18th ICCRTS

Assessing Command and Control System Vulnerabilities in Underdeveloped, Degraded and Denied Operational Environments

Topics

Topic 4: Collaboration, Shared Awareness, and Decision Making

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Abstract

Command and Control (C2) is a complex sociotechnical system. Humans, being part of the C2 system, make sense of the situation to support decision making. Communication technology distributes information and orders within a social (organisational) context. In underdeveloped, degraded or denied operational environments, some technical support systems may fail or not be available to a commander to successfully conduct operations.

The effect of the degraded or denied technical capabilities on work may not always be clearly understood within the setting of a complex sociotechnical system. Humans may have the ability to develop work-around strategies to accomplish a task in the absence of some technical supports. Cognitive Work Analysis (CWA), and specifically the Work Domain Analysis (WDA) with Abstraction-Decomposition Space (ADS), provides a framework to analyse the effect of loss of technical (physical) means on the success of the total mission. These constructs can be used in System Dynamics modelling and simulation to compare the effect of different approaches. The knowledge gained from this process may serve as input to design and development of C2 systems capable of operating in adverse conditions.

1 Introduction

Command and Control (C2) is required to support military operations, such as border safeguarding, in achieving its objectives. The purpose of C2 is to bring all available information and assets to bear on an objective to ensure the desired effects (Van Creveld 1985, Brehmer 2007). Commanders have to determine the best course of action to achieve the desired results as well as lead those under their command. “Control” is the process of determining the relationship between desired and actual results to guide taking the necessary steps to correct deviations.

C2 is also seen as problem solving within a military context to provide focus and convergence of effort (Brehmer 2005). It requires a vision of the results to be achieved which include an understanding of higher-level intentions, concepts, missions, priorities, and the allocation of resources. Successful C2 relies on the ability of people to assess the risks to operation success through a continual process of re-evaluating the situation and environment to support decision making on the most appropriate actions.

Complex situations in the operational environment, which are aggravated through denial or delay of information from sensors and communication systems, make C2 difficult. The C2 system is also a sociotechnical system with humans playing a major role. The analysis and design of C2 systems needs to consider the role humans play in solving complex problems under difficult circumstances. Cognitive Work Analysis (CWA) is a framework proposed to analyse complex sociotechnical systems (Lintern 2009, Naikar 2005, Vicente 1999). CWA helps to identify critical areas in the C2 for special consideration and analysis during design. The System Dynamics (SD) modelling and simulation approach can utilise the constructs from CWA to compare the effect of different implementation policies or operational doctrine. Through SD the behaviour of the C2 system under dynamic conditions can be analysed to help identify elements that would improve operational agility in complex environments.

The focus in this paper is on border safeguarding operations. Border areas are often remote with limited infrastructure. This paper will analyse the effect of underdeveloped, degraded and denied operational environments on the requirements for a C2 system. At first, C2 theory will be discussed to highlight its complex sociotechnical nature. This will lead to a short background on CWA to motivate its use in the assessment and design of C2 systems. The utilisation of SD is then proposed to further investigate the problems identified through the CWA.

The CWA will be applied within the operational context of border safeguarding operations. A simple border safeguarding example will be used to demonstrate the principles of using CWA in assessment of the possible impact of loss of communication or other technical support systems in underdeveloped, degraded and denied operational environments. The outcomes may lead to identification of requirements for implementing backup and other supporting systems or procedures. The impact of these issues are then modelled and simulated using a SD approach to better understand the dynamic nature of the system.

2 Command and Control

2.1 Command and Control System

C2 is required to make sense of complex situations and manage the risks during the execution of an operation. Commanders require awareness of what has happened, what is happening, and what may happen in the near future. Control is supported through feedback of actions and information from sensors and other assets.

C2 is an iterative and cyclic process that requires continuous updating of decisions to adapt to a changing situation (Brehmer & Thunholm 2011). As the communication system or supporting infrastructure is interfered with, information may be delayed or never reach its intended destination. This increases the difficulty to implement an effective solution to the perceived problem during an operation. 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 (Sterman 1994).

