Cognitive work analysis and simulation (CWAS):

Practical use of cognitive work analysis in system design

by

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DEDICATION

I would like to dedicate this work to my parents for being great role models in my life and for their support through each and every step of my education and career.

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ABSTRACT

People trust their lives with human-machine systems such as airplanes every day, making it critical for system designers to prevent human errors and accidents. Cognitive work analysis (CWA) is a method developed to analyze the cognitive requirements of such system to inform the design process. Nonetheless, because CWA was developed to deeply analyze the system, as it was originally introduced, it was not readily applicable to system design and design decision making. On the other hand, simulation modelling has been used to provide quantitative metrics for decision making. However, it lacks a comprehensive framework for modelling based on model analysis. In this research we propose the Cognitive Work Analysis and Simulation (CWAS) method to bridge the gap between analysis and simulation by using the CWA results to build a dynamic representation of the system. The simulation model provides quantifiable measures of performance, such as mental workload of system agents, which facilitates design decision making. In addition, CWAS provides a profound framework for simulation modelers in modelling. The CWAS method is demonstrated in a case study on the work process of Advanced Cardiac Life Support. CWAS adds value to the CWA research methodology by providing a structured process for using system analysis as a modeling basis for cognitive behavior simulation modelers. CWAS is meant to add value a step before actual prototyping in the product and system life cycle, making it possible to examine a larger variation of design scenarios before deciding on prototyping options.

CHAPTER 1 - INTRODUCTION

Unfortunately there are many examples of disasters caused by human factors issues. The Air France flight 447 crash in 2009 and the derailed Spanish train in 2013, for example, were both due to human factors flaws (CNN, 2013; France's Bureau of Investigation and Analysis, 2010). Using complex automated systems that could cost people's lives requires thorough investigation and perfect design to prevent any errors. One of the distinctive features of cognitive engineering, a discipline within human factors, is its commitment to analyze and model the cognitive and collaborative aspects of work to inform design of more effective systems (Roth & Bisantz, 2013).

Cognitive work analysis (CWA), originally developed for analyzing complex systems such as nuclear power plants, provides a comprehensive framework for studying system requirements and collaborative performance (Rasmussen, 1986; Vicente, 1999). CWA offers deep insight into complex human-machine systems. However, with the presentation of findings in separate diagrams, each providing significant amount of information, getting a holistic understanding of the system is not easily possible, making it hard to examine the overall performance of a system under different conditions. In addition, for making design decisions, quantifiable measures are needed, and the qualitative CWA results make the application of CWA to a product design project a difficult challenge. In this research we propose a method to overcome these limitations in CWA and enable researchers to use the CWA results practically for their design decisions.

Cognitive work analysis was well adopted by researchers and successfully implemented in various fields, such as health care (Ashoori & Burns, 2012; Ashoori, Burns, d'Entremont & Momtahan, 2014), military domains (Jenkins, Stanton, Salmon, Walker, &

Young, 2008; Stanton, 2014) and transportation (Cornelissen, Salmon, McClure, & Stanton, 2013). In addition to the wide use of CWA, researchers have suggested extensions to the CWA. Ashoori and Burns (2012) have presented a method to incorporate CWA for studying systems involving teams of operators. Furthermore, CWA has been applied to domains other than system and interface design, such as: team design, evaluation of system design proposals, and training needs (Naikar, Pearce, Drumm, & Sanderson, 2003; Naikar & Sanderson, 2001; Naikar, 2006). Stanton and Bessel (2014), in an effort to evaluate the suitability of CWA for studying ergonomics problems, found CWA to be an epitome of the essential characteristics that Wilson (2012) has defined for Systems Ergonomics.

Although the method is widely used and well established, there are limitations in applying the analysis results in action. The product design process is an iterative process (Berente, Lyytinen, 2005) that starts with an initial idea. After evaluation, new ideas are developed. Understanding the effect of several changes in the design on the entire system's performance is a great challenge using the current CWA presentation. Therefore, there is a critical need for a holistic and dynamic representation of the CWA results. In addition, making decisions is easier with quantitative data, which the current CWA does not provide. The premise of this work is that using simulation models that represent the system based on the CWA analysis and the members' workload would be a proper remedy to this gap. In this way, the analysis results will be dynamically represented, providing a comprehensive understanding of the system in action, so that a large number of scenarios and team configurations can be tested. Also, the use of cognitive workload, a key factor in system design, in the model will add a quantifiable measure for evaluating these scenarios until reaching a desirable design.

Simulation modeling has been used for studying human behavior in cognitive engineering (Pritchett, Kannan, & Feigh, 2011; Pritchett, Kim, & Feigh, 2013; Shah et al., 2005), and it provides an opportunity of studying several scenarios with almost no cost, once the model is built. An important measure in assessing design quality for a team system is the mental workload of the team members in the process. High levels of workload has been known to negatively impact performance (e.g., Wu, Liu, 2007). Thus, maintaining certain levels of human workload is one of the most important goals for system designers. A good example of mental workload simulation can be seen in Wojciechowski, et al. (2004), in which a comprehensive model of an army combat team was developed that simulated the actions as well as the mental workload of the team members. The model was tested for different role assignment scenarios to select the best alternative. However, although the simulation represents the existing tasks and the workload very well, it is limited to the specific structure of the existing system. CWA could offer a formative structure, meaning it analyzes what needs to be done regardless of the existing system setting.

Workload simulation, also adds quantifiable measures to system simulations as a performance metric in evaluating system designs. Workload assessment methods have been used for decades in military and other domains (Bierbaum, Szabo, & Aldrich, 1987; Laux & Plott, 2007; McCrasken & Aldrich, 1984). These methods provide quantitative assessments of the workload asserted to human operators.

Summary

Reviewing the literature, it seems that research with good workload simulation modeling did not take advantage of the deep analyses methods such as CWA. On the other hand, the CWA analysts did not put their results into a simulation model to take direct benefit

of their analysis in design or evaluation of systems. The present research suggests a method called Cognitive Work Analysis and Simulation (CWAS) to bridge the gap between the analytical results and the simulation modeling. Building a simulation model based on formative CWA results enables deeper scenario analysis on a simulation model and provides a holistic understanding of the system along with a dynamic representation of the analytical CWA results. In addition, the workload measures provide quantitative metrics that help decision making.

In the next chapter, relevant previous work is discussed in detail and the strengths and weaknesses of the methods are defined. In Chapter 3, the steps and phases of CWAS method are described. Chapter 4 presents a case study of applying CWAS to a socio-technical system in the health care domain to demonstrate the implementation and abilities of the method in evaluating system improvement scenarios. In Chapter 5, the applications of the method and future studies are discussed.

CHAPTER 2 - LITERATURE RIVIEW

To offer a new methodology, a comprehensive review of previous related work is required. This research leverages the strengths in different methods to bridge the gap between Cognitive Work Analysis (CWA) and system design. Therefore, in addition to a detailed introduction and evaluation of CWA, topics such as simulation modeling and mental workload assessment methods are covered as well. Though there has been enormous amount of research in simulation, this section will briefly introduce areas relevant to cognitive workload simulation. Finally, among the various workload assessment methods, the measures that fit better with the CWAS method are discussed in detail.

Cognitive Work Analysis (CWA)

Cognitive work analysis, originally introduces for nuclear power plants, is a comprehensive framework for analyzing cognitive and collaborative requirements of a system (Roth & Bisantz, 2013). The modeling approach in CWA is formative, meaning it defines what is needed to perform the task, regardless of the agent, the event and the current environment of the system (Roth & Bisantz, 2013). The formative approach contrasts with the normative or prescriptive models that suggest what should be done, or the descriptive models that present what actually is done (e.g., how do workers complete the task in the existing system). The formative approach analyzes the work with an approach that goes deeper than the surface actions, at a level that is independent of the agents and the events, which reduces the reliance on expert opinion. As the other methods mostly rely on eliciting the knowledge of the expert to find how they perform their task and strategize their decisions,

a formative CWA seeks the intrinsic characteristics of the work that do not depend on how the work is currently accomplished. For analyzing first-of-a-kind systems where there are no subject matter experts to interview, the formative approach helps finding the system specifications. In addition, this formative feature provokes innovation in system design due to not limiting the analysis to the existing environment.

Cognitive work analysis is generally known to have five main steps, as depicted in Figure 1 on the left side. Each step is briefly introduced below.
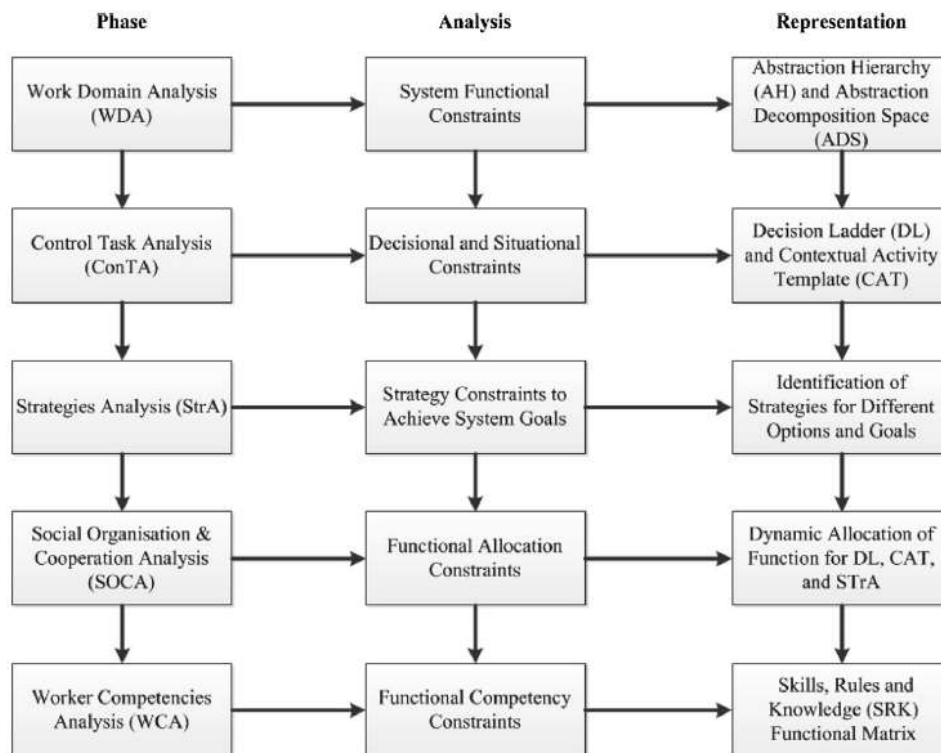

Figure 1- The five phases of the Cognitive Work Analysis method from (Stanton & Bessell, 2014).

Phase 1: Work Domain Analysis (WDA)

Work domain analysis (WDA) is meant to unveil the physical and social constraints of the activity. The output of WDA is presented in an Abstraction Hierarchy (AH) or an abstraction decomposition matrix. An abstraction decomposition matrix is a table that

presents the functions of the system in each level of abstraction. The abstraction hierarchy, as depicted in Figure 2, provides the connections between goals, functions, and resources, making it more informative than the decomposition matrix.
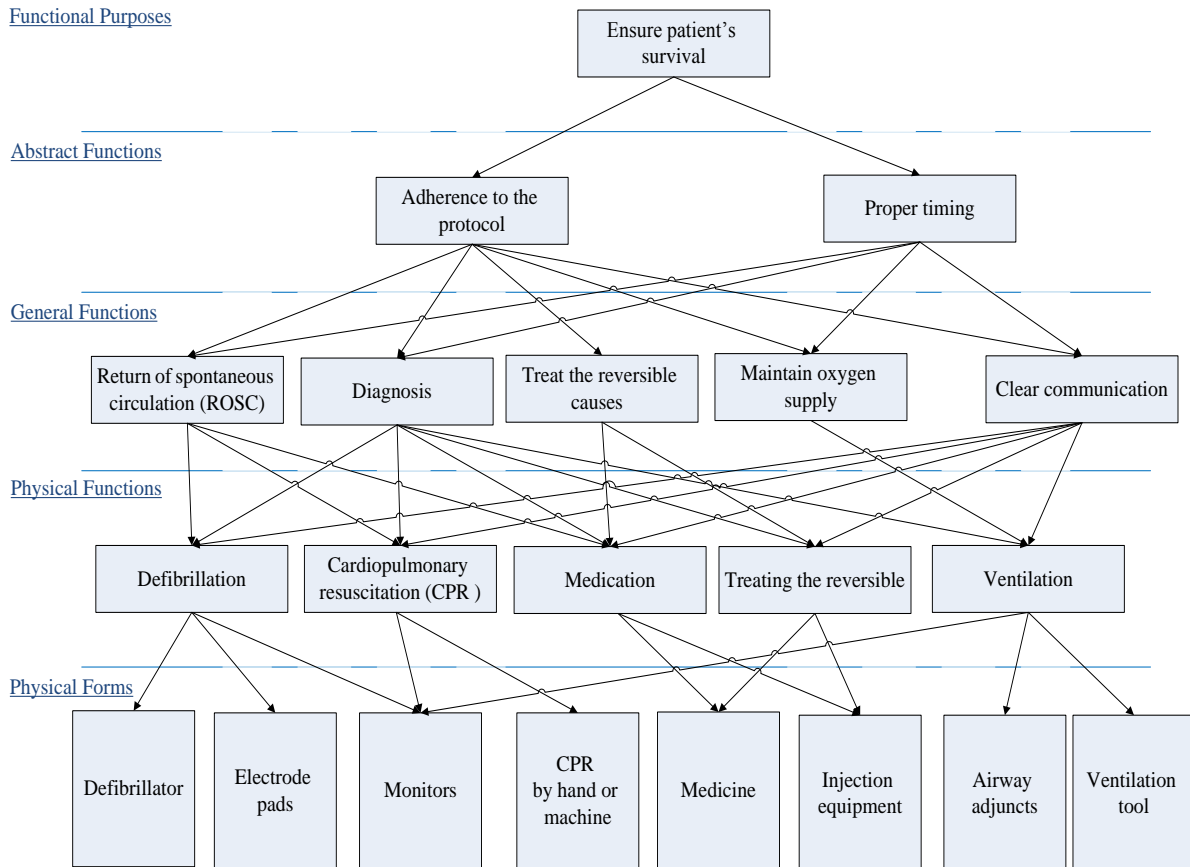

Figure 2 - Abstraction Hierarchy of an Advanced Cardiac Life Support (ACLS) Activity (see Chapter 4)

In general there are five levels of abstraction defined in WDA. The highest level is the functional purposes, defining the purpose of the system, and the lowest level focuses on the physical forms, analyzing the resources and physical objects used for the work. In other words, WDA is considered a goals-means representation of the work system with abstract system purposes at the top and tangible physical objects that are necessary for fulfilling the goals of the system at the bottom (Roth & Bisantz, 2013).

