis of the figure, are defined by the location of the aircraft. The work functions that the future UAS will be required to perform are shown in the circles (e.g., *Plan Mission, Fly and Navigate, Identify Targets, Collect and Disseminate Intelligence*). The boxes surrounding each work function (or circle) in the figure indicate those work situations in which a work function can occur. The bars extending from each work function span those work situations in which a work function typically occurs. The contextual activity template for the future UAS is supplemented by a glossary that describes each work function in terms of the essential problem faced by actors as well as typical activities.

The result of the second step of the Activity Analysis is a set of decision ladders. Specifically, a decision ladder was produced for each work function of the future UAS. Figure 2 presents the decision ladder for the *Fly and Navigate* work function. The boxes in the decision ladder depict generic information processes whereas the ovals depict generic states of knowledge. The annotations surrounding the decision ladder describe the decisions required in the future UAS in terms of a set of questions. To reiterate, for each work function, the questions reflect the recurring concerns or decisions of actors in a broad range of situations. The answers to these questions, which are formulated by actors in the context of particular situations, reflect specific states of knowledge. Shortcuts are possible from any one part of the decision ladder to another (some examples are shown in Figure 3). Hence the decisions in the future UAS can occur in any order.

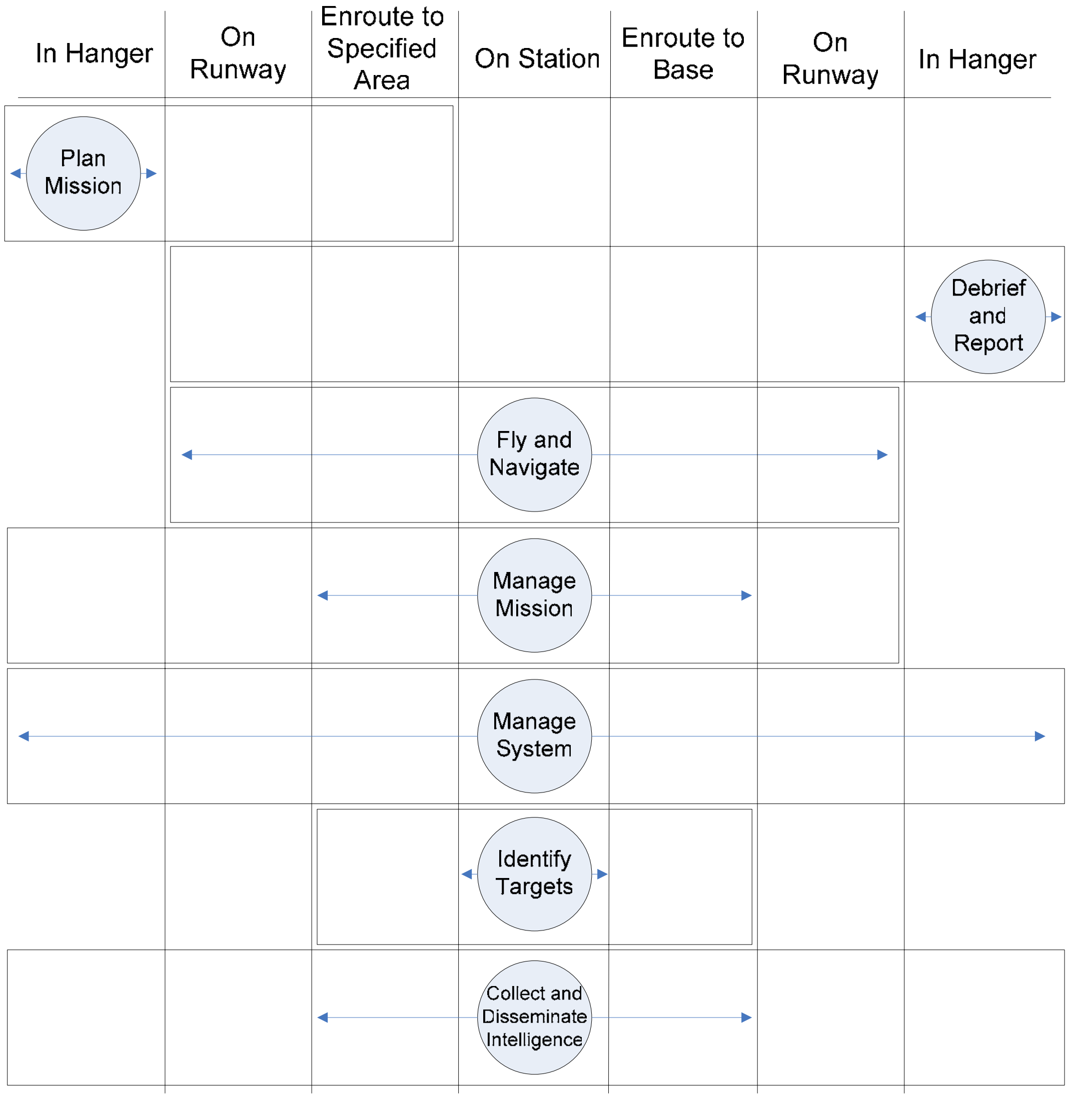

Figure 1. The contextual activity template for the future UAS

Decision Ladder Question Strategy

This section describes the question strategy that was used to develop the decision ladders for the future UAS. Figure 3 presents the decisions or questions that were motivated by the different parts of the decision ladder in a generic form. The following discussion of how these questions were applied to model decisions in the future UAS is organized around the states of knowledge nodes on the decision ladder. These nodes are discussed in the order that we found most useful to model or populate. Examples from the decision ladder for the *Fly and Navigate* work function are used to illustrate the question strategy at each node.