The C2 system is integrated within the larger military system to support decision making. The C2 system consists of equipment and people (commanders and subordinates) organised in a structure to execute tasks (Brehmer 2010), as seen in Figure 1. A basic C2 system utilise 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 output of a C2 system is a plan implemented through the distribution of orders. The plan should be based on understanding the current information within the context of the operation to result in decisions on the appropriate course of action. The resulting plan defines the required outcomes and assigns the authority, responsibility and resources to achieve the identified objectives. The quality of sense making is determined by the degree of shared awareness, social climate and interaction between the people in the C2 system.

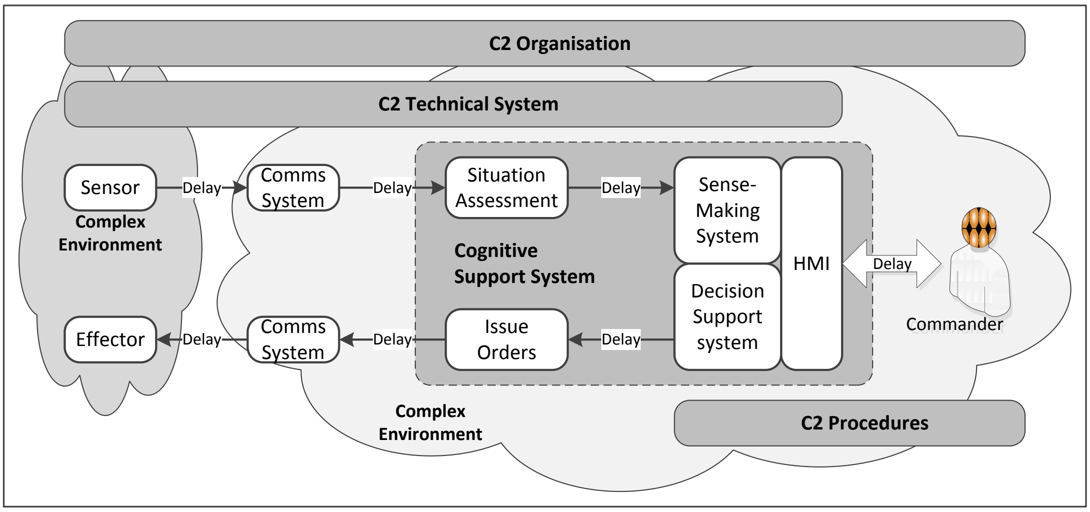

Figure 1: Command and Control System

2.2 Command and Control System Analysis and Design

When analysing or designing a C2 system, it is useful to consider all three levels of design: Purpose, Function and Form (Brehmer 2007). These levels relate to the means-to-ends relationships of why, what and how to be discussed later in this paper. 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 C2 (Brehmer 2010).

C2 is a "Function" of the higher level military system to produce effects through the direction and coordination of resources. When developing a C2 system, this higher level military system function becomes the “Purpose” of the C2 system. Therefore, the C2 system requires other lower level “Functions” to support the “Purpose” of directing and coordinating the military system. Brehmer (2007) identified Data Collection, Sense Making and Planning as the generic “Functions” of a C2 system. The “Form” of the C2 system consists of the organisation, methods, procedures and technical elements. C2 occurs throughout the military system with numerous participants, resulting in a cognitive and social aspect that requires support from the “Form”.

According to Smith (2007), making sense of all the information available is very difficult with structures and processes developed for industrial age war. In the past checklists tended to be followed with a detailed program of exactly what and how to do with which resources. The focus should rather be on having a broad outline of what to achieve, supported by the required pattern of events. Brehmer (2007) also notes that 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. 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.

2.3 Command and Control as a Complex Sociotechnical System

The environment of military operations is complex as the opposing forces influence successful execution of plans. Attacks from an adversary on the personnel and communications infrastructure will also challenge the capability of C2 system. Moffat (2003) found that to control combat as a system, the variety of states within combat itself must be similar to the controller of the combat system. He quotes Ashby’s Law of Requisite Variety to prove that because combat represents a complex system, the C2 system also has to be complex. The sources of complexity in the operational environment that impact on C2 are uncertainty, risk and time pressure. Technical systems are required to support the C2 process without attempting to remove complexity or hide it from the commanders (Hollnagel, 2012). The C2 system must continue functioning under these adverse circumstances to enable the solving of complex problems to ensure the success of military operations. Therefore, a successful C2 system for current and future military operations requires agility. Agility is the capability to cope with changes in the situation or environment. It consists of responsiveness, versatility, flexibility, resilience, innovativeness and adaptability (Alberts 2011).

