Assessment Methodology for Air Defence Control Systems

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Abstract

In Command and Control, humans have to make sense of the situation to support decision making on the required action. Development of an Air Defence Control system through a Systems Engineering process starts with assessment of existing systems to determine its ability to support operations within the modern and complex combat environment. This leads to further assessment of concepts with new technology, structures and process to solve the perceived problems. This process is difficult as Command and Control is a sociotechnical system where the human, process, structure and technical system, must be exercised in unison within a complex operational environment. This paper highlights the requirements of Command and Control system analysis and experimentation to propose an approach that considers the cognitive and social attributes of the human with the dynamic complexity of the operation environment. The importance of this approach increases within the Southern African Development Community (SADC) environment with different cultures and operational doctrines.

Introduction

Air Defence (AD) Control is part of the Ground Based Air Defence System (GBADS) and is used to ensure safe and effective defence of Vulnerable Points against air attack during operations. The AD Control system is in essence a Command and Control (C2) system that has to make sense of complex situations and manage the risks during the execution of AD Control. Complexity arises from uncertainty, risk and time pressure as a result of opposing forces influencing successful execution of plans and orders.

A C2 system is a sociotechnical system as it is composed of personnel, organisational structures, work procedures and technical equipment [1]. Despite a complex sociotechnical system being difficult to analyse and design, the agility to survive in hostile environments may be improved. During analysis of C2 systems, the human operators have to be considered along with all the supporting technical artefacts. However, human performance is complex and difficult to predict and system performance is highly dependent on the context and environment of the task.

The modern System Engineering (SE) trend is to apply modelling to capture the different views and world views on the system and its environment. These have to include the cognitive and social aspects of humans within a complex sociotechnical setting. Improving the success of the SE approach requires rigorous assessment of the problem and solution concepts to capture requirements. These have to support the design of a complex sociotechnical system that will have agility to handle real-life complex situations in a dynamic environment. Where C2 systems have to operate across cultural and doctrinal boundaries, such as during joint operations with SADC, complexity is further increased.

Humans use artefacts, consisting of technical systems and processes, to perform work in pursuit of the system objectives. In C2 this work can be summarised as sense making of operational situations to enable decision making on the appropriate action to take. Analysis of a C2 system has to focus on how humans apply artefacts in the work they perform. Constructs produced by a Cognitive Work Analysis (CWA) capture the complex technical, human, cognitive and contextual information that represent the sociotechnical system.

Since C2 is an iterative and cyclic process with inherent delays in nearly all the steps, dynamic complexity is introduced into the system. A System Dynamics (SD) modelling and simulation approach takes the structure of the system model to understand the possible dynamic and complex system behaviour. Knowledge of the expected C2 system's behaviour can in turn then support the generation of Measures of Effectiveness (MOE).

The analysis of the problem and the possible solution design concepts are performed through a series of experiments. Application of the Scientific Method demands planning of experiments with rigour and validity which requires a hypothesis and associated MOE. The hypothesis defines the cause of problem or impact of a new solution concept on a problem to produce an effect which needs to be identifiable and measurable. Within C2, hypothesis formulation and MOE identification can be supported through SD modelling and simulation with the constructs from CWA. The SD simulation can support testing of the MOE as well as predicting the effect of the cause (hypothesis).

Command and Control Principles

C2 is an iterative and cyclic process that requires continuous updating of decisions to adapt to a changing situation [2]. C2 consists of making sense of complex situations and manage the risks during the execution of AD Control. Participants require awareness of what has happened, what is happening, and what may happen in the near future. Feedback of actions and information from sensors or other assets support the control function.

The C2 system consists of equipment and people organised in a structure to execute tasks [3]. A basic C2 system utilises technical support systems consisting of assets (effectors), sensors, communications, decision support and situation awareness displays. Sensors consist of all the elements deployed in the environment to collect data, consisting of radars, optical sensors, organic sensors of the effectors, and other information sources (including human intelligence). The effectors execute orders received through the C2 system. Feedback on progress and execution of orders (also information) is fed back into the system for control.