The team ConTA model offered by Ashoori and Burns can help the representation, in case of studying teams (Ashoori & Burns, 2012). Figure 3 presents a sample of the team abstraction hierarchy, where responsibilities are defined by colors and different dashed lines.
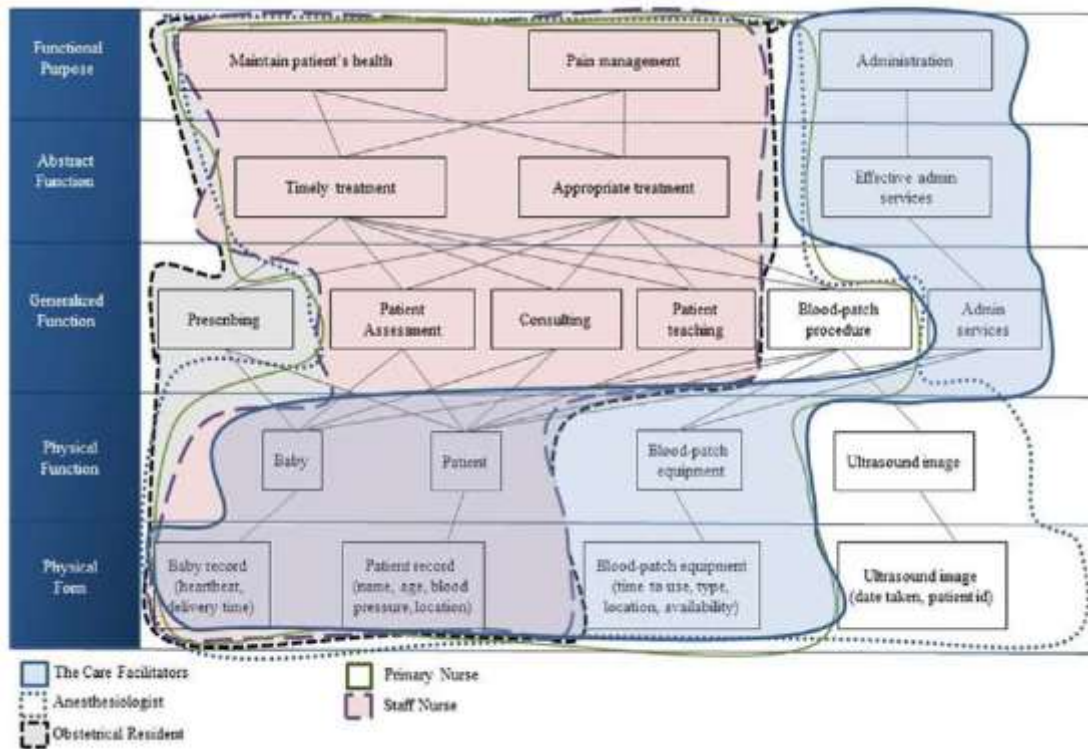

Figure 3 - Abstraction hierarchy for a team. Responsibility maps for labor and Delivery Department. From Ashoori and Burns (Ashoori & Burns, 2012).

Functional Purpose

Functional purposes are the purpose of the work system. These purposes are independent of time and the system's environment or state, and they are true as long as the system exists. At the same time, the functional purposes are the external constraints on the activity of the system, i.e., every action in the system is decided based on these purposes.

Abstract Function

Abstract function or value and priority measures define performance measures used in the work system to examine the progress toward functional purposes (Stanton & Bessell, 2014). In other words, these functions set the principles, priorities, and constraints for defining the general functions.

General Function

General functions or purpose-related functions are the functions necessary for the system to achieve its functional purposes. These functions relate the purpose independent processes to the object independent purposes (Stanton & Bessell, 2014), i.e., they add a layer to connect the abstract functions of the work system to the physical forms and processes.

Physical Function

Physical forms or object-related processes define the processes that are conducted in the system to fulfill the general functions. These processes are analyzed independent of the purpose; only the capabilities and limitations of the process with regards to the physical objects and resources are considered in this step.

Physical Form

Physical forms or physical objects are the resources and objects used in the work system to perform the physical functions. This level defines the boundaries of the system by defining all the resources and objects that are required for the work.

An extension to CWA was made by Ashoori and Burns (2013) to incorporate team CWA. In this method the responsibilities of team members are depicted on the abstraction hierarchy. This idea is important and valuable, however, the current representation is somewhat baffling and can become hard to read for a larger number of team members. In

general, applications and tools for facilitating the depiction of CWA results will reduce time and cost of CWA implementation. However, as mentioned before, even proper depiction of CWA results requires additional effort for building a holistic view of the system by connecting steps of the process.

Phase 2: Control Task Analysis (ConTA)

In this step using the constraints and resources defined in the WDA, the information needed to accomplish the tasks is determined, regardless of the agents, users or task specific actions. ConTA is specifically focused on the control tasks required for the successful control of the system (Roth & Bisantz, 2013). From a general level, ConTA can be considered a process for turning specific information into outputs such as actions or decisions (Vicente, 1999). The decision ladder is most commonly used to represent the results. The sources of information and the information flow in the system are mapped on a decision ladder. Decision ladders (see Figure 4) have circular and rectangular nodes. The rectangles represent information processing activities, and the circles represent the state-of-knowledge that is the result of the information processing. The general forms of decision ladders are identical, while the researcher adds the information needed for each box to the sides of the graph. This type of presentation, although provides the information, is not easy to integrate with other parts of the process, making it hard to see overall effects of changes in the system, e.g., if an information display was added to facilitate communication in an emergency room, how would that impact the team performance or mental workload?
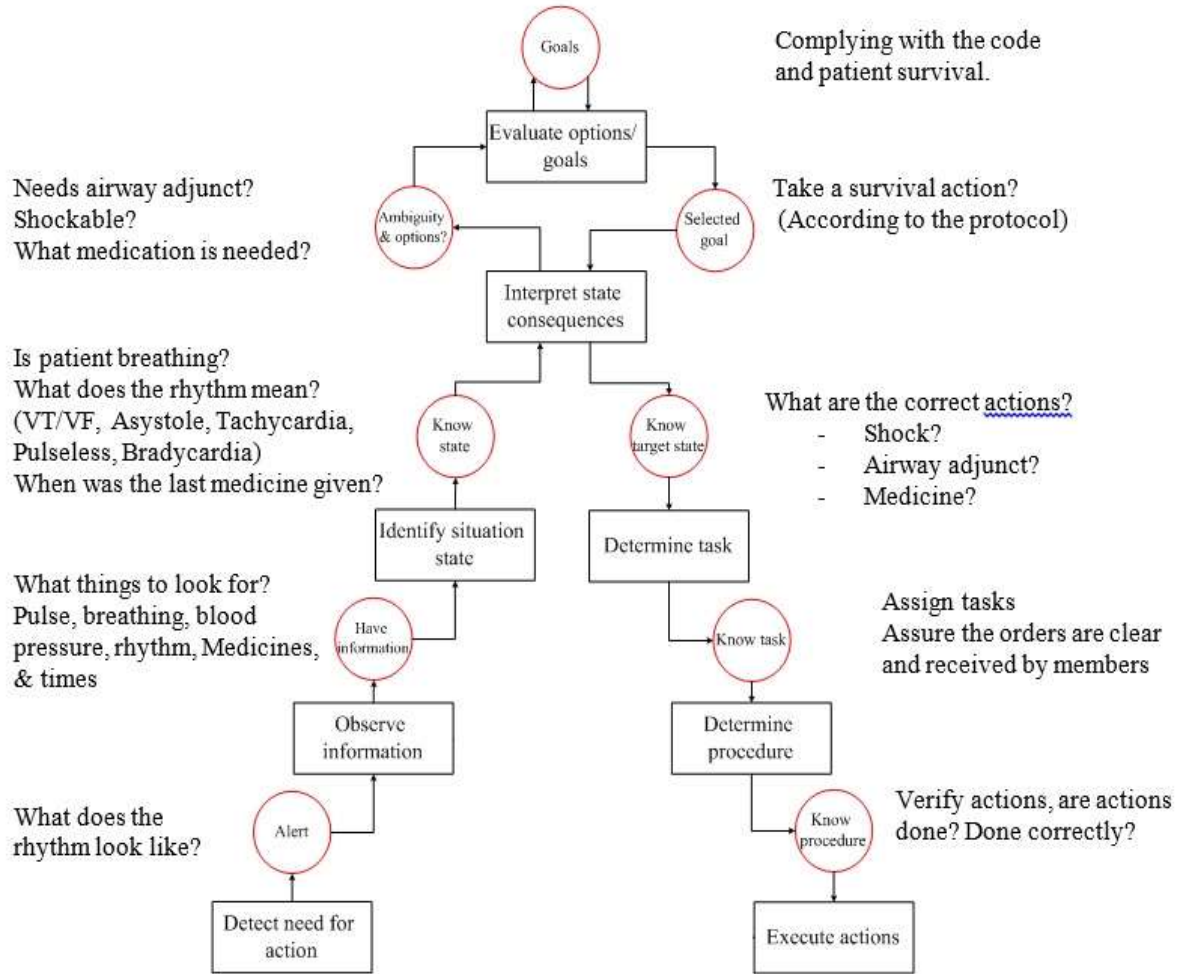
Figure 4 - Example Decision Ladder for ACLS process (see Chapter 4)

Decision ladders have two sides, left and the right. The left side of the ladder is the observation and information gathering in the work process. On each node, the information needed for arriving at a knowledge state is defined. At the very top, the information and knowledge of the system is checked with the main purpose of the system to move to the right side of the ladder. The right side of the ladder presents the planning and execution of tasks (Stanton & Bessell, 2014).

The target system may include a team of operators. In these cases, to map the information flow between team members, additional illustration tools have been suggested. As depicted in Figure 5, using chained decision ladders (Rasmussen, Pejtersen, & Goodstein,

1994) is a way to depict the information that team members need to share. Furthermore,

decision wheels have been offered by Ashoori and Burns (2012) for depicting more

complicated teams. These tools can help initiating the ConTA analysis, but using the

simulation model the representation will not be as important.
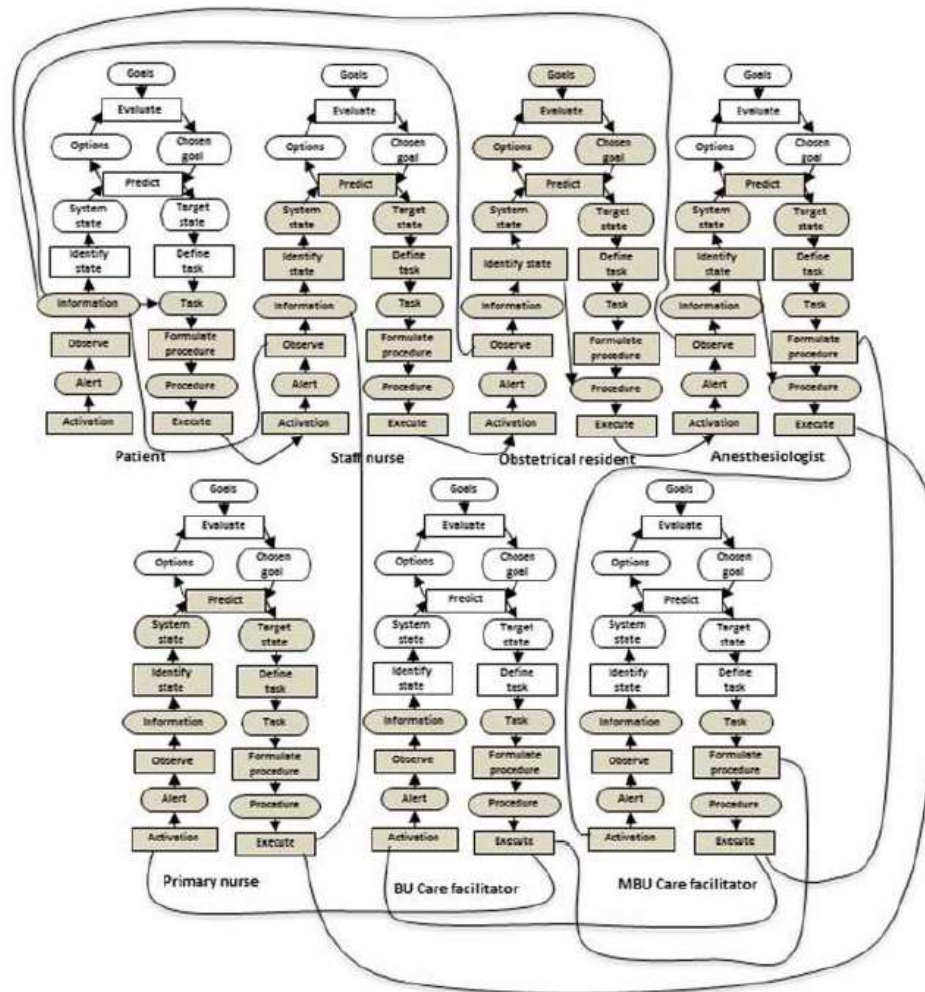

Figure 5 - Example of chained decision ladders for Labor and Delivery Department.
From Ashoori and Burns (2012)

In addition to decision ladders and its variations, Stanton and Mcllory (2012) have

suggested a Contextual Activity Template for representing the ConTA results. This sort of

effort reinforces the deficiencies in the original CWA representation.

Phase 3: Strategy analysis (StA)

This step is to capture personal differences in processing information, based on expertise or individual preferences. Using the decision ladder from ConTA, we can define shortcuts and various strategies in processing the information and decision making. Similarly, people might take different strategies for segueing from one system state to another. There are many factors that can influence these strategies, such as: experience, training, workload, and familiarity with current situation (Stanton & Bessell, 2014). Figure 6 depicts a sample representation of a strategy analysis results. Different strategies in operating a task need to be considered for a proper system design. Including the strategy analysis helps gaining a holistic understanding of the system, one of the purposes of CWAS method.
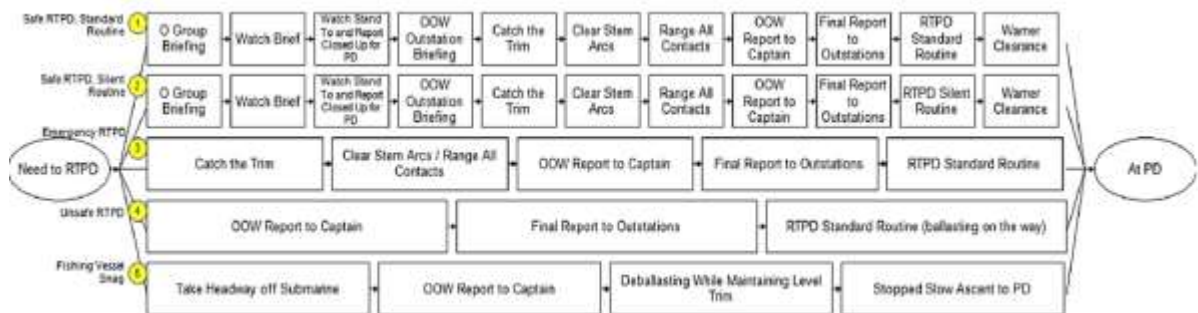
Figure 6 - Sample strategy analysis graph from Stanton and Bessel (2014)

Phase 4: Social Organization and Cooperation Analysis (SOCA)

This step analyzes how work can be distributed among multiple agents and investigates the communication and coordination among them. There are two main dimensions to SOCA. The first is about the distribution of work among agents and their coordination, which aligns with the traditional function allocation concerns. The second

dimension is the form dimension, where the authority hierarchies are investigated. The organizational hierarchy defines the type of communication and collaboration among agents.

The representation of SOCA analysis is to use one of the prior step's outputs, e.g., an abstraction hierarchy or decision ladder, and overlay this information on them using color coding (Figure 7). For the decision ladder this step identifies who provides each piece of information on the left side of the ladder and who will receive the actions or decisions on the right side of the ladder. This visual representation is very hard to track and make actionable decisions on, which is the problem we want to address with the CWAS alternative.
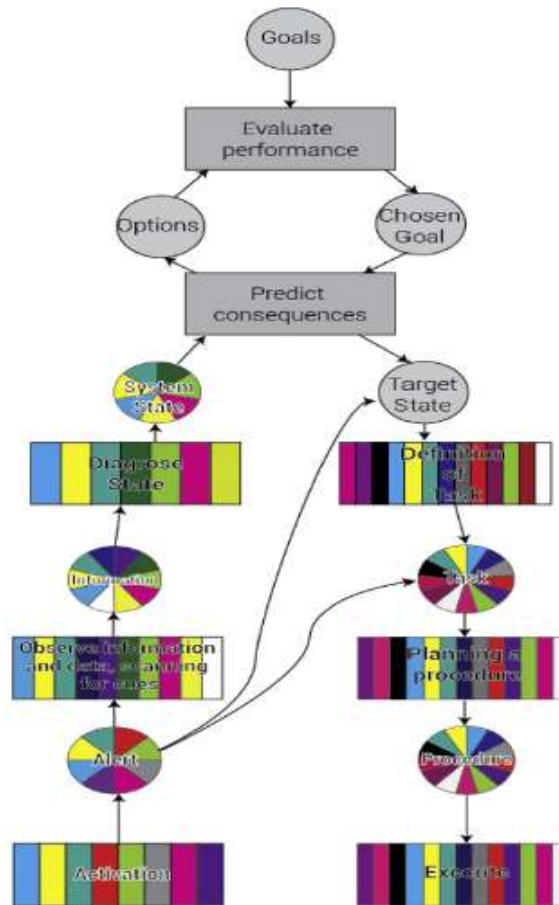

Figure 7 - Example of SOCA on a decision ladder from Stanton and Bessel (2014)

Phase 5: Worker Competency Analysis (WCA)

This step is the final step in CWA, where the skill levels needed for an agent to perform a task are defined. The required skills need to be analyzed using the information gathered from prior steps of CWA for each task and strategy. Vicente (1999) suggests using Rasmussen's skills, rules, and knowledge (SRK) taxonomy as a framework. This taxonomy divides the level of control over activities as either skill-based (highly practiced and typically sensory and motor), rule based (predefined routines), or knowledge-based (relying on metal models and requiring higher level problem solving) (Roth & Bisantz, 2013).