A C2 system is a sociotechnical system as it is composed of personnel, organisational structures, work procedures and technical equipment (Walker *et al*, 2009), as seen in Figure 1. 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. 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 (Hallberg *et al*. 2010:175). Therefore, a C2 system can be described as a Complex Sociotechnical System, making it difficult to analyse and design.

Classic System Engineering (SE) approaches, which see the human as outside of the system, may not be suited anymore (Fowlkes *et al.* 2007). 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. Cognitive System Engineering (CWA) and other supporting approaches, (SD), will be useful in planning the development or improvement of C2 systems. These methodologies will improve the understanding requirements of the C2 system to support agility in dynamic and complex operational environments.

3 Degraded and Denied Operational Environments

A C2 system requires information, in various forms, to make sense of the operational environment for planning and control during the mission. The C2 system is affected when some elements of the technical system, such as sensors and communication, reliant on supporting infrastructure, become unavailable or degraded. There may be many reasons for this; some are grouped as follows:

a) <u>Criminal or Military Action</u>. Criminal or enemy action may have the following effects:
   - i) Loss of sensors or communication system elements.
   - ii) Destruction of supporting infrastructure (*i.e*. power supply or building structures).
   - iii) Degradation of sensor and communication abilities through electronic warfare action.
   - iv) Cyber-attacks on communication and decision support infrastructure (Information Warfare).

b) Forces of Nature. The characteristics of the operational environment make sensing and communication difficult due to coverage and geographical limitations on line of sight.

c) Technical Capability and Serviceability. This includes the following:
   i) Technical maintenance related difficulties exist with sensor and communication systems.
   ii) Interoperability between the different departments participating in the border safeguarding operations may be limited.

d) Lack of Infrastructure. This includes the following:
   i) Operational environment is remote with underdeveloped infrastructure.
   ii) The cost of implementing a major communications network may not be justified by the size and objectives of the planned mission.

Degradation or denial of communication or supporting infrastructure can occur before the mission commences or during the mission. If it is part of the initial conditions, it can be planned for. However, difficulties occur during unforeseen loss of communication or other infrastructure.

4 Cognitive Work Analysis

4.1 Introduction

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. Despite constraints of the environment a variety of work patterns may be possible to solve unexpected problems and situations. Products of CWA define the required information content as well as the applicable context where it will be used within a cognitive system (Bennett *et al*. 2008, Lintern 2008, Lintern 2009, Naikar *et al*. 2006, Naikar 2005, Vicente 1999).

The theoretical roots for CWA are in Systems Thinking, Adaptive Control Systems and Ecological Psychology. It also supports the cognitive strategies and competencies employed in the sense making and decision making process. These are applied to define the information display and data distribution requirements. By designing the human operator, with his ability to use intuition and to detect complex patterns into the total system, enables the system to adapt and evolve along with the changes in the environment (Jenkins *et al*. 2009). The CWA consist of five main phases as summarised in Figure 2 (Lintern 2008, Jenkins *et al*. 2009).