The communication system is the transport medium for data between the sensors, command centre, and effectors. It is important to note the impact of delays and capacity (latency and bandwidth) on information transportation. The process of decision making, in an environment with inherent risks and delays, results in a complex dynamic system. Management of this complex dynamic system requires careful modelling to understand all the implications [4].

Making sense of all the information available is very difficult with structures and processes developed for industrial age war [5]. C2 cannot be an automated function of a “C2 Machine” as it is impossible to identify all possible permutations and combinations to develop an algorithm [6]. C2 will always require human interpretation to make sense of complex situations. The cognitive and social aspects increase the complexity in operation for the C2 system. This makes it impossible to correctly predict the outcome of every situation as people often interpret information differently, highlighting the importance to support the human functions within the C2 system.

Command and Control as Complex Sociotechnical System

C2 system can be described as a Complex Sociotechnical System, making it difficult to analyse and design. The environment of military operations is complex as the opposing forces influence successful execution of plans. According to Ashby’s Law of Requisite Variety, to control combat as a system the variety of states within combat itself must be similar to the controller of the combat system [7]. Because combat represents a complex system, the C2 system also has to be complex. The sources of C2 complexity are uncertainty of information, risk of fratricide or wrong action and time pressure. The C2 system must continue functioning under these adverse circumstances to enable the solving of complex problems to ensure the success of military operations. C2 requires agility, which is the capability to cope with changes in the situation or environment through responsiveness, versatility, flexibility, resilience, innovativeness and adaptability [8].

A C2 system is a sociotechnical system as it is composed of personnel, organisational structures, work procedures and technical equipment [1], as seen in Figure 1. During analysis of C2 systems, the human operators have to be considered along with all the supporting technical artefacts. C2 system performance is highly dependent on the context and environment of the task (mission) being performed. Different human decision makers in the hierarchy may have different levels of responsibility, decision cycles, timelines, agendas, culture and methods of decision making [9].

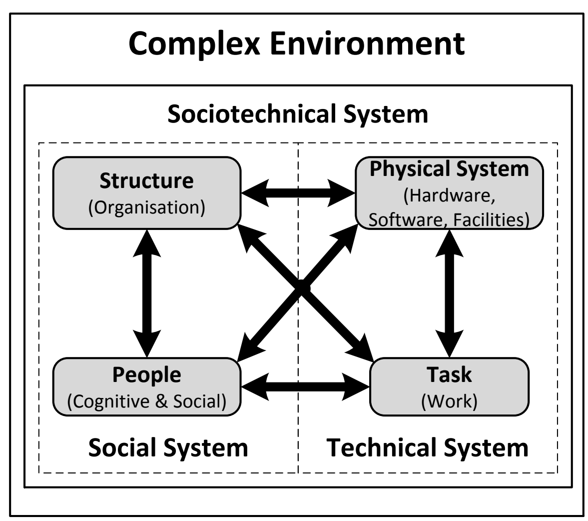

Figure 1. Complex Sociotechnical System

Classic SE approaches, which see the human as outside of the system, may not be suited anymore [10]. The cognitive and social aspects of humans have to be considered within a complex sociotechnical design approach. The ability of humans to be agile flexible has to be utilised in the C2 system design. CWA and SD will be useful in development or improvement of C2 systems through understanding requirements of the C2 system to support agility in dynamic and complex operational environments.

When analysing or designing a C2 system, it is useful to consider all three levels of design: Purpose, Function and Form [6]. These levels relate to the means-to-ends relationships of why, what and how. Understanding the purpose (what is required to be achieved), as well as how the system achieves its purpose in a given case, is the key to understanding and developing C2 [3].

Air Defence Control

The aim of AD Control is to defend own assets against air attack through optimisation of AD firepower as well as preventing fratricide or collateral damage. AD Control is a special case of the basic C2 process and system discussed above. The time pressure, execution risk and uncertainty in AD Control are higher than most other military applications of C2. Successful AD Control is highly dependent on human and machine interaction in order to make sense of imperfect information within a very short time period.