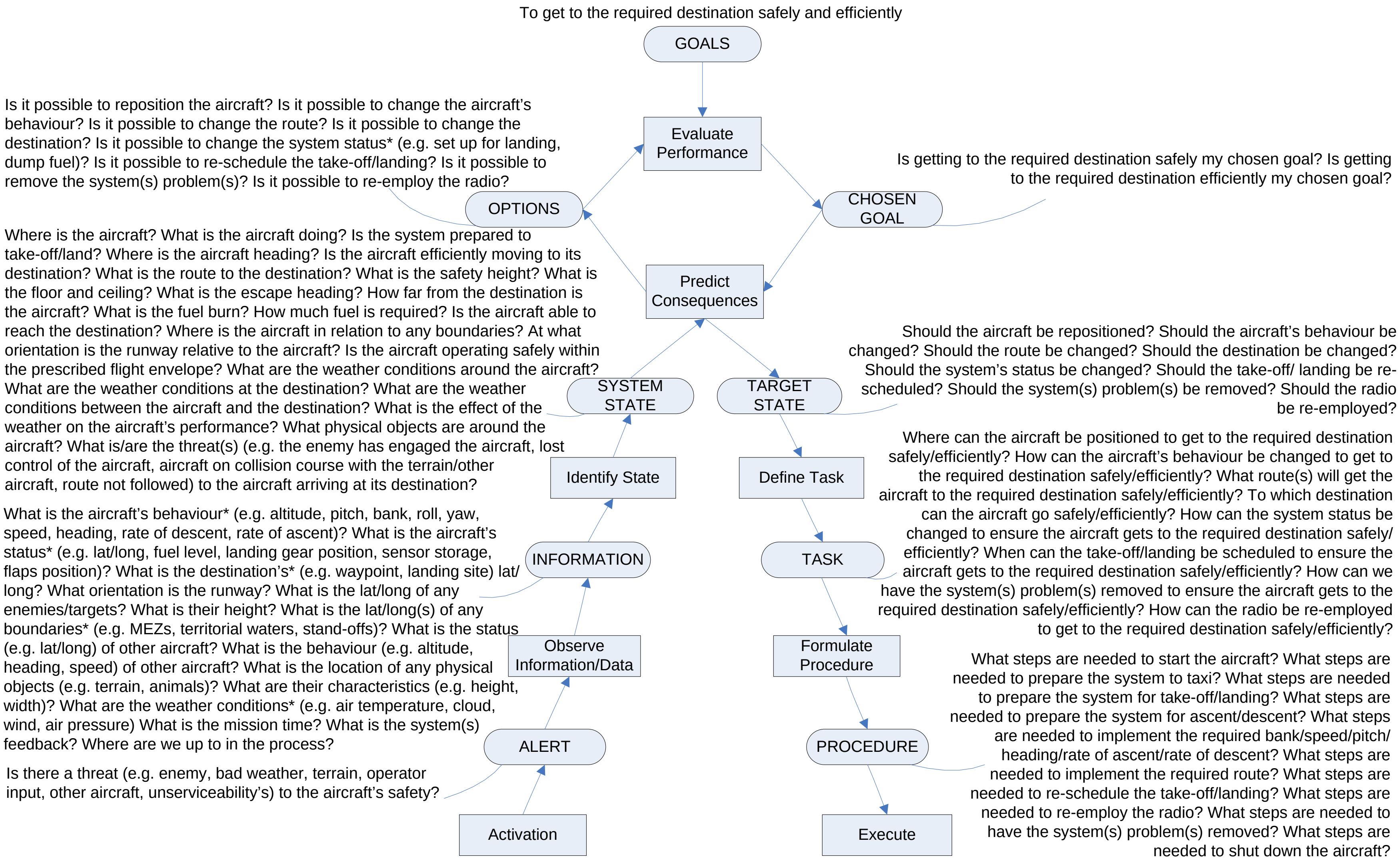

Figure 2. The decision ladder for the *Fly and Navigate* work function.

(* Indicates that the examples provided can be consistently applied to a term whenever it is used in the decision ladder)