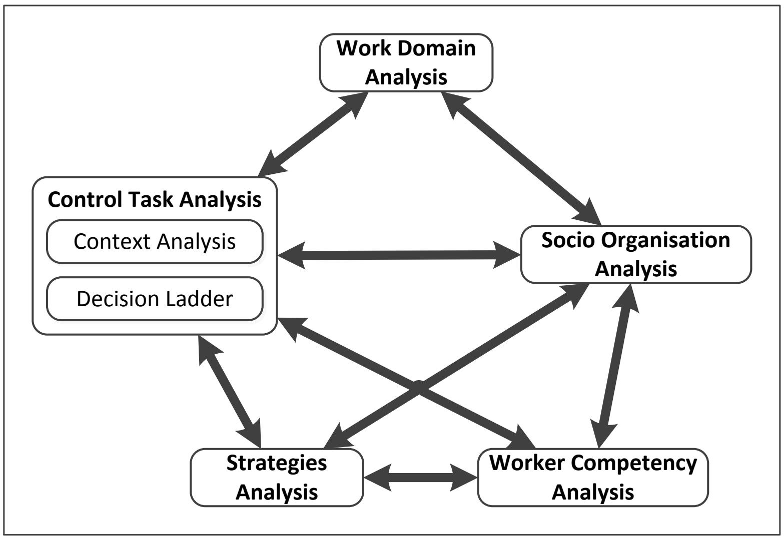

Figure 2: Cognitive Work Analysis Framework

CWA supports the development of cognitive systems that allow human decision makers to perform their work effectively and to be flexible with the required technology and supporting organisational structures. 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) (Vicente 1999). It considers the ecological constraints that may shape the execution of tasks as well as the cognitive approaches of the users of the system (Bennett *et al*. 2008:360). The decision making embedded in the C2 system process should be representative of a typical expert problem solver's natural reasoning. The products of CWA support the definition of required information content as well as the applicable context where it will be used. CWA goes beyond the allocation of tasks to either machines or people, to whoever fits the requirements best. It addresses the design of the human capabilities into the operation of the total system (Lintern 2012).

This paper focuses on assessing the effect of underdeveloped, degraded and denied operational environments on the C2 system and its ability to support a mission. CWA provides a framework to analyse a C2 system to assess the influence of loss of technical and infrastructural means on the ability to achieve the aims of a C2 system. The results of the analysis may support generating requirements for C2 system development as well as assist in planning of the missions using current equipment and infrastructure. For the purpose of this paper only the Work Domain Analysis (WDA) will be discussed as its constructs will be the main contributor in assessing the effect of underdeveloped, degraded and denied operational environments.

4.2 Work Domain Analysis

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 WDA provides the foundation for a complex sociotechnical system analysis and design through understanding the effect the environment has on achieving the purpose. This analysis uses an Abstraction Decomposition Space (ADS) to identify and model the goals and purposes of the cognitive system in relation to the ecological constraints to provide a reasoning space about the environment. This is required where systems, the environment, and their interaction are dynamic with many possible instantiations (many-to-many relationships). With WDA being event-independent, the categories of constraints identified are applicable to the many scenarios (Naikar *et al*. 2005).

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. This links into C2 where problem solvers within the C2 system need to understand the purpose of the system, the values and priorities of the system, the physical resources available as well as what the abilities of those resources are. The output of this step is not task or event driven, but leaves space for events that may or may not be anticipated (Vicente 1999).

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. 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 physical constraints, such as the laws of nature, tend to be causal. However, there also exist intentional constraints on the organisational objectives such as social laws, conventions or values, formal or informal rules of conduct and operator intentions (Naikar *et al*. 2005). The levels of the abstraction decomposition space are:

a) System Purpose. The System Purpose provides the reason why this specific cognitive system is being developed.

b) Values and Priorities. The reasoning process requires the principles, standards or qualities to be maintained during execution of the process.

c) Knowledge, Insight and Semantics (General Functions). This level provides the domain functions required to execute the work in satisfaction of the system purpose. These functions must be performed, independent of the physical elements utilised.

d) Facts, Ideas, Opinions (Physical Functions). The physical functions are implemented through the activation or use of the physical objects.

e) Source Objects (Physical Objects). The physical elements present in the work domain available to perform the work.

The CWA framework provides a tool to organise and present information and knowledge about a system. Subject Matter Experts (SME) are used for their operational experience to provide insight on mental models, heuristics and work-arounds. The WDA begins with identifying the purpose and boundaries of the analysis as well as how the constructs will be used. Next follows identification of the ecological elements (environmental constraints) in terms of causal or intentional relationships to guide the type information required. SMEs and existing system or doctrinal information may be used. SMEs and other stakeholders are also used for validation of the constructs. The means-to-ends relationships between the physical resources and functionality need to be highlighted to guide possible problem solving strategies. Within the abstraction levels the elements can be viewed at different states of decomposition as required by the level of analysis (Naikar 2005).

The WDA and its products, specifically the ADS, will also be useful in identifying relationships between work (functions) and the physical systems that they are dependent on. For the analysis of C2 systems for border safeguarding the factors having influence on the physical system should also be listed. The constructs can be applied in planning C2 system tests during simulated and field exercises. These will be useful in assessing system vulnerabilities and possible work-arounds available. 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. A 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.