It is crucial to support the AD Control operator in decisions concerning the identification and hostility of aircraft. Having multiple nodes and command centres operating on the same AD network also adds a social consideration. Developing AD Control systems requires rigorous assessment or the problem and experimentation with different solution concepts. This has to be performed within the sociotechnical context where the impact of humans, technical systems, tasks and organisational structures have to be considered.

Experimentation Theory

The word “Experiment” derives from the Latin word “Experimentum” which means a test or a trial. The Webster’s Dictionary defines it as “any action or process undertaken to discover something not yet known or to demonstrate something known” [11]. This requires a “scientific method” based on systematic process of observation, experimentation and analysis. The aim of experimentation is to grow the current body of knowledge and to enable the development of new capabilities.

The main difference between experimentation and other research methods is that something manipulated to see what happens [12]. This needs to take place under controlled conditions with precise measurements, which requires a scientific method based approach. The scientific method can be applied in capability development and experimentation, as seen in Figure 2.

During the Discovery phase problems and future requirements need to be clarified using operational lessons learned, war-games and other sources. The output is an initial concept to propose solutions in the form of a hypothesis. The Experiment phase consists of designing and conducting the experiment as well as analysis of the data. The Evaluation phase compares the results to the hypothesis to identify gaps that still exist. This step also ensures that the lessons learnt are captured and implemented.

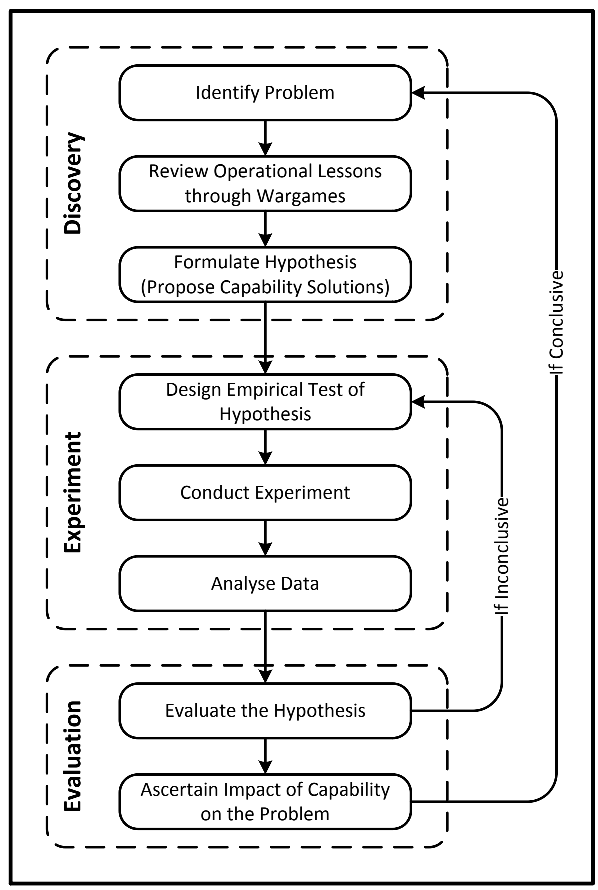

Figure 2. Scientific Method

Control in the experiment is required to isolate elements that might influence the results. This is not so easily achieved in the social domain to eliminate biases. A valid experiment requires support for its conclusions and eliminating the things that will place doubt on it. Experiment validity implies a thorough experiment design to provide sufficient evidence to make a conclusion about the truth or falsity of the causal relationship between the manipulated variable and its effect. This highlights the issue of “Cause and Effect” which is central to constructing an experiment hypothesis.