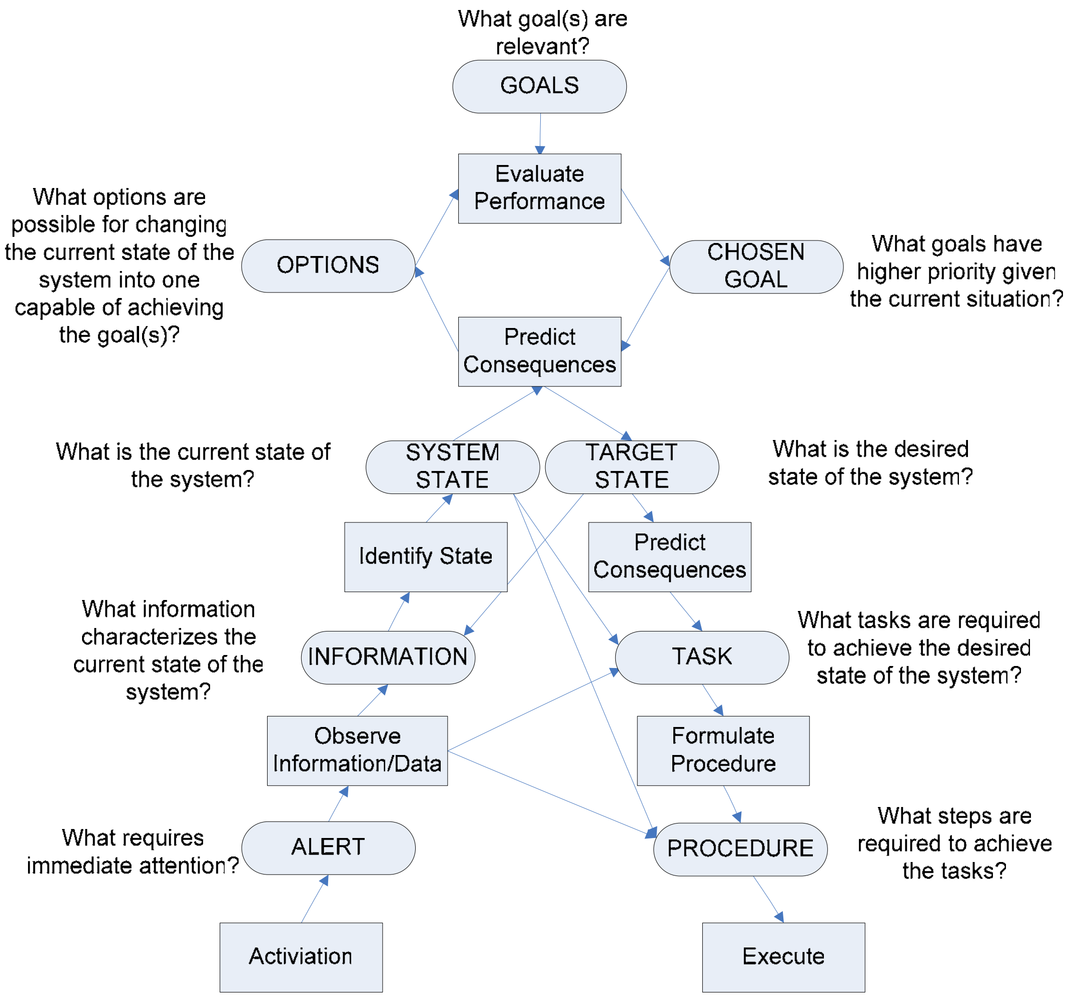

Figure 3. The decision ladder and the generic decisions or questions motivated by each of its parts.

Goals. This node guides the decisions that are represented at every other node on the decision ladder. Decisions relating to the information or tasks that are relevant to a work function, for instance, will depend on the goal to be achieved. We therefore found it useful to populate the goal node first. This process involved identifying the goal of a work function and any constraints which may influence how that goal is achieved. To illustrate, for the *Fly and Navigate* work function, the goal is to get to a required destination. The constraints that may influence how this goal is achieved are safety and efficiency. This information may be placed in the form "To (insert goal) (insert constraints)", which produces the overall goal statement "To get to the required destination safely and efficiently". We did not find it necessary to put this statement in the form of a question because the overall goal remains constant across a variety of recurring classes of situations. Decisions or questions relating to the constraints to emphasize in achieving the goal of a work function in specific situations are reflected at the chosen goal node.

Two other points are worthwhile mentioning in relation to the goal node. First, we found that activity in the UAS system was usually best characterized by having only one goal per work function. If analysts find that they have two or more qualitatively different goals, it may be worthwhile examining whether the goals are more faithfully or usefully represented as belonging to two separate problems or work functions. Second, we found that constraints relating to safety and efficiency were relevant to the goals of all of the work functions. No other constraints were identified at this stage, although it should be recognized that the goal itself may be viewed as a work-function specific description of the constraint of effectiveness.