The worker competency analysis results, similar to SOCA, are depicted on other graphs such as the StA results. The WCA can be used to identify the worker competency requirements in recruiting and training requirements of a system (McIlroy & Stanton, 2011).

Limitations of CWA

CWA has been criticized for being hard to implement and not being a pragmatic approach for designing systems, specifically decision support systems (Potter, Gualtieri, Roth, Engineering, & Easter, 2003). These researchers presented a method named Applied Cognitive Work Analysis (ACWA), which offers a framework to use the CWA analysis to make a decision support tool. However, this method has not much in common with the original CWA that its name. It is a brand new method mainly with a programming and UML approach, a probable reason for it not being widely adopted by researchers. In addition, it is solely developed for building decision support systems and does not incorporate other design aspects of the system, such as team member roles and task allocation or use of new equipment and other devices.

We believe using a simulation model to make a holistic and dynamic representation of the CWA results will help understanding the system in action. On the other hand, by adding the workload measurements a quantitative measure is available to the researcher to make design decisions. The next section will introduce related aspects of simulation modeling.

Cognitive Simulation

Simulations are a representation of a real system, while computer simulations refer to quantifiable representation that can predict future given the current state and inputs (Pritchett, 2013). Cognitive engineering has used simulation models to simulate human behavior, workload, or performance in a given environment and situation. These simulations are intended to support design of technology, procedures, and training (Pritchett, 2013). In the following subsections we discuss different approaches in cognitive simulation that CWAS can use and their previous applications in cognitive engineering field. Next, the main paradigms of simulation, i.e. discrete-event, system dynamics, and agent-based, are briefly introduced. Table 1 provides a summary of the paradigms and approaches used in cognitive simulation and modelling.

Table 1 - General paradigms and approaches in cognitive modelling and simulation.

Simulation Approach	Cognitive workload Cognitive behavior Situated cognitive behavior	Simulation Paradigm	Discrete Event System Dynamics Agent Based Hybrid

Cognitive Simulation

Simulations are representations of a real system (e.g., flight simulators, patient simulators, etc.), while computer simulation refers to a quantifiable representation that can predict future given the current state and inputs. These simulations are intended to support the design of technology, procedures, and training (Pritchett, 2013). The scope of the simulation model is defined based on the desired impact on the system.

Cognitive engineering researchers have used simulation modeling with different approaches. In each simulation approach, part of the system represents the events in the environment, and the other part represents the cognitive behavior of the system (Pritchett & Goldsman, 2000). For instance, the environment for an air traffic control agent might be the objects on the radar screen as well as radio communications. The frequency of objects appearing on screen or importance of radio communication might vary throughout the process. On the other hand, the agent (the air traffic controller) has a separate internal model for behaving in reaction to those environmental inputs. The physical functions defined in the abstraction hierarchy, provides a framework for tasks and actions in the system to simulate the environmental events (Pritchett et al., 2011; Pritchett, 2013). A separate section of the model simulates the agent and her appropriate responses to represent the cognitive behavior within the system.

In the Cognitive Work Analysis and Simulation (CWAS) method offered in this work, it is critical to make a correct choice of the simulation approach and paradigm. This introduction is meant to provide general guidelines for making the simulation modeling

decision. Cognitive simulation research can be summarized into the following three approaches.

<u>Workload simulation</u>

The first approach focuses on the workload of the agents (operators) modeling the effect of environmental events on the workload. The agents in the system are generally passive and only react to the events in the environment. Their behavior or mental models are not included in the simulation, making the modeling effort simple. Since the model doesn't make assumptions on human mental models and cognitive behavior, it is easier to validate and the results are more dependable. In addition, many behavior models are a function of workload or task load on agents. This modeling approach provides the pure workload and task load that can be used for further analysis.

This approach is a good fit for systems with defined structure of actions and communication, since the workload can better estimated. Examples are military combat teams or standard medical procedures such as Advanced Cardiac Life Support (ACLS). In these systems, since the agents have limited choices in their choice of actions and communications, their behavior is mostly affected by their workload rather than individual behavior functions.

<u>Human-Computational performance models</u>

There is a variation of in modeling with this approach. Mainly the focus is on using human mental processing capacities and modeling human behavior in response to different situations. The earlier models focused on modeling an individual agent's brain (or cognitive capacity) and not much on the environment. The more recent models, consider using agent based simulations, assigning behavior functions to agents and evaluating a wider range of

agents and studying behavior. These models make assumptions about agents' mental models and make mathematical objective functions for agents. Validating these models is a great challenge. In addition, the behavior functions are set for agents that perform exactly as planned, limiting the model for analyzing crisis scenarios or more realistic behavior analysis.

Situated human performance

Situated human performance models, unlike the prior approaches, intend to model the human agents managing a range of tasks when situated in an operational context (Pritchett & Feigh, 2011). Pritchett (2011) has offered a simulation framework named WMC (Work Models that Compute) to model this type of system, particularly in function allocation problems. An example of this simulation approach is the function allocation problem in aviation – which pilot will perform which action (Pritchett & Feigh, 2011; Pritchett et al., 2011, 2013). In these models, the simulation examines performance of the agents under different function allocation scenarios. This framework uses the abstraction hierarchy to build the basis of the simulation. Using the abstraction hierarchy enriches the simulation model, helps with consistency and at the same time provides a higher level understanding of the system. However, because there is limited information available on an abstraction hierarchy, the use of decision ladders can help the model to incorporate the information flow in the system, as suggested in CWAS.

In addition to the cognitive modeling, there are different simulation paradigms that can be used for the modeling purpose. These paradigms are known to be discrete-event, system dynamics and agent based modeling. Each of these paradigms is briefly described in

the following subsections. This is the second aspect to consider for simulation modeling in CWAS.

Discrete-event simulation

Discrete-event (DE) systems generally have a top-down modeling approach and are process oriented, where the main focus is modeling the system in detail rather than the entities. In DE simulation the entities (objects) are passive, meaning actions and processes are applied to them and they usually don't have independent behaviors (Siebers, Macal, Garnett, Buxton, & Pidd, 2010). The structure of the environment and tasks is more like a flowchart or transport network, and there are limited resources in the model (Borshchev & Filippov, 2004). DE simulation has been used for a much longer time than agent-based simulation which was introduced in early 1990s (Siebers et al., 2010).. Some of the main tools used for DE simulation are Arena by Rockwell automation (Borshchev & Filippov, 2004), Micro Saint Sharp (MSS) by Alion Corporation, and Enterprise Dynamics (ED) by In Control Simulation Solutions. Micro Saint is most commonly used for simulating and modeling human performance (Angelopoulou, Mykoniatis, & Karwowski, 2015).

This simulation paradigm is prominent in shop floor simulation, manufacturing and health care service (Borshchev & Filippov, 2004; Jun, Jacobson, & Swisher, 1999). DE simulation helps find the bottlenecks in a process and aids in examining different improvement solutions. Similarly, this paradigm can be applied to mental workload to find workload peaks and test improvement solutions in cognitive systems (Keller, 2002).

System dynamics (SD) simulation

System dynamics as defined by its developer, J. Forrester, is "the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification

(in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise" (Forrester, 1958). System Dynamics modeling uses stock and flow diagrams. It has very limited details about the system (highest abstraction) and uses feedback loops (Borshchev & Filippov, 2004). When elements in a system can have feedback to each other or to themselves, e.g., the overall macroeconomic system of a country or an ecosystem. When not looking at individuals but more interested in general trends and flows in the system, SD modeling is an appropriate approach. SD models do not observe individual agents or entities; rather they look at the high level strategic flow of variables in the system. SD models, in contrast to DE, are continues simulations using differential equations the values vary in every given time. This type of simulation has been used in combination with DE simulation in models, DE for the environment events and SD for the continues measures (Pritchett, Lee, & Goldsman, 2000).

Agent-based (AB) modeling

In this type of simulation, the intention is to study individual behaviors. Therefore, the objects are active. There are individual behavior rules for agents, entities have direct or indirect interaction with each other, and the environment reacts to the actions of agents. In such contexts, agent-based simulation is used. With AB similar problems to SD can be modeled, however, the focus of attention is on the individual behavior, whereas in SD the focus is on general trends (Borshchev & Filippov, 2004; Siebers et al., 2010).

Mental Workload Assessment

In order to have a reliable simulation model to represent workload, it is important to use a proper workload assessment method. There are two main categories of workload

measurement techniques: subjective and physiological. The subjective measures are based on the opinion of the participant or an expert. Some of the more frequently used methods are NASA-TLX and VACP.

NASA Task Load Index (TLX)

NASA-TLX is a method developed by NASA to measure human workload in six different constructs (Hart & Staveland, 1988). The index has six main subscales which the participant rates from 0-100. The categories are: mental demand, physical demand, temporal demand, performance, effort, and frustration.

The total workload is the weighted average of all subscales. This method has been widely used in research (Lopez, Gerling, Cary, & Kanak, 2010; Mouzé-Amady, Raufaste, Prade, & Meyer, 2013; Muth, Moss, Rosopa, Salley, & Walker, 2012). However, it is prone to individual biases in evaluation. Although there are standardization techniques to reduce the individual differences, since there are no rubrics available, consistency is not guaranteed.

Visual, Auditory, Cognitive, and Psychomotor (VACP)

Introduced by McCracken and Aldrich (1984) in the US Army Research Lab, VACP divides the sources of workload into these four main resources of cognition: Visual, Auditory, Cognitive, and Psychomotor. For each resource there is a rubric that defines the load between 0-7. The total workload is the summation of the four resources. It is subjective, however, due to the rubric it sticks to a consistent structure for a basis of comparison.

A desirable feature of CWA is its formative structure, enabling analysis of first-of-a-kind systems. For these cases, or where an existing setting of the system is not readily

available to study participants, VACP is a workload assessment method that works well. By knowing the requirements of the task, the workload can be assessed. In the design process this analysis usually takes place before prototyping since the system most likely does not yet exist or is not ready for actual data collection.

In general in with workload measurement we are not as concerned about the exact values of workload, rather we are more interested in the peaks in workload in the process. Therefore using subjective measures has been widely accepted and helpful for analyzing systems. It is also the suggested method for using in CWAS.

Physiological Measures

There are several tools that measure physiological symptoms of humans and try to associate that with workload. The EEG, heart rate, electrodermal activity (EDA), pupliometry, and electro-oculograph (EOG) are examples of these tools (Lean & Shan, 2012; Miller, Rietschel, McDonald, & Hatfield, 2011). There is considerable amount of variation in the signals due to physiological individual differences. Attaching these sensors to participants is not always easy or possible, but sensors are being improved both in accuracy and ease of use. With more frequent use of these sensors, stronger data analysis becomes possible, helping to decode the signals from each tool more accurately.

For workload measures in CWAS, the subjective methods, particularly the VACP method, are a proper fit. However, for using the simulation for further analysis in the system and tool design life-cycle (after prototyping and development) the physiological workload measures can be implemented as well. With the higher amount of physiological data

available, better data analysis can be possible, making the physiological workload

measurement more applicable to the CWAS process at that later stage.

CHAPTER 3 - THE COGNITIVE WORK ANALYSIS AND SIMULATION (CWAS) METHOD

The proposed Cognitive Work Analysis and Simulation (CWAS) method facilitates the use of CWA in system design, improvement, and evaluation by augmenting it with a simulation model. The intention is to transition the formative feature of CWA (independent from agent and event) into the simulation model, making the simulation model flexible for changes in design without significant changes in the modeling program. In this way, the simulation model is not just a representative of the current design or existing system, but rather it is a flexible model of the information flow in the system with which many designs can be tested. This method has two stages with three main steps in each stage, as depicted in Figure 8.
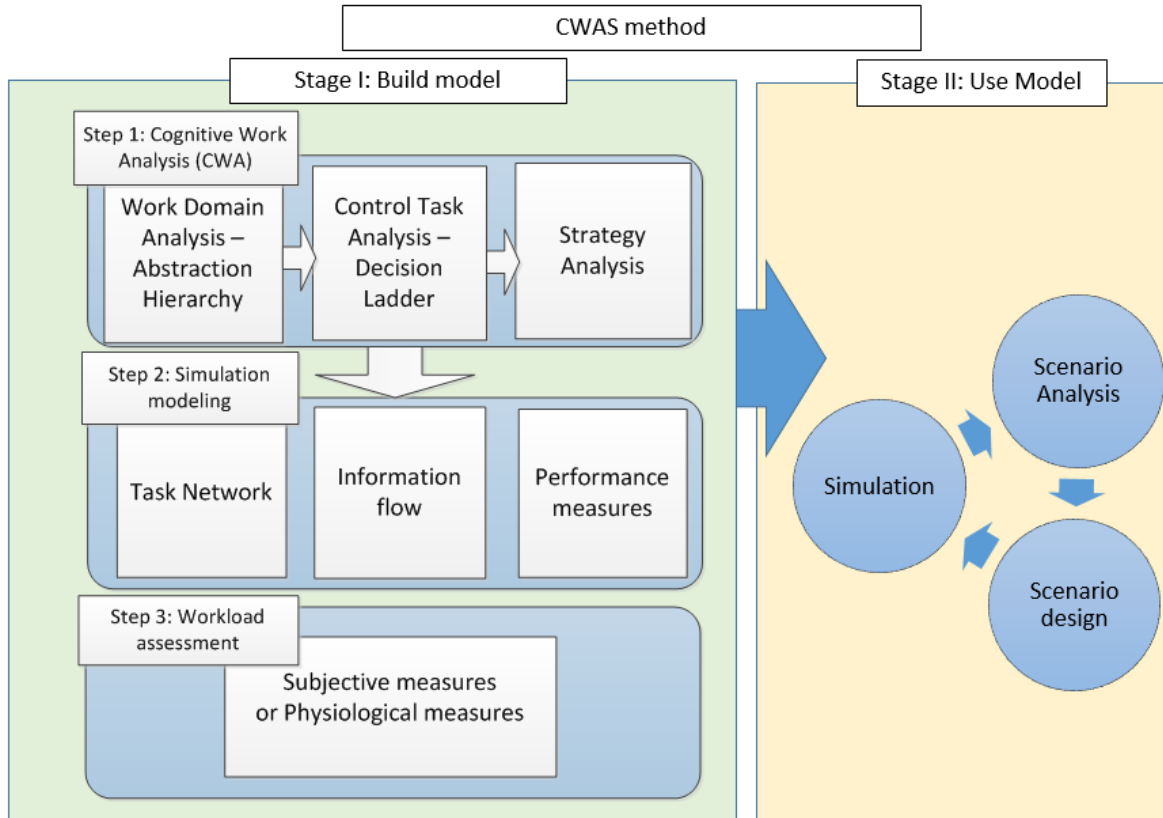
Figure 8- The CWAS method stages and steps. Stage I starts with a CWA as Step 1,and Step 2 takes the analysis and builds a simulation model. In Step 3 the workload assessment happens as all together forms a simulation model of the system. In Stage II all possible

Stage I, system analysis and building the simulation model, encompasses three steps that altogether provide a simulation model. The researcher starts with conducting CWA on the system (Step 1). For CWAS method the first three steps of CWA provide sufficient information for modeling. Although, the final two CWA phases, SOCA and WCA, provide supplementary understanding of the system, they are not necessary for CWAS modeling. For CWAS, there are three outputs needed from CWA: the abstraction hierarchy, the decision ladder, and the strategy analysis chart. In Step 2, or simulation modeling, he uses the CWA results to construct the simulation model. The simulation model represents both the events/actions in the system and the sources of information for the operator. Having defined

the different sources of information, the researcher uses workload assessment methods to collect workload in certain tasks. The assessed workloads are added to the simulation model to have a fully functioning representation of the system with quantitative performance measures. Per CWA, the tasks and information sources are independent of the events and agents, making the model flexible to test several scenarios easily.