Experiments require credible results to be of value for decision makers. Rigour implies experiment validity, meaning the ability of the experiment to connect cause and effect. Internal Validity is achieved when a new artefact is applied to cause a required effect where the cause precedes the effect, the observed effect can be related to the cause and the cause is the only plausible explanation for the effect. External Validity is achieved if the results of the experiment have utility in the real world. An experiment fails when no sufficient evidence exist to determine whether the manipulated variable caused the effect. The experimenter must be aware of the threats to the validity and make conscious compromises to have success. General guidelines for a successful experiment are:

- Developing a solid hypothesis.
- The new capability under test must be stable and performs as advertised.
- The participants and users have to be adequately prepared to use the new capability.
- Take care that the experiment measures are sensitive to new capability impact to be consistently and accurately measured.
- Conditions must not fluctuate within a trial.
- The experiment scenarios must be realistic with acceptable sample size.

Measures of Effectiveness and Measurements

MOEs measure how well a system performs its higher-level functions within a given operational environment. However, for complex sociotechnical systems, such as C2 systems, defining the relevant MOEs is a difficult task as they cannot be isolated from the environment [13, 14, 15]. They are often integrated within a higher order system to support a mission. Therefore, the MOEs of the C2 system are integrated into the MOEs of the parent system. Within military systems synergy, and other emergent properties, are often required between commanders and different force elements for a successful mission execution. A possible solution is to turn to the behavioural or “soft” sciences for methods to derive useful and representative MOEs.

MOEs refer to the effectiveness of the C2 system, regardless of how it is physically implemented. MOEs first identify the required properties of a system in a top-down approach. This is kick-started through a study of the mission, doctrine and operational concept of the system under consideration. The focus should be on the aspects that will promote good and timeous decisions for mission success. The focus should not be on the decisions themselves or a model of the C2 system. These normally involve cognitive aspects of humans that are almost impossible to measure. These elements should be present in the products of a CWA, specifically the Work Domain Analysis, which is discussed later. The following are typical MOEs for C2 systems [13, 16]:

- Quality and age of Information.
- Relevance of Information in Situation Picture.
- Understanding and Perceptions of the Battlespace.
- Speed and quality of Decision Process.
- Quality in Decisions.

Air Defence Control Experimentation

The aim of this section is to propose an approach for complex sociotechnical system assessment suited for the AD Control environment. This approach will be useful for the development of a Human Machine Interface (HMI) that supports threat identification and evaluation. Here the support of human cognitive ability needs to harnessed in coping with complexity from time pressure, information uncertainty and execution risk. As this is a sociotechnical system, the way work is performed under different situations also affect the success of the system. To this end experimentation is required to assess the ability of the system to satisfy the objectives of the overarching system.

To this end, the Scientific Method needs to be expanded to indicate the role of supporting methods and tools in the experimentation process, as seen in Figure 3. The two main methods presented to augment the experimentation process are the CWA and SD modelling and simulation.