System State. This node presents decisions about the current situation or state of the system. The situation assessments that are necessary depend on the overall goal of a work function. Therefore, to populate the system state node, we found it useful to examine what situation assessments are required to achieve the overall goal of a work function. For example, for the *Fly and Navigate* work function, the overall goal is to get to a required destination safely and efficiently. A situation assessment that is necessary for achieving this goal relates to how weather is affecting the aircraft's performance. Thus a recurring concern or decision of actors that was modelled at the system state node is "What is the effect of the weather on the aircraft's performance?".

An important distinction between the system state node and the information node is that decisions relating to the former usually rely on two or more qualitatively different classes of information. If only one class of information is required for a decision, we found that this decision is usually more faithfully or usefully represented at the information node. An example of this distinction is provided at the information node.

Information. This node presents decisions relating to the information that defines the current situation. The process we found most useful for populating this node was to review the system state questions and examine what information is needed to answer those questions. Thus this strategy relies on specifying the system state questions first. For the *Fly and Navigate* work function, a system state question is "What is the effect of the weather on the aircraft's performance?". The information required to answer this question relates to the weather conditions (e.g., air temperature, cloud, wind) as well as the aircraft's behaviour (e.g., altitude, speed, pitch, bank). Hence the recurring concerns or decisions of actors that were modelled at the information node include "What are the weather conditions (e.g., air temperature, clouds, wind)?" and "What is the aircraft's behaviour (e.g., altitude, pitch, bank, speed)?".