Stage II of the method, scenario design and analysis, is where the design scenarios are tested and analyzed. After a comprehensive analysis of the system and modeling in Stage I, it is time to test various design scenarios and analyze the outcome to compare the system performance under each situation. As depicted in Figure 8, this stage is an iterative activity in which the analysis of each design provokes new ideas for a better design until reaching a desirable outcome.

The CWAS method provides a testbed for several design scenarios for a complex socio-technical system prior to prototyping. For example, if there were a limited budget for improving the advanced cardiac life support (ACLS), and there were several proposals for improvement, the CWAS method would provide a holistic and quantitative understanding of the impact of each proposal on the system performance. The quantitative aspect comes from the mental workload of the agents (system operators) and other performance measures defined in the simulation model, such as time, accuracy or success in accomplishing a task.

Since Step 1 is primarily CWA, the rest of this chapter details the Steps 2 and 3 of this method, along with Stage II. The next chapter will present a case study where the CWAS method is implemented.

<div style="text-align:center">Stage I: System analysis and building the simulation model</div>

Step 2: Simulation modeling

The intention in this phase is to represent the CWA analysis findings in a simulation model. First, the proper modeling approach and paradigm needs to be determined from the various simulation modeling choices. The researcher should decide what modeling approach to use based on the nature of the target system. Characteristics of each simulation approach and paradigm were discussed in Chapter 2, and those details can aid in making the simulation choice. Based on the simulation paradigm and approach the researcher can decide what software or programming structure to use for her simulation.

As mentioned above, complex socio technical systems usually encompass safety critical systems that by nature require a more structured set of actions and communication protocols. These protocols limit the variability in agent behavior, and thus the model can be focused on the reactions to the events. Therefore, the discrete-event simulation paradigm is a proper modeling approach for many of these systems. The method and case study presented in this research are based on discrete-event simulation modeling. A simulation model has three major components: the task network, the information flow, and the workload/performance measure.

<u>Task network</u>

The task network is a graphical representation of the actions in the system, which can be depicted as a flowchart or any similar network diagram. The task network is the representation of the tasks and actions in the system, to simulate the events and processes of the system independent of the agents. The tasks in the simulation model come from the physical and general functions defined in the abstraction hierarchy (Step 1 CWA output) that are accomplished to fulfill the system purpose. This idea has been used in function allocation before (Pritchett & Feigh, 2011; Pritchett, 2013).

To have a simulated environment, timing must be added to each task. Timing and data collection is a main part in any discrete-event simulation modeling. The data can be collected by observation of the actions if the system exists or estimated using work and motion studies or similar cases for first-of-a-kind systems. By implementing the task network and timing into the simulation model, the researcher has made a representation of the system. To validate the model, the model results need to be compared with the actual system. Timing of the events is a key factor in validating a simulation. However, depending on the performance measures and nature of the system, the validation criteria might include other factors as well. For instance in an ACLS case, the number of rounds of Cardiopulmonary Resuscitation (CPR) that a patient would receive before reaching a steady state could be another factor. The next step is to add the information sources to map the workload.

<u>Information flow</u>

In order to keep the model flexible for different scenarios, we use the CWA's Decision Ladder (DL) to study the information flow. Based on the decision ladder the information needed for each task is defined. This keeps the information independent from the

information source and information user. This structure allows for changes in information sources (e.g., decision support tools or different information displays) to be easily implemented in the model. In terms of programming, this approach aligns with the notion of object-oriented programming. By defining each source and user of information as objects and assigning attributes to them, the model becomes more generalizable and easily adjustable to different variations of system design. The sources of information are also determined using the DL. In the CWAS method, each piece of information is an object independent of the information source or information user. By adding the information flow to the simulation, we allow the agent collaborations and communications to be studied, thus studying the effect of change in the distribution of information to be studied. For instance, the researcher can study the effect of a shared display presenting critical information to ACLS team members, or different communication protocol in military or sport teams.

For each piece of information the workload is defined based on the provider (source of information) and the information user (receiver of the info). This will keep the information independent of agents, making it easy to substitute different agents in the system without having to change the information flow. For instance, reading heart rhythm from a screen can impose different levels of mental workload for an expert or a novice user.

The level of granularity and object-oriented structure depends on the time and budget scope of the project. The scope defines the degree of variation in test scenarios. The object-oriented approach enables more flexibility but requires more effort. In cases where there are marginal changes to be analyzed, even by using a simpler approach (not necessarily object-oriented) we can make a functional model. The degree of modularity is a tradeoff decision to be made by the researcher. For first-of-a-kind systems or cases where many variations of

system design is going to be tested, more modularity is worth. For studying limited, defined cases of improvement the model could be made simpler only allowing those cases to be tested. However, if the model is going to be used long term, more detail will pay off the modeling effort.

<u>Defining performance measures</u>

In every simulation, it is crucial to define the purpose of the simulation, i.e., what question is to be answered by this model. Knowing the purpose allows the determination of the performance measures. Performance measures are factors in the system that are monitored; the system's performance is assessed on that basis. Knowing what to track in the model and how to incorporate it is an important point to keep in mind while developing a simulation model. In CWAS, mental workload is included as a main performance measure. However, depending on the system and the researcher's choice, other performance measures can be included, e.g., accuracy in task accomplishment or timing of the actions.

Step 3: Workload Assessment

Having defined the information sources, the workloads for each action are evaluated and assigned using workload assessment techniques. As discussed in Chapter 2, a subjective method and particularly VACP is an appropriate method for CWAS. Since usually CWAS happens before prototyping, VACP provides a consistent method for assessing mental workload for different system design scenarios without having to prepare the system for testing with participants.

Workload assessment is based on the tasks, information sources and information users. For each task and source of information, workload needs to be assessed and added to

the model. The workload may vary depending on the user's expertise or familiarity with the task. The subjective measures can be estimated from interviews or observations. After the workloads are collected, the numbers are inserted to the simulation model and it is ready for scenario analysis.

Stage II: Scenario design and analysis

This stage is an iterative process, as shown in the CWAS method graph, and is used to define scenarios, simulate, analyze the results and iterate. The analysis triggers ideas for improvements until reaching a desirable state. In any scenario the workload, the timing of the events, and any system-specific performance measures are evaluated to improve the design, until achieving the best design. Based on the system, there can be an emphasis on reducing the maximum or average workload of team members to reduce the possibilities for error, or it could be used to improve a particular performance measure in the system. For first-of-a-kind systems of function allocation among team members the number of possibilities can get very large with multiple agents and team settings. Simulation optimization techniques can be helpful finding optimal designs.

Scenario design

The main goal of the CWAS analysis is to enable system analysts to study the effect of different design scenarios practically (i.e., to enable a holistic understanding of the system and quantitative actionable data for decision making). In this Step, any improvement proposals for an existing system or design scenarios for a first-of-a-kind system should be clearly defined. It is important to determine the sources of information based on the

information flow (Decision Ladder) in those scenarios and assign their associated workload values. These scenarios range from radical changes, e.g., changing the roles and responsibilities or number of members, or replacing a team member with an intelligent agent to minor changes such as adjusting the information display or adding the use of decision support tools.

Scenarios could influence the model in different ways. When adding new equipment to the process, the mental or psychomotor workload could be affected. Scenarios could involve adjusting for the effect of different levels of expertise among team members. In such cases, the analysts examine the system's performance with varying numbers of novice and expert team members. The results could yield the maximum number of novice team members with which the team would still have an acceptable performance. These scenarios would affect the workload, reaction time and decision making strategies, instead of the flow of information. Another genre of scenarios could be testing the system under crisis situations, e.g., evaluating the team performance when there are a limited number of people or resources in the team or a lack of information.

Running the simulation model

Once the scenarios are ready, it has to be implemented in the model. Once the workload values are added, it is time to run the model for results. Since simulations use random number generation, the results may vary slightly in any iteration. It is a good practice to reiterate the simulation for several times to be able to see several possible outcomes. This approach provides more confidence in data analysis in the next step.

Scenario and data analysis

In this phase the results of the simulation are analyzed. Considering the defined performance measures, every scenario is compared with the desired performance threshold. If the main goal is to reduce maximum workload, or balance the workload of team members, these numbers are collected and compared among different scenarios. Finally, the best alternative is selected. Running the model for several iterations adds the probability of observing extreme cases (worse cases happening all together) and examining system's performance in those cases is valuable to the analysis. Using more simulation data in the analysis leads to stronger conclusions and more confidence in the results. In the next chapter a case study is introduced to show the steps of implementing the CWAS process in action.

CHAPTER 4 - CASE STUDY: IMPLEMENTING THE CWAS METHOD ON THE ACLS PROCESS

To demonstrate the CWAS process, we conducted a case study on the ACLS (Advanced Cardiovascular Life Support) process. ACLS involves a medical team that needs to synchronize and act quickly to make certain decisions in a short time to save a patient from cardiac arrest. The system involves interactions of humans and machines (the monitors and equipment). Dealing with humans' lives brings in the safety criticality, and the variation in cardiac arrest causes and patient situations adds complexity to the system, making the ACLS case a proper representation of a complex socio-technical system, critical enough to undertake a thorough analysis to eliminate all possible sources of human error.

In this study, the ACLS process was analyzed using the CWAS method to find the average workload in the process, and to examine a number of possible improvement scenarios. Team members in ACLS have roles, and the analysis results indicated a high workload for the team Leader and the Recorder role. Two scenarios were developed to evaluate the impact on improvement: 1) adding a portable tablet device, with an app for the Recorder to facilitate the process and share the information with the Leader, and 2) adding a decision support tool for the Leader.

This chapter starts with a brief background of the ACLS process and roles. Next, the CWAS method is implemented, and the stages and steps to analyze the scenarios are described. Finally, the best scenario is suggested.

4.1. Background

Sudden cardiac arrest accounts for over 300,000 deaths every year in the United States. According to heart disease and stroke statistics (2013), the survival rate was about 9.5% for out-of-hospital incidents and 23.9% for in-hospital cardiac arrest. Advanced cardiovascular life support (ACLS) is "a series of team-based, sequential and time constrained interventions, requiring effective communication and coordination of activities that are performed by the care provider team on a patient undergoing cardiac arrest or respiratory failure" (Khanal et al., 2014). This protocol has been widely accepted and implemented in the field of cardiac arrest internationally. An international committee (ILCOR) released the International Guidelines for CPR and ECC in 2000. Considering the criticality of dealing with human lives, it is necessary to make sure correct decisions are made. In the past six decades, many contemporary management techniques have been developed and tested for cardiac arrest (DeBard, 1980). These guidelines were updated in 2005 and again in 2010 (Kalus, S. 2012).

Researchers have actively attempted to determine the parameters that influence survival rates and to make statistical models that predict chance of survival (DeVita, Schaefer, Lutz, Wang, & Dongilli, 2005; Marsch et al., 2004; McEvoy et al., 2014; Rittenberger, Bost, & Menegazzi, 2006; Schneider, Mauer, Diehl, Eberle, & Dick, 1995).. However, according to AHA (the America Heart Association), survival is a factor of how quickly the sequence of actions in the protocol are conducted in the early management of a

cardiac arrest. (Kalus, 2012).Thus, the AHA and most health care providers offer regular training to their personnel, to reinforce correct implementation of ACLS.

Processes

The general process of ACLS is composed of a series of actions in a cyclic pattern (Sinz, Nvarro, & Soderberg, 2011). Once a cardiac arrest is diagnosed, there are several actions to do and decisions to make. There are 2-minute rounds of actions, at the end of every 2-minute team steps aside from the patient for about 10 seconds to observe the vital signs of the patient for diagnosis and actions in the next 2-minute round. In general the ACLS actions are the following steps.

Diagnosis: The process initiates with a diagnosis of a cardiac arrest. A "code blue" is called to get the ACLS team in the room. Once the activity is started, the diagnosis will be a part of each round in the process.

Maintaining the oxygen supply: According to the patient's breathing status and consciousness there are basic and advanced tools that need to be used to achieve this goal. Regardless of the tool, one person needs to take care of the oxygen supply during the entire process.

Maintaining blood flow: In order to maintain the blood flow to critical body organs, cardiopulmonary resuscitation (CPR) is one of the most important parts of the ACLS process. In this action, the CPR provider needs to place her hand in an appropriate position on the patient's chest and give appropriate presses for at least two minutes in each round.

Medications: According to the patient's case, there are a variety of medications that are necessary for the patient's survival. The correct diagnosis and timely injection is another important action in the process. To deliver the medicines to the patient, an intravenous (IV) or intraosseous (IO) access point is established. The IO injection requires a medic or certain training to do this.

Defibrillation: based on the patient's heart rhythm, a sudden strong electric shock (defibrillation) could be helpful to resuscitate the heart activity. In such cases, defibrillation pads should be attached and the defibrillator needs to be set to a certain power.

Roles

The ACLS team is usually comprised of six people, each responsible for a role. However, in reality, one person can conduct more than one role. Therefore, in cases of a shortage, fewer people are also able to function. ACLS can be conducted inside or outside a hospital. In this research we focus on in-hospital ACLS.

Figure 9 illustrates the positioning of team members around a patient in an in-hospital ACLS team. The Leader is in charge of the decisions and assigns roles to members. The process usually starts with a 2-minute CPR, while another person maintains the oxygen supply. At the end of the 2-minute, they stop CPR for a few seconds to observe heart rate activity, and to diagnose the rhythm. After the diagnosis, the CPR is started again for another two minutes. Meanwhile the Leader decides and declares the actions to be done, e.g., deliver shock and give appropriate medication. There is a Recorder role that keeps track of time, medications and actions in the process, and observes team performance. The Recorder declares the end of the 2-minute CPR periods, or rounds.
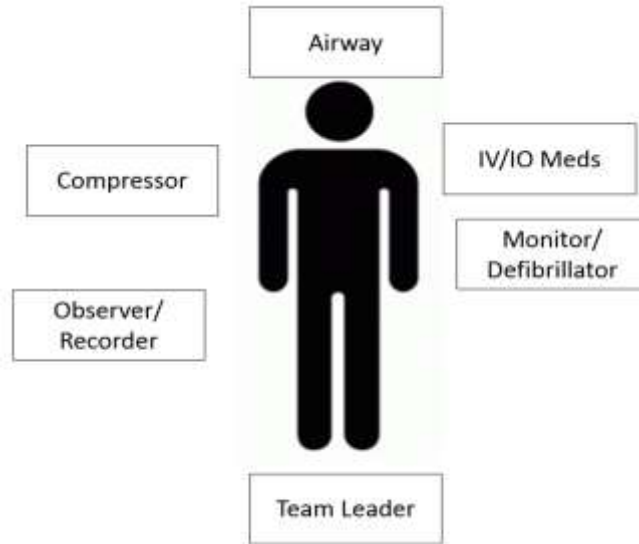
Figure 9 - The in-hospital ACLS team member position in relation to the patient, from Sinz et al. (2011). Team members are named by the equipment or actions they are in charge. The person in charge of compression (CPR) swaps roles with the person in charge of defibrillator to maintain the quality of CPR.