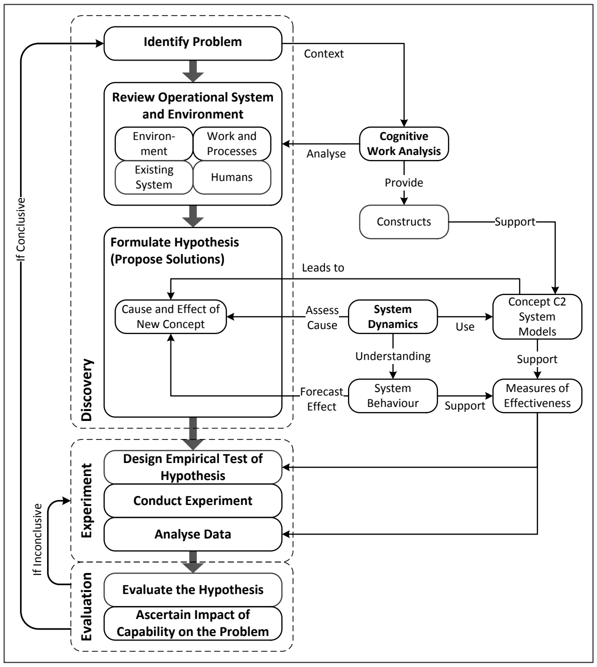

Figure 3. Experimentation Method

Cognitive Work Analysis

One approach to the development of C2 systems is the CWA framework, which is steadily gaining momentum in this field. CWA was developed to assist in the analysis, design and evaluation of large-scale sociotechnical and complex systems where people can, and have to, adapt to changes in the environment. The theoretical roots for CWA are in Systems Thinking, Adaptive Control Systems and Ecological Psychology. It also addresses the cognitive strategies and competencies employed in the sense making and decision making process. Despite constraints of the environment a variety of work patterns may be possible to solve unexpected problems and situations. These are applied to define the information display and data distribution requirements [17, 18, 19, 20, 21, 22, 23].

CWA develops formative (how work can be done) designs for decision support systems. This is contrasted to normative models (how the system should behave) and descriptive models (how the system is actually behaving) [23]. It considers the ecological constraints that may shape the execution of tasks as well as the cognitive approaches of the users of the system [17]. The products of CWA support the definition of required information content as well as the applicable context where it will be used. CWA addresses the design of the human capabilities into the operation of the total system [24].

The designer of the cognitive system requires an understanding of the functional structure of the enterprise under consideration; what the operator must do and how the environmental constraints impact on it. The CWA framework uses the Work Domain Analysis (WDA) with an Abstraction Decomposition Space (ADS) to organise and present information and knowledge about a system from Subject Matter Experts (SME) and other sources. The ADS identify and model the goals and purposes of the cognitive system in relation to the ecological constraints to provide reasoning space about the environment. It is useful in identifying relationships between work (functions) and the physical systems that they are dependent on. This is required where systems, the environment, and their interaction are dynamic with many possible instantiations (many-to-many relationships). These means-to-ends relationships are used to guide possible problem solving strategies. With WDA being event-independent, the categories of constraints identified are applicable to the many scenarios [22].

In the ADS, the constraints related to the purpose define the values and priorities of the work to be performed while the physical constraints determine the physical objects, with their functional capabilities and limitations. As a whole, this defines the problem and possible solution space for the workers. The abstraction dimension integrates a global, top-down view related to the human operators trying to achieve the purposes of the system, with the bottom-up view of physical resources. This links to the discussion on the design of a system applying a Purpose-Function-Form relationship. These means-to-ends relationships are used to assess the propagation of effects of decisions and actions throughout the system on the fulfilment of the intended purpose The presence of many-to-many relationships indicates the multiple options for action in order to achieve the objectives of a system as well as multiple functions requiring the same means of physical objects. It also highlights the multiple intended or unintended side effects from decisions and actions [22].

An example for a WDA for AD Control is shown in Figure 4. From the diagram the Physical objects are related to the Purpose Related Functions through the Object Related Functions. It is clear that any of the functions require multiple Physical objects and *vice versa*.

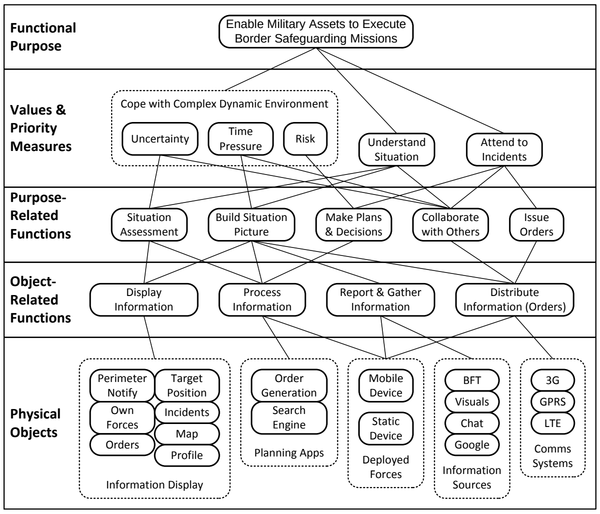

Figure 4. WDA for AD Control

Despite the value of the information from the CWA for understanding the structure of the C2 system, it still doesn't provide information on the dynamic behaviour of the system in the operational environment. The SD approach can be used to model the system for simulating the effect of different parameters on the behaviour of the system. The SD approach will be presented in the next section.