5 System Dynamics

5.1 Background

The concept of SD was developed during the 1950s and 1960s at the Sloan School of Management at MIT (Forrester 1968:398). It was originally called "Industrial Dynamics", aimed at investigating the feedback in social systems. The different modes of behaviour as a result of high-order nonlinear systems were related to complex problems in management and economic decision making. SD is one way of applying systems thinking in the analysis of problems (Forrester 1994: 52). This work was taken further by Sterman (2000:34) to support learning about complex systems. As observations about the world are biased and filtered, perfect information is never available for decision making. To enable learning, the limited and imperfect information must be trusted even if it is ambiguous. SD can be used for double loop learning (Sterman 2000: 23).

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 (Lofdahl 2006: 6). SD explores what would happen in a system within a number of 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 (Meadows 2008: 44).

Feedback in the system causes most of the complexity in the system. Dynamic complexity may exist in simple systems, with low combinatorial complexity, due to 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 making decisions and converting them into action compound the effect of dynamic complexity. This makes controlled experiments difficult and expensive. Delays cause the dynamic complexity to slow down the learning loops as well as reduce the amount of learning in each loop through instability. Instability may also lead to oscillation in the system (Sterman 2000).

5.2 Modelling

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 (Meadows 2008). 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 (Sterman 2000). SD utilises the following constructs to model and support simulation of complex systems (Sterman 2000, Meadows 2008):

a) Causal Loop Diagrams. A Causal Loop Diagram (CLD) is used to represent the feedback structure of the dynamic system. 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.

b) Stock and Flow Diagrams. Stock and flow diagrams 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 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.

5.3 Simulation

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. This is too difficult and complex for mental simulation. People cannot perform intuitive scientific thinking about the problems in systems. Virtual worlds are used as low cost laboratories to exercise decision making skills, conduct experiments and test assumptions. In the virtual worlds it is possible to compress and dilute time. The same actions can be repeated under different conditions through controlled experiments. Even the level of random variation can be controlled. However, a disciplined scientific process must be applied to support effective learning and prevent typical simulation pitfalls (Sterman 2000).

The simulation model is developed, from the information gathered in the SD process, into a formalised structured form ready for simulation. This process 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. The sensitivity of the model behaviour and possible solutions are assessed within the same set of uncertain assumptions.

6 Application Example of Cognitive Work Analysis

6.1 Border Safeguarding

6.1.1 Background

The work system (cognitive system) under analysis in this paper is the C2 system to support border safeguarding operations for the military forces deployed on a border. Border safeguarding entails the control of the enforcement of state authority with respect to national land, air and maritime borders. Operations are not only conducted on the border, but also in rear areas to enhance operational manoeuvrability. The operations include effective monitoring of the border, control over illegal border crossings and the prevention of the violation of territorial integrity. This requires direct action such as movement control, follow-up actions and search operations which involves joint planning, co-ordination and implementation within existing co-ordinating structures. The typical priorities of border safeguarding operations are:

a) Cross-border crime such as rustling of livestock.
b) Firearms-smuggling.
c) Drug-smuggling.
d) Smuggling of stolen and untaxed goods, often part of organised crime.
e) Illegal immigration.
f) Human trafficking.

6.1.2 Tasks

Military or police forces are often responsible for monitoring and patrolling of the borderline between official border posts while the ports of entry are controlled by other departments. The following tasks and activities are associated with the monitoring and patrolling of the borderline:

a) Erection or deployment of aids such as sensors, barrier systems and border monitoring systems.
b) Conducted of foot patrols (using tracker dogs), vehicle, mounted, motorcycle and air on the border as well as in depth.
c) The arrest, transport and guarding of suspects based on information or reasonable grounds.
d) The search of areas or buildings looking for illegal immigrants or contraband.
e) The seizure of illegal goods.
f) The recording of evidence and the furnishing of proof and exhibits for prosecution.

6.2 Border Safeguarding Work Domain Analysis

Every CWA for C2 is different as it depends on the purpose, context or level of operation. The CWA leads to a better understanding of the environmental constraints to support requirements definition for a C2 system. The CWA for the C2 system required by military forces for border safeguarding is performed within the context as described above. The aim of this CWA is to determine the possible difficulties C2 can experience as a result of underdeveloped, degraded or denied communication environments as well as propose possible solutions. The constructs presented in this paper are not as a result of an in-depth analysis but an example for demonstrating the application of the proposed methodology.