Leader: The leader is the person in charge of making the decisions, assigning roles to team members, and giving members their tasks. The leader needs to be well familiar with the ACLS standard steps, drugs and the causes of a patient's condition that are reversible.

Airway: There is always one person to maintain the airway. This role needs some expertise in being able to insert airway adjuncts (basic or advanced), and give proper breaths to the patient.

Compressor: The person in this role needs to give 2 minutes of CPR with the least possible interruption. It is very important to push hard enough and in the correct position. Since this role is labor intensive, two of the team members usually switch their roles after each 2-minute round.

IV/IO Meds: One person is in charge of the establishing the IV/IO access and delivering the drugs during the process. In case that an IO is needed, rules might require a paramedic or a medic (e.g., according to state regulations).

Monitor and defibrillation: This role is responsible for attaching the patient to the monitor, installing the patches, and defibrillating when needed.

Observer/recorder: Since many of the actions in the process are time dependent, this role is responsible for recording all actions and their times, notifying the Leader and members of certain times, and observing the team members' performance.

Figure 10 depicts the decision process of the team leader and gives the sequence of activities in a typical ACLS process. The process starts with the diagnosis of a cardiac arrest and calling a code. CPR starts from the moment when the ACLS team arrives. From that point on, the process breaks down into a series of 2-minute rounds. In the first round, the team leader assigns the roles. The team attaches the patient to the monitors, maintains the oxygen flow, and starts CPR for 2 minutes. Simultaneously the IV/IO access is established. After the first 2 minutes, they stop the CPR and air and observe the heart activity for about 10 seconds. CPR, Oxygen, and recording are actions that happen during each 2-minute period. In each period, depending on the case, a medicine may need to be injected. In case of a shockable rhythm, defibrillation may also be part of the process. The patient's symptoms can vary from one scenario to another in different rounds of CPR. Amidst all the actions, the Leader needs to focus on the causes of the cardiac arrest to take actions to reverse those causes.
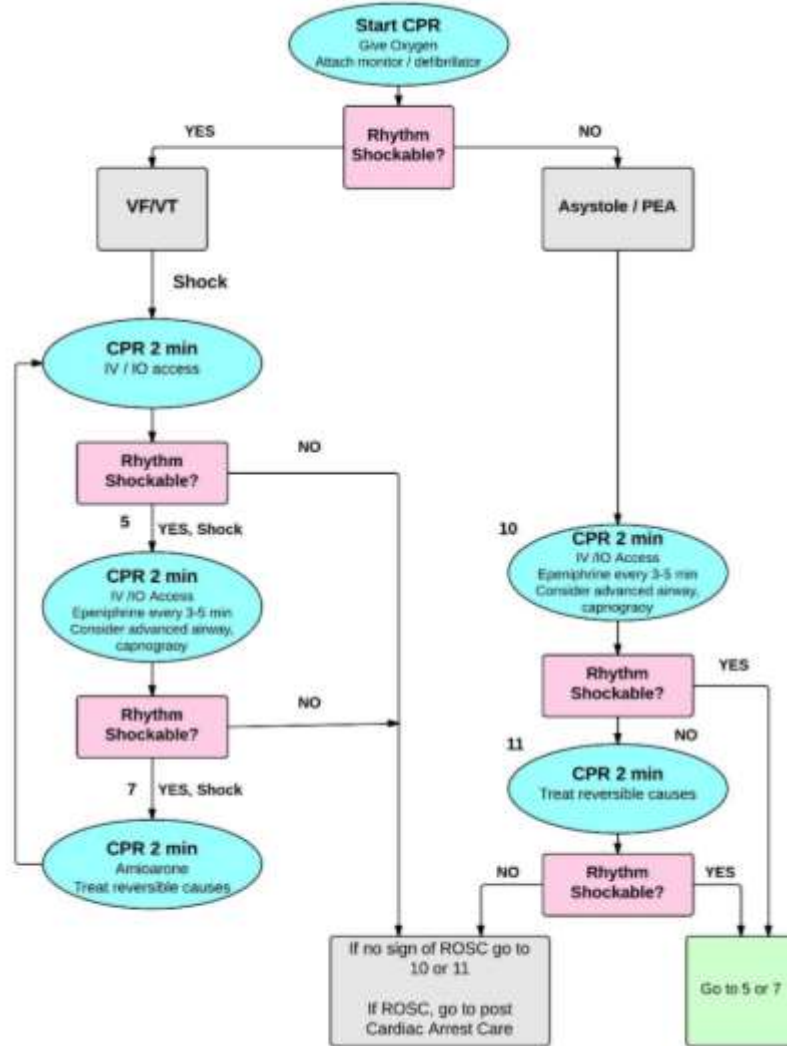
Figure 10 - The ACLS mega code (decision tree), from (Sinz et al., 2011)

Many researchers have studied the ACLS process, both inside and out of the hospital,

to uncover problems and introduce possible remedies (Khanal et al., 2014; Lo et al., 2011;

Marsch et al., 2004; McEvoy et al., 2014; Schneider et al., 1995). After many years of

continuous monitoring and improvement, the main tasks of the ACLS process have almost

reached an optimal state. In fact, the protocol is so well accepted that performance evaluation

is also based on compliance with the protocol. The recent research, however, is mainly

focused on the importance of clear and quality communication, and adherence to the protocol

(Kinney, Boyd, & Simpson, 2004; Marsch et al., 2004; McEvoy et al., 2014). Although there

are required regular ACLS training sessions for health care providers, studies show that even trained personnel are sometimes unable to provide effective resuscitation in proper time (DeVita et al., 2005). According to the roles, the Leader and the Recorder have the most communication, and the Leader has most decisions to make, making them the two team members with highest mental workload. For the Leader, the main concern is diverging from the protocol, an incident that occurs most when there is flawed communication (Mellick & Adams, 2009). Therefore, in this study the intention is to analyze the ACLS team and find proper improvement plans to overcome these challenges.

4.2. Implementing CWAS on the ACLS process

As mentioned, the CWAS method is designed for analyzing complex socio-technical systems such as ACLS. The goal is to use the formative cognitive work analysis results and make a simulation model of the system with which different improvement scenarios can be tested.

The purpose of this case study is to demonstrate the implementation process and the features of CWAS method. Therefore, the relatively structured process of ACLS was selected. As ACLS is already adopted worldwide, there are abundant sources of introduction, from instructional videos to handbooks and pamphlets. The data about the process were collected through using the official handbook of American Heart Association (AHA) and several instructional videos available online (Ali, 2012; American Heart Association, 2010, 2013; Kalus, 2012; Patrawi, 2011). In addition, several research articles helped with understanding the different aspects of the process and the problems that health care personnel face (Marsch et al., 2004; McEvoy et al., 2014; Mellick & Adams, 2009; Rittenberger et al.,

2006). In addition, considering the process is standardized, the timing of every event in the process is well defined. Therefore, using those standard timings and studying the tasks in the process led to a proper understanding of the system for conducting the analysis.

4.2.1. CWAS Stage One

As shown in Figure 8, the first stage is to do the CWA and build a simulation model. The CWA provides the basis for the modeling. It also defines the sources of information, so that in Step 3 the workload assessment can be made for tasks and decision making.

4.2.1.1. Step 1: Cognitive work analysis (CWA)

The very first step in the CWAS process is to conduct the CWA analysis. As mentioned, for most of the modeling purposes the first three components of cognitive work analysis will be sufficient. The CWA analysis of the ACLS is presented in the following subsections.

4.2.1.1.1. Step 1 Part 1: Work Domain Analysis (WDA)

With work domain analysis, the intention is to define the physical and social constraints of the activity. The Abstraction Hierarchy (AH) represented in Figure 11 shows the five levels of abstraction, from the overall functional purpose of the system to the individual components of the system at the lowest level. The different levels of abstraction are explained in detail below.
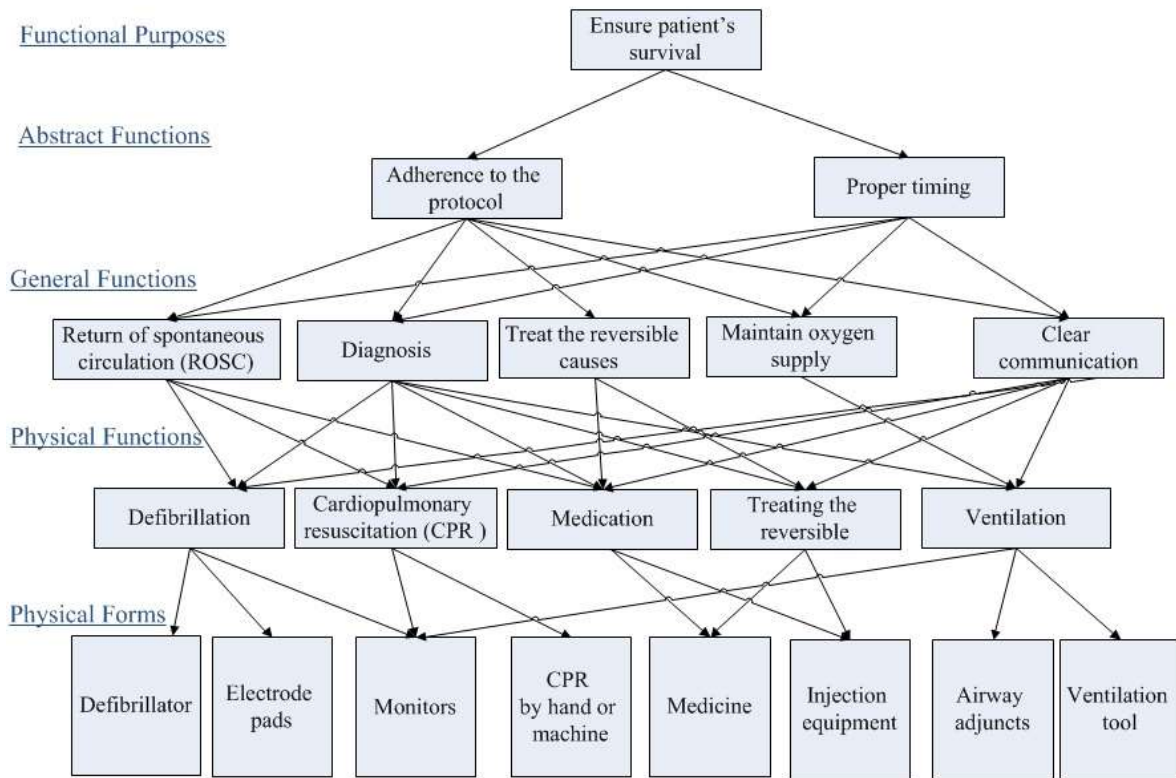
Figure 11 - The Abstraction Hierarchy (AH) of the ACLS process. The five levels of abstraction are depicted to present the system's goals and constraints.

Functional Purpose

The functional purpose or the ultimate goal of the system, is to ensure the patient's survival. This entire team and process has only one purpose, saving the patient from cardiac arrest.

Abstract functions

The abstract goals or the values and priority measures of the system are: adherence to the protocol and proper timing. As mentioned, the ACLS protocol is so validated that the performance of teams is evaluated based on their adherence to the protocol. On the other hand, the first three to five minutes after a cardiac arrest are very important in resuscitation. The proper timing of actions in those few minutes is a crucial factor in evaluation as well.

General functions

General functions or purpose-related functions are the functions of the system that are necessary for achieving the functional purpose defined at the top level. In this system, there are five general functions. Return of spontaneous circulation (ROSC) and maintaining the oxygen supply keep key body organs alive. The diagnosis in the beginning of each round defines the actions to be taken. Treating the reversible causes is to maintain a steady state for the patient once resuscitated. Finally, clear communication and leadership, as noted in the literature cited above, is a critical function when declaring actions (Marsch et al., 2004). For instance, using closed loop communications to make sure each assignee is clear about his or her assignment is particularly helpful.

Physical functions

The physical functions are the main tasks that happen in ACLS. The defibrillation and cardiopulmonary resuscitation (CPR) are to maintain the circulation. The ventilation is to maintain the oxygen supply. The medicine injections treat the reversible causes or help resuscitation. In all of these actions, clear communication between Leader and team members is necessary.

Physical Forms

The lowest level of the AH is the physical forms which represents the resources and tools used to implement the physical functions. The list of those items is noted in Figure 11.

4.2.1.1.2. Step 1 Part 2: Control task analysis (ConTA)

Control task analysis, the second part of CWA, is meant to introduce the information that is required for the main decision processes. As suggested in CWAS, the decision ladder

was used to depict the findings. Figure 12 was created to identify the information required in each step of analysis and decision making for an ACLS Leader.

The rectangular boxes in the DL represent the information processing activities, and the circular nodes are the knowledge state. The decisions to be made in an ACLS are based on the flowchart of decisions in the protocol (Figure 10). The decision making happens in the diagnosis function. The leader collects information from the heart rate monitor, the Recorder and the patient's status and makes a decision. The decision needs to be well communicated to the team members. The left side of the ladder includes the information gathering and observation activities, while the right side represents the planning and executing activities. In studying decision ladders, it is well accepted that shortcuts can happen in processing the information. These shortcuts can be due to an expert or novice difference or due to the highly procedural nature of the task (Roth & Bisantz, 2013; Stanton & Bessell, 2014). Based on our analysis of ACLS and the procedural structure of ACLS we considered some shortcuts in processing the information, meaning some inputs instantly trigger actions (e.g. VT/VF heat rhythm needs defibrillation). These shortcuts are introduced in the next part of the CWAS, strategy analysis.