System Dynamics

The concept of SD was developed during the 1950s and 1960s at MIT to investigate feedback in social systems through systems thinking [25]. The different modes of behaviour as a result of high-order nonlinear systems were related to complex problems in management and economic decision making [4, 26].

SD can be used to support the high level assessment of C2 systems in terms of volume and timing of information to understand the social and technical interaction in a dynamic environment [28]. SD explores what would happen in a system in different scenarios and not necessarily to predict the future behaviour of a system. The aim is to learn about possible behaviour of the system. Therefore, the validity of a model is not reliant on how realistic the driving scenarios are, but whether the system responds with a behaviour represented by realistic patterns [29]. Feedback is a major cause of the complexity in a system. Dynamic complexity may exist in simple systems due to nonlinear or complex interactions between the agents or components over time. The complexity within the components has a smaller contribution than the interaction between them. The delays in sense making, decision making planning and implementation of orders compound the effect of dynamic complexity. This makes controlled experiments difficult and expensive instability may also lead to oscillation in the system [4].

The behaviour of a system is defined as its observed behaviour over time in terms of growth, decline, oscillation, randomness and evolution. The structure of a system consists of its stocks, flows and feedback loops that are interlocked. Behaviour is as a result of the structure of the system and can be assessed through analysing a series of events. When behaviour is viewed over a relatively long time, the underlying system structure will be better understood [29]. The feedback present in dynamic systems can be positive or negative. Positive feedback causes self-reinforcing or amplification to generate growth within the system. The result of negative feedback is self-correcting and counteracts or opposes change to be self-limiting in the support of balance and equilibrium within the system. SD utilises Causal Loop Diagram (CLD) and Stock and flow diagrams to model and support simulation of complex systems [4, 27].

A CLD is used to represent the feedback structure of the dynamic system, as seen in Figure 5. CLDs consist of variables in the system being connected by arrows to show their causal influences and relationships. It is important to identify the delays in each loop as they are critical in creating dynamics, causing inertia in the system that may lead to oscillations. Stock and flow diagrams, as seen in Figure 6, are required to show the structures that represent the physical processes, delays and stocks that are related to the dynamic behaviour in the system. Stocks are accumulations of resources, things that can be counted in the system, that are of importance in the model. Stocks and flows are investigated over time to understand the complex dynamic behaviour of a system. It also serves as the inertia and memory of the system. Stocks change over time through flow of elements through the system.

Since mental models are incomplete and without parameters, functional forms, external inputs and initial conditions, some form of simulation is required. Simulation supports the understanding and development of mental models. Simulation is required to assist people to assess the effect of feedback loops.