Another strategy that can be used to populate the information node is to make a list of the sources of information that are relevant to a work function, and then examine those sources to identify the information that they offer. For example, a map display is a source of information for the *Fly and Navigate* work function. A map display provides information about the latitude and longitude of the aircraft as well as the latitude and longitude of the destination. Thus some of the recurring concerns or decisions of actors that were modelled at the information node are "What is the aircraft's status (e.g., lat/long)?" and "What is the destination's (e.g., waypoint) lat/long?". When using this strategy to populate the information node, only information relevant to achieving the overall goal of a work function should be included and not necessarily all of the information that a source offers. Hence one benefit of the first strategy is that since information questions are developed from the situation assessments that are required to achieve the overall goal of a work function, an additional evaluation of the relevance of those questions is unnecessary.

Regardless of which strategy is used for developing the information questions, only one class of information should be required to answer each question. The information question "What are the weather conditions (e.g., air temperature, cloud, wind)?" relies on only one class of information, specifically, information about weather. Similarly, the information question "What is the aircraft's behaviour (e.g., altitude, pitch, bank, speed)?" relies on only one class of information, specifically, information about the aircraft's behaviour. In contrast, as mentioned earlier, system state questions require at least two qualitatively different classes of information to be answered. For example, the system state question "What is the effect of the weather on the aircraft's performance?" relies on two qualitatively different classes of information, specifically, information about the weather and information about the aircraft's behaviour. What is defined as a class of information may depend on the characteristics of the system under analysis as well as the intended application of the analysis.

Alert. This node presents decisions relating to occurrences that require actors' immediate attention. The strategy we found most useful for populating this node was to examine the information questions and assess whether in any circumstance that information would require immediate attention. For example, out of all of the questions represented at the information node of the *Fly and Navigate* work function, it was assessed that only information relating to a threat to the aircraft's safety would require immediate attention. Therefore, a recurring concern or decision of actors that is modelled at the alert node is "Is there a threat (e.g., enemy, bad weather, operator input) to the aircraft's safety?". Decisions or questions relating to the information node appear to be best represented using an "Is there…?" format.

Options. This node presents decisions about options that are possible for changing the current state of the system into one capable of achieving the overall goal of a work function. The strategy we found most useful for populating this node was to examine the system state questions in order to identify the system states that could pose obstacles to the achievement of the overall goal. Following that, the options that are possible for altering those system states (or removing those obstacles) so that the overall goal can be achieved were defined.

To illustrate, for the *Fly and Navigate* work function, a system state question is "What is the effect of the weather on the aircraft's performance?". A system state that could pose an obstacle to the achievement of the overall goal of this work function is that the effect of the weather on the aircraft's performance is such that the aircraft will not get to its required destination safely and efficiently. The options that are possible for changing this system state so that the overall goal can be achieved include repositioning the aircraft so that the weather does not have the same effect on its performance, altering the aircraft's behaviour (e.g., speed, heading) to compensate for the effect of the weather on the aircraft's performance, adopting an alternative route to the required destination in order to bypass the effects of the weather, or changing the destination of the aircraft.

Decisions relating to the options node were placed in the "Is it possible…?" format so that the answers to the questions at this node are framed in terms of options. Hence one of the recurring concerns or decisions of actors modelled at the options node for the *Fly and Navigate* work function is "Is it possible to reposition the aircraft?". If the answer is yes, in any given situation, then repositioning the aircraft is an option. If the answer is no, then repositioning the aircraft is not an option. Note that a wide range of other answers are also possible to such questions like "not sure", "maybe", "yes if X is the case", or "no if Y is the case".

Three additional points are worthwhile noting in relation to the options node. First, the options identified at this node are potential target states for the system. In other words, the options reflect what the target states of the system could be. Once a particular option is selected, it becomes the system's target state. The potential target states for the system are modelled explicitly on the right leg of the decision ladder but, as will be discussed shortly, the questions at the target state node simply rephrase those listed at the options node.

Second, if the current state of the system in a particular situation does not pose obstacles to the achievement of the overall goal of a work function, then the current system state is likely to remain the desired or target state of the system.