The decision ladder plays a key role in the CWAS process. Based on the information needed for each task and decision, the sources of information are defined and used in the next step of the CWAS process, building the simulation model.
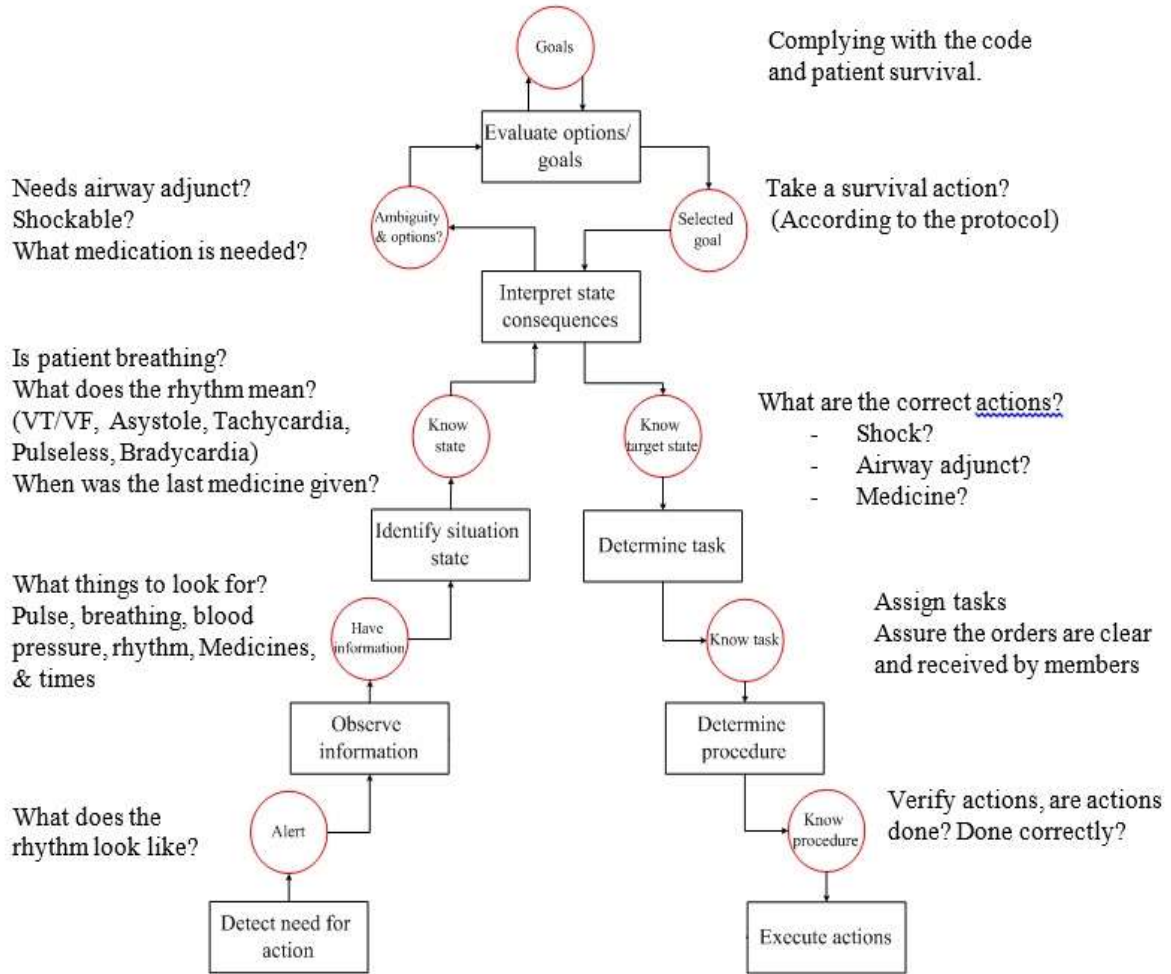
Figure 12 - Decision ladder for the team leader in ACLS process

Figure 13 depicts the flow of information between the Leader and the Recorder in a chained decision ladder. By definition of the roles, the Recorder needs to record every action in the process, therefore, any decision made by the Leader is an input to the Recorder. On the other hand, the Leader asks the Recorder for information on previous medication or patient's general info. These requests are a load to the Recorder and an input to the Leader. The decision ladder plays a significant role in clarifying the flow of information in the system and between team members.
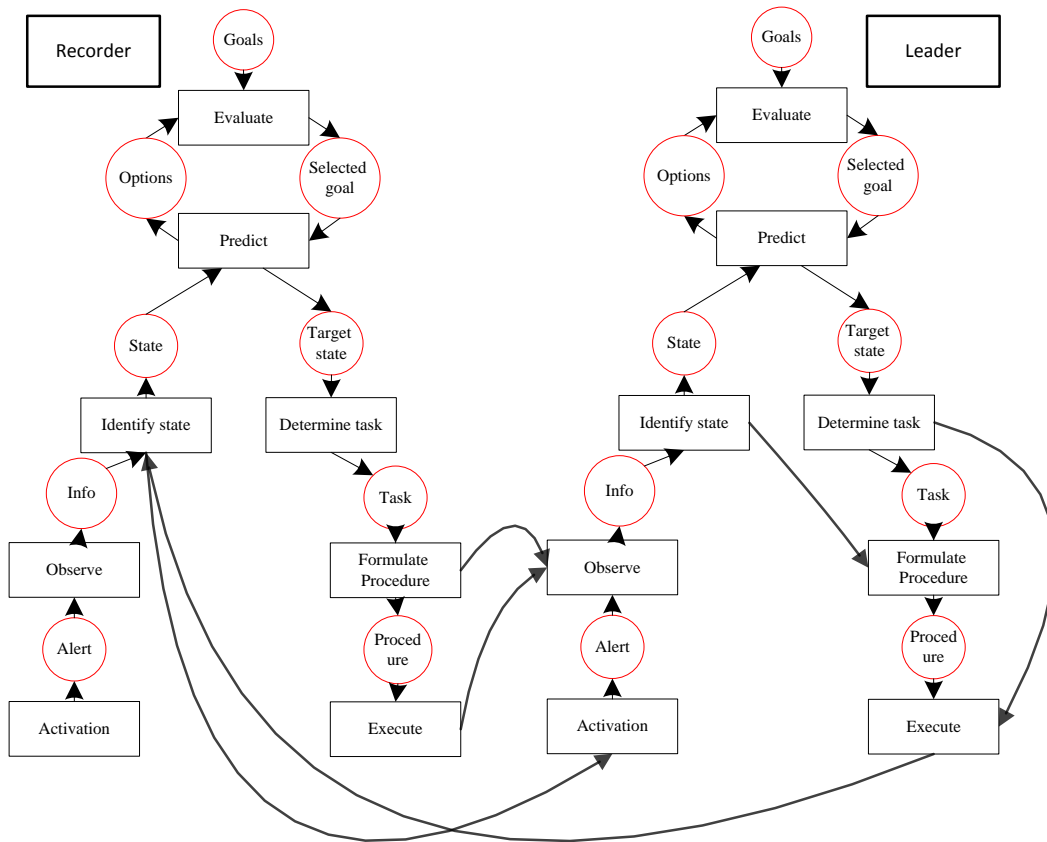
Figure 13 - Team leader and Recorder's chained decision ladder.

4.2.1.1.3. Step 1 Part 3: Strategies analysis (StrA)

In this part we analyze alternative strategies in implementing the same tasks in a system. Considering the highly standardized process of ACLS, the tasks for the Leader cannot be implemented differently. The strategies are in fact the ACLS protocol depicted in Figure 10. However, we can view shortcuts on the decision ladder as slightly different strategies. For instance, more experienced physicians might take shortcuts in the decision ladder. Some possible shortcuts are presented in Figure 14. For example, one could eliminate the upper part of the decision ladder model that relates to goal evaluation due to the single goal in this process as shown in diagram (a) in Figure 14. For more skilled or experienced

leaders, this information flow might be shorter and faster as shown in diagrams (b & c). By

knowing the state of the patient, they could immediately relate that state to the actions

required. They are still following the protocol, but they can immediately relate the symptoms

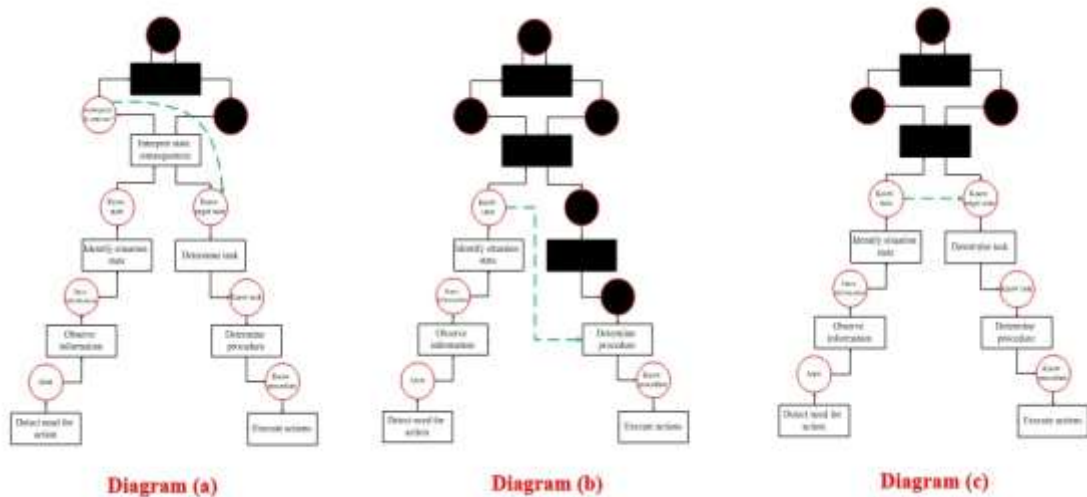to the defined action in the protocol.

Figure 14 – Different strategies in ACLS decision making. Shortcuts in the decision ladder stem from experience. The blocks shaded in black were skipped blocks in that specific decision making process.

With these results, based so far solely on CWA, if we wanted to change the number

of team members, the distribution of roles, or the team design, the formative structure of

CWA would let that happen, but the impact of those changes in the system would not be

apparent by solely using these graphs. Even in less-complicated scenarios like adding a

decision support tool, it is hard to follow the effect of a change on the entire system using the

traditional CWA outputs. This is while, according to Naikar, evaluating system design

proposals is one the expected applications of CWA (Naikar, 2006).

In this case study we specifically want to evaluate the effect of a decision support tool and a communication application for the Leader and Recorder. Thus, we used the CWAS method to analyze these scenarios.

4.2.1.2. Step 2: Simulation modeling

The first decision in a simulation modeling is deciding on the proper simulation paradigm. The ACLS process is a standardized procedure, and therefore the team members are not as flexible in taking actions and do not have much unpredictable behavior. This implies that the objects in the model (the team members) are passive, in that they don't actively react to the environment. On the other hand, the main event in the process is the diagnosis moment based on the patient's status. In this moment the Leader needs to analyze the symptoms and make a decision. The fact that the input from the patient happens at a certain timing interval makes the environment passive to the team as well. In other words, the environment and the team do not actively influence each other, the team receives the patient status as environmental input, and makes actions based on the protocol. On the other hand, the patient has a situation that may or may not be cured by the team actions, making the environment and team members (agents) independent. All these characters make the system a perfect fit for a discrete-event simulation.

There are a variety of tools for discrete-event simulation. In this study we used Micro Saint Sharp (MSS), a product of the Alion Science and Technology Corporation. As noted in Chapter 3, the simulation model has two layers. The first layer is to represent the events (tasks and actions) and the environment of the system. The second one is to implement the workload. The steps of modeling are described as follows.

4.2.1.2.1. Task network

The main actions of the system are derived from the abstraction hierarchy. The general and physical functions provide the list of tasks in the process. In addition, the process flowchart (see Figure 10) was useful defining the tasks. Since the modeling is focused on the Leader and Recorder, the general function (higher level of abstraction) was used for the task network. As depicted in Figure 15, in the initial task network, the detail of the physical actions of team members, e.g., CPR or defibrillation, was not modeled. Instead, the actions are all grouped in blocks representing those tasks.
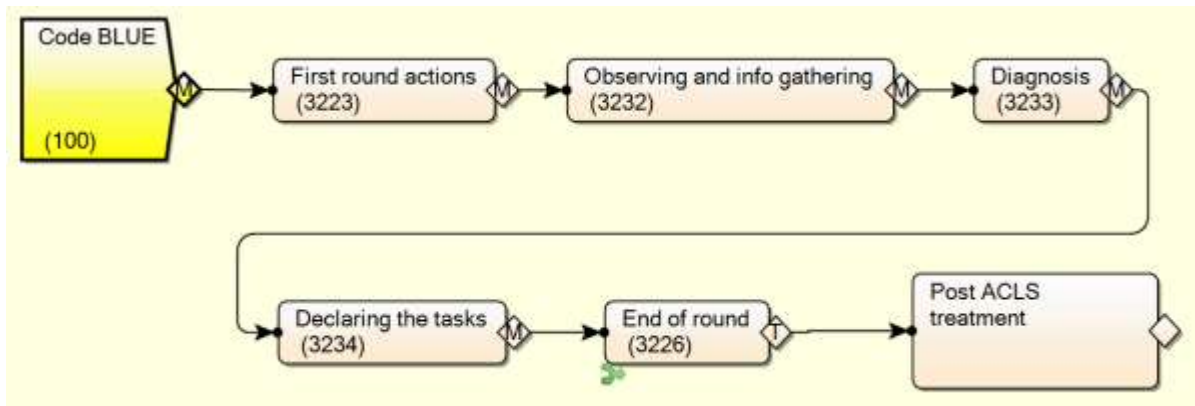

Figure 15 - ACLS task network, based on the Leader perspective. The numbers are assigned by the Micro Saint Sharp tool and do not represent any specific information other than task ID.

The process starts with a code blue, which is an entity generator in the model, generating the patient's scenario. A random number of rounds (between 4 to 6) is assigned to it as an attribute to indicate the number of rounds needed before resuscitation. In this way, we add some variation to the model while retaining what is usually needed before resuscitation. The first round actions are the actions specific to the first round, e.g., CPR and connecting the patient to monitors, etc. The entity (team member) goes to this task block only during the first round. In any other round of CPR, the other tasks are common. First, observation and information gathering, then diagnosis by the leader (a mental activity), and declaring the task

to team members. If the total number of CPR rounds assigned to the entity are met, the patient moves to the "Post ACLS treatment," which is the end of the model.

All of these events have timings according to the protocol. The Observation and info gathering is about 10 ± 2 seconds. In this period all the team members stand aside and check the vital signs of the patient. Each round is two minutes during which team members perform the tasks that the Leader has assigned to them. In the model a normal distribution was used for timing of tasks, the mean being the protocol designated time and a variation added.

Although the modeling approach in this method is focused on the workload of team members, this task network will provide a basis for adding as many team members for the analysis as desired, by including their workload and communications. The task network drives the environment of the simulation. In the next step we demonstrate the way to add individual workloads to the model members. This is part of the flexibility that the CWAS model offers.

4.2.1.2.2. Information flow

Based on the decision ladder, the information needed for making a decision was defined. For each piece of information, a number of attributes were defined: the information source or provider, the information user, and the workload for providing and reading info. Since the only decision maker is the Leader in ACLS, the focus is on the information that Leader needs. To maintain the formative quality of the CWA analysis in the simulation model, the information should be recorded regardless of the source that currently provides the information. For example, in the current system much of the information is provided by the Recorder, but in the model it should be independent. The Recorder will fall in the provider attribute of that information, which will later help define the workload.

An example follows. For coding the information on a previous round's medication, Table 2 gives a schematic representation. For each information source defined in the decision ladder, an object is defined with the list of attributes. These attributes can change and vary based on the testing scenario with minimal adjustments to the model. The modeler much decide how formative and generalizable the model should be based on the number of testing scenarios and the time and budget of the project.

Table 2 - Information flow mapping for the simulation model. By defining the source and user of information in each task, the information flow can be easily tracked in the system.