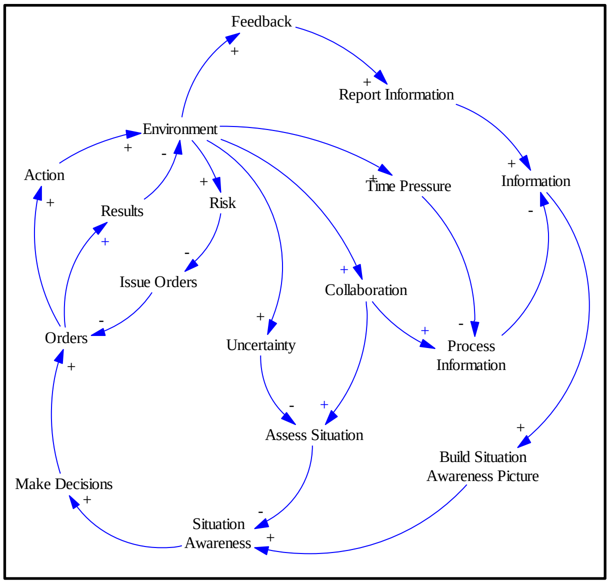

Figure 5. Example of Causal Loop Diagram

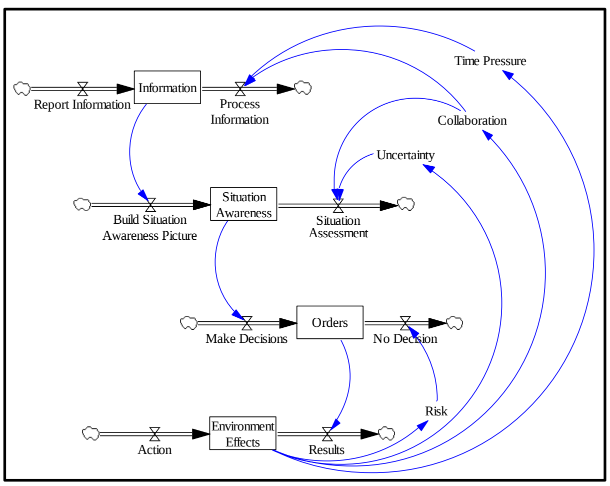

Figure 6. Stock and Flow Diagram

Virtual worlds are used as low cost laboratories to exercise decision making skills, conduct experiments and test assumptions in compressed or diluted time. The same actions can be repeated under different conditions through controlled experiments. However, a disciplined scientific process must be applied to support effective learning and prevent typical simulation pitfalls [4].

Simulation helps to identify weak assumptions and concepts as well as resolve contradictions to test the understanding of the problem. Testing is used to compare the simulated behaviour of the model to the actual behaviour of the system under investigation. This is to ensure that variables compared to useful concepts in the real world and equations are checked for dimensional consistency.

Air Defence Control Assessment Process

The roles of CWA and SD support the problem discovery and hypothesis formulation phase of the process. The CWA analyse the current information on the system and operational requirements within the context of the problem that is defined in the first step. All available information from documents (doctrine) and SMEs are captured in constructs with means to ends relationships, such as the Abstraction Decomposition Space to support further discussions. This understanding should lead to various models of the C2 system and its operation in the environment. The models incorporates the way people apply technology within the constraints of the organisation and the environment to achieve organisational objectives.

The C2 system models are used to support hypothesis generation through identification of specific cases to produce desired effects. SD modelling can then be applied to assess different cause and effect relationships within the context of the MOE. This brings into consideration the dynamic complexities found in C2 systems. The purpose of the SD is not to predict how successful the system will be, but to forecast the effect of certain causes to support understanding possible system behaviour. This step can help identify possible deficiencies in the hypothesis before expending time, effort and funds on experiments. The C2 system models and expected behaviour also leads to identification and refinement of MOE. This serves as input to the detailed design of the experiment and guides the analysis of recorded data.

The eventual output of this iterative and cyclical process provides Ad Control concepts assessed with cognisance of the sociotechnical and dynamic nature of the environment. The application of CWA and SD supports the development of solid hypotheses to lead to successful experiments. Thoroughly assessed and validated concepts will go a long way to ensure effective C2 systems.

Conclusion

This paper highlights the importance of well planned and executed experiments to assess AD Control concepts to support traditional SE processes. Experiments needs to take into consideration the fact that C2 systems are complex sociotechnical systems that require a lot more than only testing the technical elements. Furthermore, these system operate in a complex and dynamic environment, placing more constraints on humans, decision support and communication systems. The approach described in this paper is applied for planned Project FELLOWSHIP experiments.

CWA and SD are proposed as supporting tools to assist in the development and assessment of complex sociotechnical systems. The insight gained from these approaches also supports the planning and designing of experiments. A solid and validated hypothesis and supporting MOEs will go a long way towards ensuring successful experiments to assess the suitability of C2 concepts.

The proposed analysis approach to complex sociotechnical systems will provide a capability to support SADC countries in acquisition of C2 systems. This further enhances the “home grown” capability at the CSIR and should offer huge opportunities to provide an alternative acquisition source to SADC countries.

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