Third, the questions listed at the options node are not concerned with how a particular option (or potential target state) might be implemented but simply with identifying the option itself. For the *Fly and Navigate* work function, consider the question "Is it possible to reposition the aircraft?". This question is concerned with identifying whether or not repositioning the aircraft is an option. It is not concerned with identifying where the aircraft should be repositioned to or what steps are necessary to reposition the aircraft. Decisions relating to where the aircraft should be repositioned to are modelled at the task node of the decision ladder whereas decisions relating to the steps necessary for repositioning the aircraft are modelled at the procedure node of the decision ladder.

Chosen Goal. This node presents decisions relating to which constraints have higher priority in achieving the goal of a work function given the current situation. To illustrate, the overall goal of the *Fly and Navigate* work function is "To get to the required destination safely and efficiently". As mentioned earlier, this statement has two parts: (1) the goal of the work function, which is to get to the required destination, and (2) the constraints that may influence how that goal is achieved, which are safety and efficiency. Assuming that the aircraft has to get to the required destination, the choices that are available relate to how the constraints on achieving this goal are prioritised. Thus the recurring concerns or decisions of actors modelled at the chosen goal node are "Is getting to the required destination safely my chosen goal?" and "Is getting to the required destination efficiently my chosen goal?". It is important to emphasize that representing these decisions separately does not reflect an absolute choice between safety and efficiency per se. Instead, representing these decisions separately reflects the fact that either safety or efficiency may be given higher priority in selecting an option that will allow the system to get to the required destination. It is also possible that no option is available for getting to the required destination safely or efficiently so that the option that is selected is to change the destination of the aircraft. The general format of the questions at the chosen goal node is “Is (insert goal) (insert constraint) my chosen goal?”.

Target State. The target state node presents decisions relating to the desired state of the system. The desired state of the system is a state that the system must be in to achieve the overall goal of a work function. The strategy we used for populating this node was simply to rephrase the questions at the options node in the form “Should (insert option)?”. This strategy reflects the fact that the options indicate what the desired states of the system could be. For the *Fly and Navigate* work function, one of recurring concerns or decisions of actors modelled at the target state node is “Should the aircraft be repositioned?”. If the answer to this question is yes, then the desired state of the system is to reposition the aircraft. If the answer is no, then repositioning the aircraft is not the system’s desired state. As indicated in the discussion of the options node, many other answers to such questions are possible.

Similarly to the options node, the target state node is not concerned with how the desired states of the system might be implemented or achieved. Instead, decisions relating to how the system’s desired states might be achieved are modelled at the task and procedure nodes of the decision ladder. Relevant examples are provided in the earlier discussion of the options nodes.

Task. This node presents decisions relating to the tasks that are required to achieve the desired state of the system. The strategy we found most useful for populating this node was to examine the target state questions and identify the tasks that are required to achieve each of the potential target states of the system. For example, for the *Fly and Navigate* work function, one of the potential target states is to reposition the aircraft. A task that is required to implement this target state is to decide where to reposition the aircraft. Thus one of the recurring concerns or decisions of actors that was modelled at the task node is “Where can the aircraft be positioned to get to the required destination safely/efficiently?”. The task statements that we developed reiterate the overall goal of a work function for the sake of clarity. To illustrate, if the overall goal of the *Fly and Navigate* work function was not included in the decision just described, the task question would be “Where can the aircraft be positioned?”. Including the overall goal in this question emphasizes that this decision is not concerned with identifying all of the possible positions that the aircraft can be placed in per se, which are infinite, but with identifying a position(s) that the aircraft can be placed in so it gets to the required destination safely/efficiently.