Previous round of medicine	Source of information
	Information User
	Workload for perceiving
	Workload for reporting

Understanding the information dynamics of the system, the model needs to be adjusted for incorporating the workloads (see Figure 16). The Team leader and Recorder's tasks are marked in the figure. According to the actions occurring in the system, the workload of the Leader and Recorder are adjusted. The workload assessment is discussed in the third part of this step.
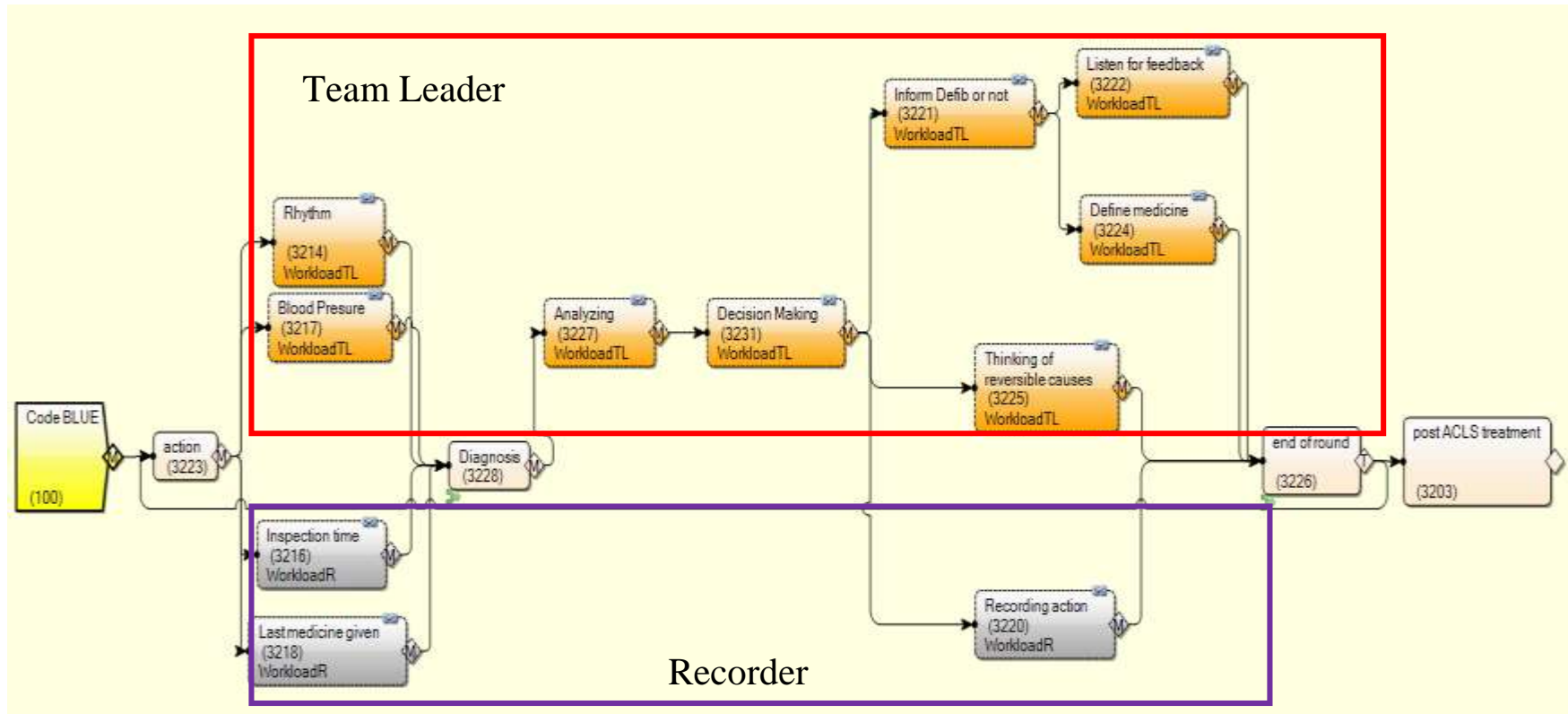
Figure 16 – ACLS task network including the Leader and Recorder workload. The numbers are task IDs assigned by the simulation software and do not contain any important information.
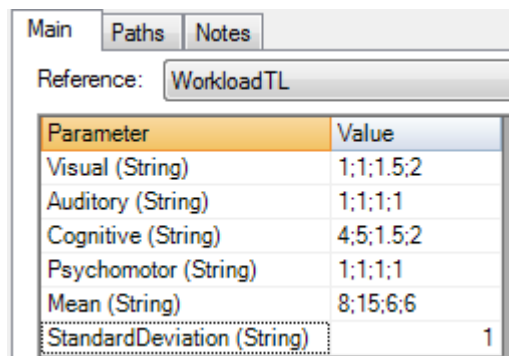
4.2.1.2.3. Workload assessment

For each of tasks on the task network and the information sources and providers, a workload assessment is required. The VACP method (Visual, Auditory, Cognitive, and Psychomotor) (Bierbaum et al., 1987; McCrasken & Aldrich, 1984) was used in this study. For each action and information perception event, the workload for expert and novice was estimated based on our understanding of the process and using the rubric, and was added to the model. For instance, prompting for information from the Recorder or reading it from a shared display, would incur different levels of workload. The basis was

Table 3 - VACP scale descriptor (rubric) from (Bierbaum et al., 1987; McCrasken & Aldrich, 1984). *VACP in this rubric is in a sclae of 0 to 7. Seven is the maximum capacity of that resource (e.g., auditory), the greater the number the more that resource is being consumed.*

	Visual		**Auditory**
0.0	No Visual Activity	0.0	No Auditory Activity
1.0	Visually Register/Detect	1.0	Detect/Register Sound
3.7	Visually Discriminate	2.0	Orient to Sound
4.0	Visually Inspect/Check	4.2	Orient to Sound
5.0	Visually Locate/Align	4.3	Verify Auditory Feedback
5.4	Visually Track/Follow	4.9	Interpret Semantic Content (speech)
5.9	Visually Read (symbol)	6.0	Discriminate Sound Characteristics
7.0	Visually Scan/Search/Monitor	7.0	Interpret Sound

	Cognitive		**Psychomotor**
0.0	No Cognitive Activity	0.0	No Psychomotor Activity
1.0	Automatic (simple association)	1.0	Speech
1.2	Alternative Selection	2.0	2 Discrete Actuation (button, toggle, trigger)
3.7	Sign/Signal Recognition	2.6	Continuous Adjustment (flight/sensor control)
4.6	Evaluation/Judgment (single aspect)	4.6	Manipulative
5.3	Encoding/Decoding, Recall	5.8	Discrete Adjustment (rotary, vertical thumbwheel, lever position)
6.8	Evaluation/Judgment (several aspects)	6.5	Symbolic Production (writing)
7.0	Estimation, Calculation, Conversion	7.0	Serial Discrete Manipulation (keyboard entries)

The workload was implemented in the model using the "Reference Tasks" feature in Micro Saint Sharp. For each action or task, a string of workload values were assigned, and based on the scenario (expert or novice, or communication tool or traditional) the model would select the associated workload. Figure 17 is the workload for the "Analyzing" task for the Leader. There are four possible cases in this model, expert or novice Leader, and using or not using a supportive tool. See the "Scenario design" section below for more detail.

Figure 17- Workload for the analyzing task. There are four numbers for the possible four cases: expert and novice, with or without decision support tool. These numbers are from using the rubric and personal understanding of the process based on interviews and observations. These numbers need further validation before actual analysis.

Before running scenario analyses on the model, validation is required. Since the actions and timing of the model are based on the protocol, the tasks in the system behave as they should in the protocol. This means the model is a proper representative of the process under normal situations. The rubric in VACP (Table 3) provides consistency in workload assessments, making the model less sensitive to individual biases. In addition, in this model the focus is on the workload of the Leader and Recorder, who have very few time consuming actions to take and rather have more cognitively loaded actions. This makes the model less sensitive to the timing of the events and more focused analysis on workload.

4.2.2. Stage II: Scenario design and analysis

The purpose of modeling in Stage I was to enable scenario analysis. In this case study we examined two scenarios where there is a communication tool and a decision support tool suggested to help the Recorder and team Leader to communicate and to offer decision guidance. Analysis of the scenarios indicated the impact of each scenario on the system.

It is worth noting that, CWAS does not guide the design process, rather it facilitates the design process. As mentioned, testing and prototyping is an expensive process, which might result in eliminating a number of design scenarios even before prototyping and testing. However, with CWAS, once the simulation model is built, several design variations can simply be tested and evaluated to ensure that a broader selection of design possibilities is explored.

4.2.2.1. Scenario design

The first step is to design the possible improvement scenarios and assess the change in workloads. In this system, two improvement scenarios were designed.

Scenario I: Recording and communication application

This scenario suggests that a tablet application be designed for the Recorder to facilitate the recording tasks and time keeping. At the same time, a synchronized display will share the recorded information with the Leader. For the Leader, it will present the patient information, such as previous medication, the choice of defibrillation, and symptoms prior to the arrest, as well as the round of work and the previous injection. For the Recorder, the app would have a built-in 2-minute timer so that the Recorder will need only to click on the

actions that occur; times would automatically be recorded. Also, the end of the two minutes

will be notified by an alarm and a red mark on the screen. This application is designed to

reduce the workload of the key team members and facilitate communication. A mocked-up

interface of the recorder app is depicted in Figure 18. A scenario without any new features
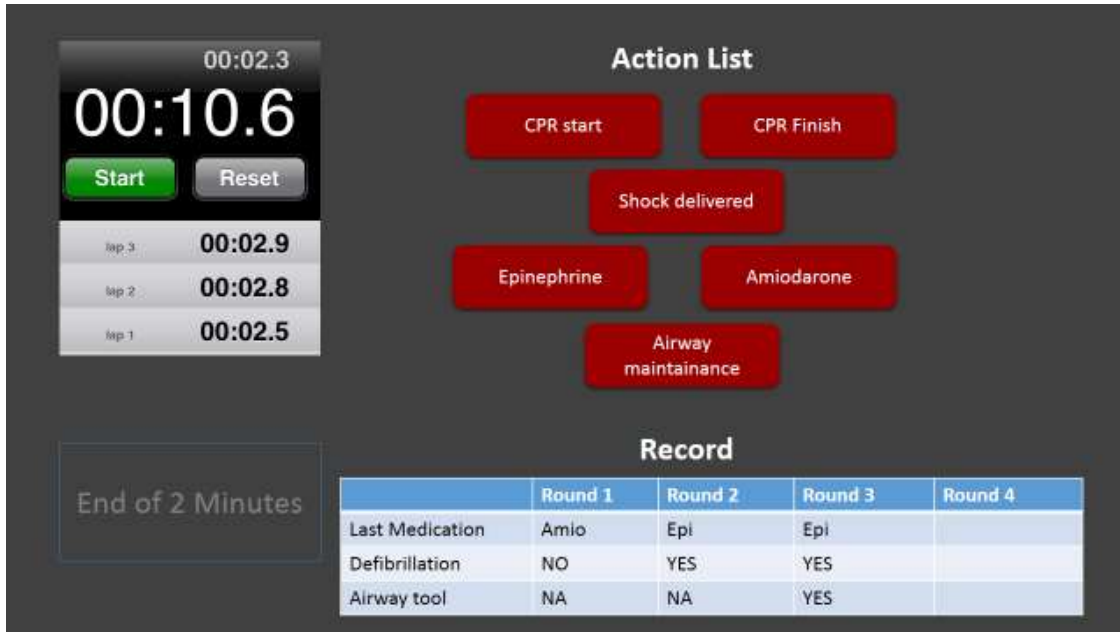
(system as it is) is used as a baseline.

Figure 18 – A mockup of the Recorder's interface of the communication application in Scenario I.

The Recorder in a traditional ACLS system uses a timer and a sheet of paper to record

every event and write the time. Having to write, read time from the timer, and monitor the

events is many tasks to be done simultaneously. To add to this load, the Recorder needs to

declare the end of two minute CPR and also provide the Leader with information on the last

medicine and patient's status. This application will remove the writing and time tracking

effort from the Recorder and, by sharing the info directly with the Leader, will make the

process easier for both team members.

Figure 19, shows the end of two minutes alarm to the Recorder, in which the red rectangle blinks. Also, the information for previous rounds is recorded, so that it can be reported to the Leader readily.

Figure 19 – The end of two minutes alarm to the recorder, which blinks bright red.

Scenario II: Communication application with a decision support tool for the Leader

In this scenario, in addition to the communication and recording tool, there is a decision support tool (DST) helping the Leader to make decision based on the protocol. After each inspection, the tool suggests the possible diagnosis, and the medication needed based on the ACLS protocol. The interface will remain the same for the Recorder. This DST is designed to help Leaders adhere to the protocol, even when highly loaded.

The scenarios are not perfect designs in terms of design principles or ergonomics. They are rather mock up representations of a possible improvement, solely to demonstrate some analysis that CWAS makes possible.

4.2.2.2. Running the simulation model

For each scenario we assessed the workload associated with each information source based on personal understanding of the process, using VACP rubric. In this model, the performance measures were the workload of the Leader and Recorder, therefor these factors will be the basis of scenario analysis. Table 4 presents the workload assessment for the Recorder in Scenario I for expert and novice recorders, as an example.

Table 4 - Recorder's workload assessment for Scenario I (using the recording tool). Workloads assessed using the VACP rubric and personal understanding of the process. The numbers are on a 0-7 scale. The higher the number the more resource consuming the task.

Recording task	Novice		Expert	
	Without tool	With tool	Without tool	With tool
Visual	5.0	2.0	5.0	2.0
Auditory	2.0	1.0	2.0	1.0
Cognitive	2.0	1.2	1.5	1.0
Psychomotor	3.0	2.2	2.6	2.2

According to the rubric and considering the Recorder's task, there is a high visual load for to detect events in the ACLS process, spot the time on a timers, and write it down on the recording sheet. This process was considered visually locate/align in the VACP rubric, assigning 5 to the visual workload. However, with the since the writing and checking the timer is eliminated from the task, the workload was estimated at 2, between visually register and visually discriminate. For Psychomotor, the workload was assessed at 3 for the novice, considering the fact that not fully adopted to the recording process puts the workload between manipulative and continuous adjustment. For an expert, the process is well

established, so it is only continuous adjustment, suggesting 2.6 for workload. Similar

assessments were done for all actions in the model.

      Table 5 represents the workload of Leader in the decision making step of ACLS, with

and without a DST in Scenario II. The main load in this step is the cognitive workload which

is aimed by the DST. For novice team Leaders, decision making is decoding action in the

process and recalling what they associate with in the protocol, making it a 5.3 load according

to VACP rubric. For the expert leader, however, the protocol association is automatic they

need to focus solely on judging the situation, making it a 4.6 workload. The workloads were

assessed similarly for all tasks in the process.

Table 5 - Workload estimates for team Leader in Scenario II

Decision making task - Leader	Novice		Expert	
	Without DST	With DST	Without DST	With DST
Visual	2.0	2.0	1.5	2.0
Auditory	2.0	2.0	2.0	2.0
Cognitive	5.3	1.2	4.6	1.0
Psychomotor	0.0	0.0	0.0	0.0

4.2.2.3. Scenario and data analysis

      I ran the model for each of the two scenarios for 50 iterations and compared the

results. Each iteration in the simulation is initiated with a random number of CRP rounds

(between 4 to 6) before the patient reaches post ACLS status. Each iteration of ACLS resets

everything, meaning there is no fatigue accumulating along the way. In essence, in every

iteration the team is in the same initial state. The average total workload was used as a comparison metric in this work.

Scenario I, the recording and communication application, was expected to help the Recorder more with the average workload. Figure 20 is a sample output of the simulation model, plotting the total workload for both the Leader and Recorder in Scenario I.
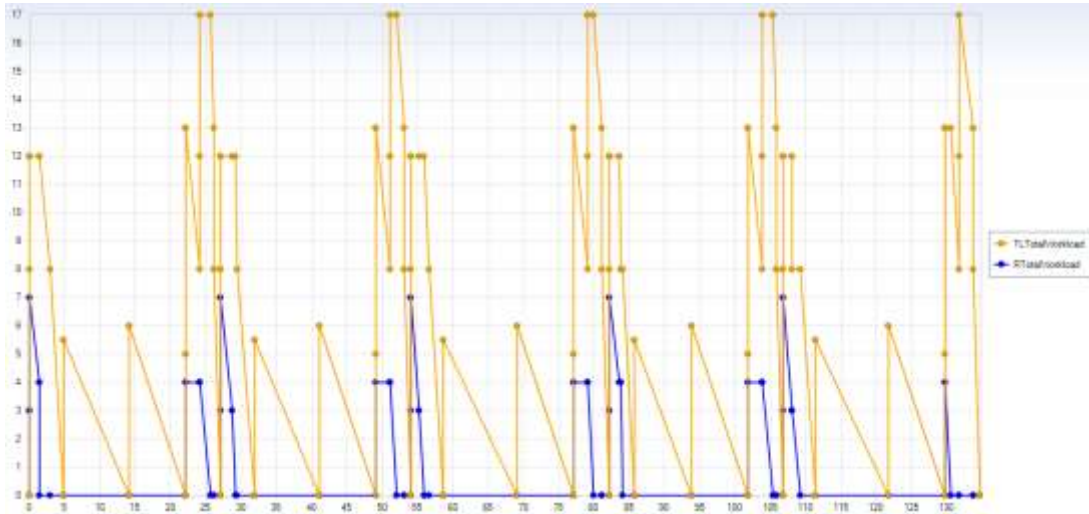

Figure 20 - Sample output of simulation model in Scenario I, depicting the Total workload for the Leader (yellow) and Recorder (blue) in one itertion of ACLS

The variation in the model comes from the randomness in the timing of each action and the random number of CPRs (between 4 to 6 rounds) in each of the 50 rounds of the simulation. As depicted in Figure 21, the average workload for both expert and novice recorders will drop considerably. Table 6 provides detail of the total workload for the recorder.

Table 6 - The Mean and Standard Deviation of total workload in 50 rounds of simulation for Recorder under each scenario. Expert and novice team leaders were considered for each scenario.

	Expert		Novice	
	Mean	SD	Mean	SD

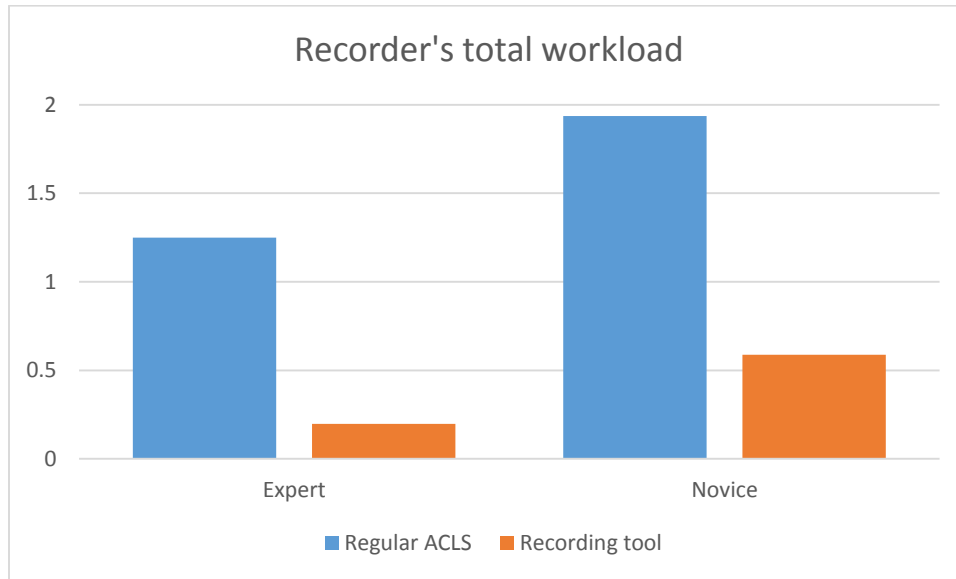| Regular ACLS	1.2	2.6	1.9	3.7
Recording tool	0.2	0.9	0.6	1.6

Figure 21 - The average total workload of the Recorder, with and without the communication and recording application.

For the Leader, the results for all cases were put together in Figure 22. Table 7

provides more detail on the exact values and standard deviation of the total workload in each

scenario. As observed, a novice Leader will benefit both these tools more than an expert

Leader. This matches intuition: since the diagnosis process is a heavier burden for a novice

Leader than for an expert, the decision support tool will help the novice more.

Table 7 - The Mean and Standard Deviation of total workload in 50 rounds of simulation for team Leader under each scenario. Expert and novice team leaders were considered for each scenario.

	Expert		Novice	
	Mean	SD	Mean	SD
Regular ACLS	7.9	3.2	8.4	3.0
Recording tool	7.6	1.9	8.1	3.1

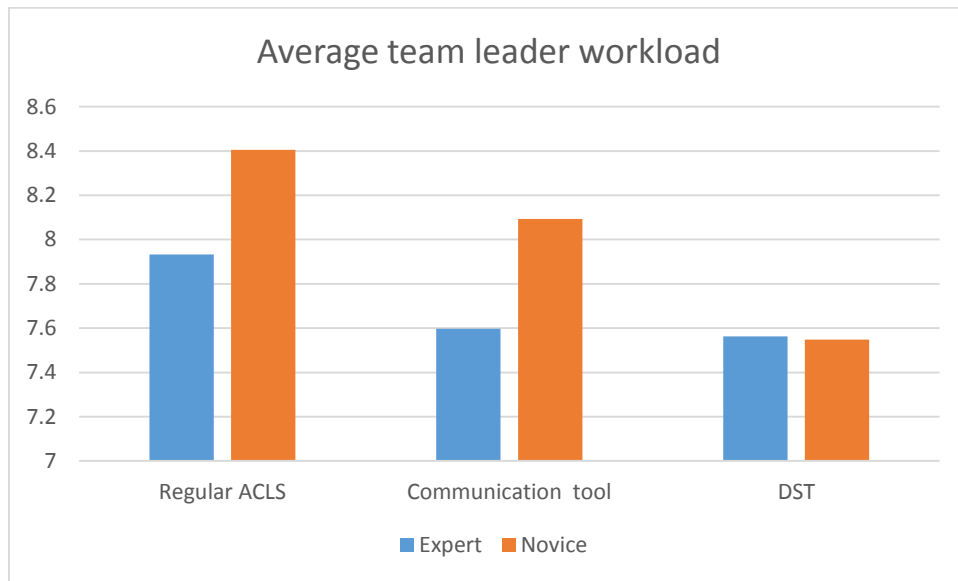| DSS	7.6	2.2	7.4	3.5

Figure 22 - The Leader's average total workload in all scenarios for expert and novice team leaders. No tool, only communication, and DST and communication.

Based on these results we can see the effect of a communication tool and a decision support tool on the system. Based on the outcomes, the scenario of using the communication tool as well as a decision support tool will help both the Leader and Recorder reduce their workload. Lower levels of workload would help reducing the probability of human error.

With CWAS we were able to simulate the process in a model representing the information flow and the associated workload in ACLS team. Having this model allowed us to evaluate the value of the suggested DST. With the simulation model, we took our analytical understanding of the system to make a dynamic representation ready for any test and analysis. In addition, providing quantitative measures for design decisions makes CWA more practical, as presented in CWAS. With this model, various other scenarios, such as different number of team members, using tools for automatic ventilation, defibrillation or

injection can be tested on the system to find the best design option based on the system goals

and budget.

It is worth mentioning that, in these scenario analyses the assumption is the designed

tool or system is well designed and implemented. In CWAS we are testing to what extent a

well-designed DST would improve the workload. Once the DST scenario was selected

among the other alternatives for prototyping, then the user experience principles and human-

in-loop studies are required to assure implementation quality.

CHAPTER 5 - DISCUSSION AND CONCLUSIONS

CWA is meant to help with design and evaluation of complex socio-technical systems. According to Naikar (2006), one of the applications of CWA is to evaluate different system design proposals. However, as discussed throughout this work and indicated within the case study, the outputs of CWA are hard to use in practical design decision making and system performance analysis. Also, gaining a dynamic view of the system performance is difficult with CWA. The ability to change parameters of system design and observe the impact on the target human-machine system is crucial for system design.

In this study, the Cognitive Work Analysis and Simulation (CWAS) method uses standard practices in cognitive simulation and offers an object-oriented approach to transition the formative nature of CWA to a simulation model. With the CWAS method the actual potential of CWA is realized and more practical design analysis is made possible.

To demonstrate the capabilities of CWAS method and the steps of its implementation, a case study was implemented on an Advanced Cardiovascular Life Support (ACLS) process. The case indicated how CWAS adds value to the traditional CWA by providing a holistic understanding of the system, enabling dynamic scenario analysis, and offering quantitative performance measures for design decision making. At the same time, CWA provided a profound basis for constructing the simulation model. In this analysis, based on the workload, we were able to evaluate the effect of two improvement scenarios on the system performance and workload. The type of actionable data that was achieved from the model was not available using the traditional CWA. Although only two scenarios were tested, the model provided a basis for many other alternative scenarios.

Previous CWA analysis research papers, e.g., Stanton and Bessel (2014), could have benefitted adding a simulation model using this method. They thoroughly implemented the CWA method and detailed the system specifications carefully for a submarine return to periscope depth scenario. According to the manuscript they spent at least 87 hours of observation, interview and validation for their system understanding, and perhaps several other hours to analyze the system. To add the simulation steps to the model, the workload estimation would roughly need an additional 15-20 hours and the simulation model would need 35-45 hours of work. Assuming 120 hours the total CWA time, they could have furthered their findings to actionable design decisions using CWAS, adding less than 50 percent of the observation and analysis time.

CWAS Applications

CWAS is meant to be a step before actual prototyping in product and system life cycle. The deep understanding in CWA is combined with a dynamic representation of the general features of the system, making it possible to observe the probable outcomes of certain design scenarios. Since prototyping and human-in-loop testing, typical steps in product development, are usually expensive, companies might make conservative decisions on design scenarios to avoid possible failures. However, CWAS facilitates initial evaluations of higher-risk innovations and radically new designs. With CWAS, there is an opportunity to test very different designs and observe the high level performance of the system under each design scenario, at a very low cost once the model is made. In this way most reasonable scenarios can be tested and a number of them can be shortlisted for prototyping, making the

decision making process more objective while giving the decision makers more confidence in their decisions.

Designers creating first-of-a-kind systems (e.g., a new space shuttle) would benefit simulation modeling most significantly, since for designing a new system there are numerous alternatives in design, the simulation enables examining more possibilities, encourages innovation, and gives researchers confidence in their decision. The structure of the simulation modeling is flexible for implementing alternative scenarios. In addition, for systems that do not exist yet, the use of VACP workload assessment makes the process simple and consistent, while other workload assessment methods (physiological) are not available.

CWAS is also applicable to designing tools to improve existing systems. However, the system needs to be complex enough to require a CWAS analysis, and the prototyping should require enough capital to make this process cost effective. As noted above, the level of generalizability in the model is based on the magnitude of variation in scenarios. This tradeoff implies that when analyzing less complicated systems and scenarios, the model can be made simpler, making CWAS applicable to those systems with a reasonable effort.

It is critical to note that simulation models are only as good as the data and assumptions made (Lacy, 1993), raising the concern of how reliable the resulting models are. In CWAS, we build the model based on a thorough analysis of the system, i.e., CWA, to ensure reasonable assumptions on the model. On the other hand, the inputs and workloads need to be carefully acquired, using best assessment techniques available and expert opinion. Because many of the numbers are rough estimates at this stage, it is critical to conduct a sensitivity analysis to find the level of robustness in the design decision. Taking these steps

into account, simulation models can contribute significantly to the design decision making process.

CWAS does not guide the design process, rather it facilitates the design process. As mentioned, testing and prototyping is an expensive process, which might result in eliminating a number of design scenarios even before prototyping and testing. However, with CWAS, once the simulation model is built, several design variations can simply be tested and evaluated to ensure that a broader selection of design possibilities is explored.

CWAS Implementation

The CWAS method leaves the choice of the simulation modeling approach to the designer. The main purpose of CWAS is to bring the CWA results into design decisions. We suggest applying workload assessment techniques to quantifiable performance measures. The workload modeling is easy to implement, making the additional steps to CWA minimal.

In general, the choice of modeling is a tradeoff between detail and accuracy, along with implementation difficulty. To take the CWA analysis into design decision making, the current CWAS method (i.e., adding simple workload simulation) is a proper solution. This applies to high level, design proposal evaluation before prototyping. In addition, for research that is focused on studying details of human cognitive behavior using simulations, the CWAS method can provide a framework for better structuring their model. Using deep analysis such as CWA for a simulation model will enrich the quality of the model and its findings. For such cases, CWAS can be considered an extension to Pritchett's (2011) simulation framework using abstraction hierarchies. In CWAS, as in abstraction hierarchies, the flow of information is included in the model via decision ladders. Also, providing the strategies that agents may use for accomplishing their tasks will enrich the simulation model. Table 8 represents a brief

illustration of this section to provide researchers with general guidelines in their modeling

choices. Based on the purpose of the study CWAS contribution, and the simulation approach

and paradigm were defined. The next two columns provide a rough estimate of the steps and

skills additional to CWA that are needed. And finally referring to the level of detail and

validation process in each case.

Table 8 - Different implementations of CWAS and their chractiristics. A guideline for CWAS application. This table is a rough characterization of different study approaches.

Purpose of study	CWAS contribution	Simulation approach	Simulation paradigm	# Additional steps to CWA	# Additional skills to CWA	Level of detail	Validation process
CWA - Understanding the system to inform or evaluate design	Providing holistic and dynamic representation of the model, and offering quantitative decision metrics.	Workload / task load simulation	Mainly discrete-event	Medium	Medium	Low (Overall system view)	Simple - Since providing low detail fewer assumptions are made in the modeling process.
Studying human behavior in a complex system	Providing a deep understanding of the system for simulation modeling.	Cognitive behavior or situated cognitive behavior	Agent-based, hybrid	High	High	Medium – High (depending on the model)	Hard – Since usually the behavior functions are based on assumptions of human behavior, the model can be very sensitive to those assumptions. Hard to validate; however, in general provides helpful insight.

Limitations

The CWAS method is based on standard practices in analysis (CWA) and simulation. However, the method has only been tested on a discrete-event system with highly standardized procedures, ACLS. To examine the capabilities and limitations of CWAS, the method needs to be tested more broadly with several systems and simulation approaches and paradigms to find the effectiveness of CWAS in those domains. For instance, testing the method for a spaceship crew, with a system in which there is a higher level of flexibility in human behavior and actions, and also greater variation in the environment, would be an interesting case for examining CWAS.

The suggested structure of CWAS is most appropriate for overall and high-level system understanding rather than detailed individual behavior. This approach makes the implementation easier, however, in that it limits the detail provided by behavior simulation approach. CWAS has tried to limit the additional steps to CWA to make it more affordable for implementation.

Furthermore, in adding simulation and workload estimation to CWA, CWAS does make the process more time consuming and complicated, demanding somewhat different skills—modeling. The available simulation packages do not provide an exact transition tool from CWA to simulation. However, there has been a tool developed for facilitating the CWA process and illustrating the results (Jenkins, Stanton, Walker, & Salmon, 2009). Similarly, there have been simulation engines developed to model cognitive behavior (Pritchett et al., 2011). Having tools that facilitate implementation of CWA in the simulation model will ease CWAS processes.

Finally, CWAS assumes perfect implementation of the design scenario, meaning the system performance is analyzed for having a perfect design in the scenario (e.g., the recording tool, in the ACLS case, has an appropriate interface and functions as expected). However, in action weak implementation might result in different performance outcomes. For instance, if the interface for the recording tool were weakly designed, the frustration caused by poor design can counterbalance the reduction in workload when using the tool. Nonetheless, in the stage of analysis prior to prototyping, this assumption is not unreasonable. The details of design and implementation need to be considered when actual prototyping starts, benefitting user experience techniques and human-in-loop studies.

Future work

To expand the CWAS method, developing a software application that facilitates the process is a necessity. This tool needs to have the main structure of a CWA process and all of its steps, so that researchers can enter the inputs and be able to see the resultant graphs. For example, for a certain activity, all levels of abstraction in functions would be entered as an input, and the system would create the abstraction hierarchy and the abstraction decomposition matrix. At the same time, the physical and general functions would be recorded as objects that could be used in forming the task network. Similarly, with a decision ladder (DL), a default DL could be presented to the researcher as an interface for information input and then depict the final DL once done. The sources of information on the decision ladder should become information objects for the information flow of the simulation model.

This tool, could facilitate both the CWA analysis and the simulation modeling. Automating the illustration of results in CWA would allow researchers to focus on the

analysis and visualize their results in real time. The real time representation could help them find possible errors in the analysis earlier, saving time and enhancing quality. On the other hand, by using the CWA data to form the objects in the simulation, a considerable portion of redundant work is taken away. It will also provide consistency between the analysis and the simulation model. The simulation modeling approach is flexible for any simulation paradigm and approach, so existing simulation software packages or simulation engines could be used for building such a tool.

Another area for further investigation is to examine the effectiveness of CWAS with more systems and scenarios to find strengths and possible gaps in the method. The systems should be selected from different work environments and tasks to ensure that most possibilities are investigated. Additionally, the CWAS method was only tested for a discrete-event simulation model in this case study. Adding an example of agent-based simulation is required to showcase the performance of CWAS in that area.

Finally, the choice of simulation modeling in CWAS is based on the researcher's discretion. After several cases have been studied using CWAS by different simulation approaches, the best practices in each approach can be collected to form a clearer guide for all researchers who want to use the CWAS method.

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