Procedure. The procedure node represents decisions relating to the steps that are required to achieve a task. The strategy we found most useful for populating this node was to review the questions at the task node and examine what steps are required for the tasks to be achieved. For the *Fly and Navigate* work function, a task question is “Where can the aircraft be positioned to get to the required destination safely/efficiently?”. To place the aircraft in a desired position, a certain bank, speed, pitch, heading, rate of ascent, and rate of descent of the aircraft is required. Thus a recurring concern or decision of actors that is modelled at the procedure node is “What steps are needed to implement the required bank/speed/pitch/heading/rate of ascent/rate of descent?”. It is worthwhile pointing out that this question is not concerned with what steps are necessary to decide where to position the aircraft but what steps are necessary to get the aircraft to a desired position. The format we adopted for the questions at the procedure node is “What steps are needed…?”. This format does not specify or assume a fixed sequence of steps but recognizes that the steps that are necessary in any given situation may vary.

Discussion

This paper presented an approach for modelling decisions in future systems that is both explicit and consistent. Specifically, the approach involves the use of a question strategy to develop decision ladders for future systems. By providing an approach for modelling decisions in future systems, this strategy makes it possible to design interfaces, crew concepts, training programs, and workspace layouts for future systems that are well tailored to their work demands. The question strategy may also be used to develop decision ladders for existing systems.

It should be acknowledged that question formats for modelling decisions are also used in more conventional forms of analysis. Decision-action diagrams, for instance, model decisions in the form of questions (Kirwan & Ainsworth, 1992). It appears, though, that the types of questions or decisions modelled with decision-action diagrams and the decision ladder are fundamentally different. One significant difference between the two is that the questions employed in decision-action diagrams have a small and finite set of answers or results. For example, a decision or question modelled in a decision-action diagram in the classic text by Kirwan and Ainsworth (1992) is "Is feeder balanced and steady?". The decision-action diagram shows that this decision has three possible answers or results: yes, too high, or too low. In contrast, the types of questions motivated by the decision ladder accommodate infinite answers or results, including ones that cannot be predicted or specified upfront. Consider, for instance, the question "What is the effect of the weather on the aircraft's performance?". Another difference between the two approaches is that whereas decisions or questions in decision-action diagrams are modelled in fixed sequences, the decisions or questions on a decision ladder can occur in any order. In these ways, the decision ladder seems to offer an approach for modelling decisions that provides a more adequate representation of the complexity of the decisions faced by actors in complex sociotechnical systems. A more systematic analysis of the differences between the decision ladder and more conventional approaches for modelling decisions is worthy of further consideration.

Finally, it should be acknowledged that validation of the decision ladder question strategy is still necessary. The validation of this strategy can only occur meaningfully with application to complex sociotechnical systems. Validating the decision ladders for the future UAS for maritime surveillance is challenging because the system does not exist. So far, the approaches that we have adopted for validation are interviews with subject matter experts in maritime surveillance, specifically, operators of an existing maritime patrol aircraft in Australia, and participation in systems engineering workshops related to the future UAS (Elix & Naikar, 2008). In the future, two other options for validation are possible. First, the decision ladders may be validated using a variety of techniques when the UAS for maritime surveillance is brought into existence. Second, the decision ladders may be validated by evaluation of the usefulness of the designs produced with this approach. Currently, the decision ladders are being used to design a team for the future UAS for maritime surveillance.

References

Elix, B., & Naikar, N. (2008). An analysis of activity in a future unmanned aerial system for maritime surveillance operations in Australia. *Manuscript submitted for publication.*

Kirwan, B., & Ainsworth, L. K. (Eds.). (1992). *A guide to task analysis*. London: Taylor & Francis.

Naikar, N., Moylan, A., & Pearce, B. (2006). Analysing activity in complex systems with cognitive work analysis: Concepts, guidelines, and case study for control task analysis. *Theoretical Issues in Ergonomics Science*, *7*, 371-394.

Rasmussen, J. (1980). The human as a systems component. In H. T. Smith & T. R. G. Green (Eds.), *Human Interaction with Computers* (pp. 67-96). London: Academic Press Inc. (London) Ltd.

Rasmussen, J., Pejtersen, A. M., & Goodstein, L. P. (1994). *Cognitive systems engineering*. New York: Wiley-Interscience.

Vicente, K. J. (1999). *Cognitive work analysis: Toward safe, productive, and healthy computer-based work*. Mahwah, NJ: Lawrence Erlbaum Associate.