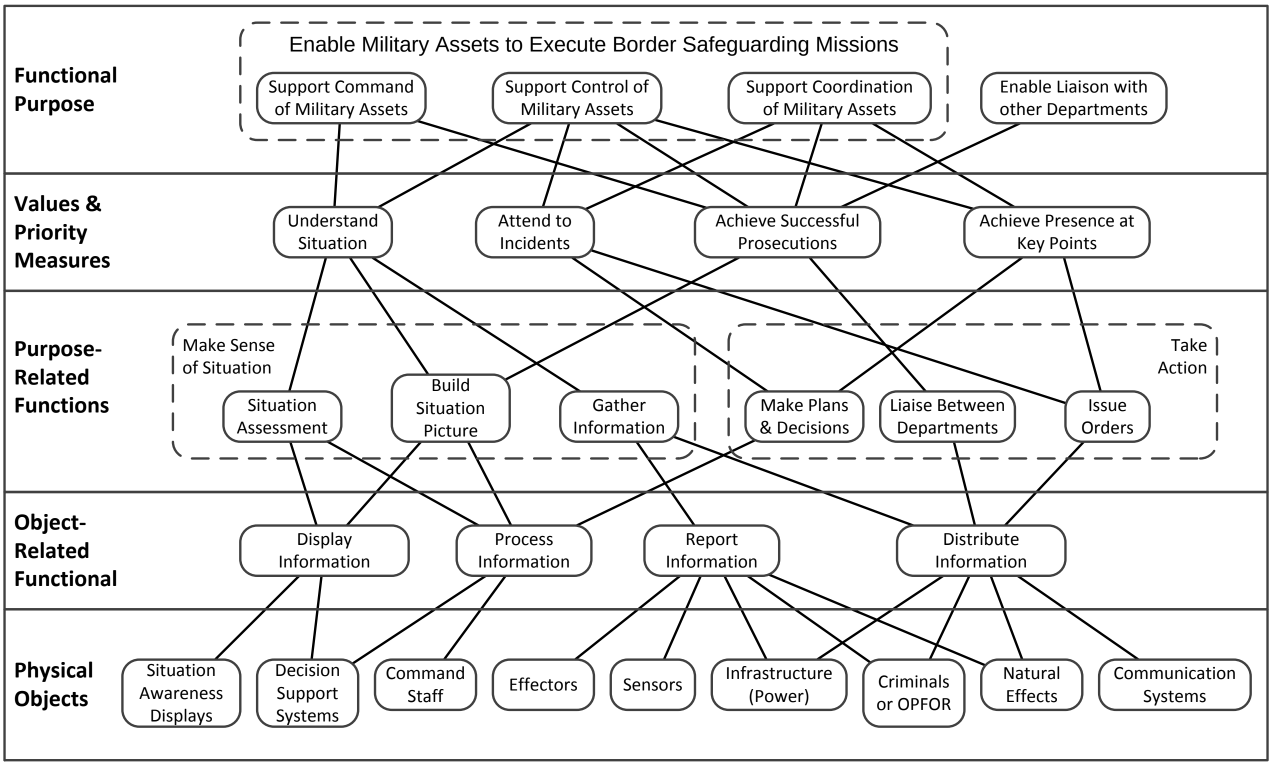

Figure 3: Abstraction Decomposition Space

The first step is the WDA that results in the ADS for a typical C2 effort in support of border safeguarding operations, as seen in Figure 3. The information was retrieved from documents, discussions with SMEs and personal experience. The different levels of abstraction and decomposition are:

a) Functional Purpose. The functional purpose of the C2 system is to enable military assets to execute border safeguarding missions as well as liaise with other participating departments. This can be decomposed into sub functions of command, control and coordination of the military assets to perform border safeguarding.

b) Values and Priority Measures. The main values of the C2 system must adhere to border policing policies, prosecution laws as well as national and international laws of armed conflict. The main priority measures to drive the success of the system, as identified during the WDA, include understanding the situation, number of incidents attended to, number of successful prosecutions, achieving a presence at key points.

c) Purpose Related Functions. The purpose related functions are divided into making sense of the situation and to take the appropriate action. While taking action, some form of control is required to ensure the mission can be adapted to changes in the context and environment.

d) Object Related Functions. All the object related functions refer to information, indicating its importance in the C2 system. Therefore the technical elements of a C2 system are required to report, distribute, process and display various forms of information.

e) Physical Objects. The physical objects within the C2 system, as well as the elements in the environment having influence, will shed light on the effect of degradation and denial on its effectiveness. This will be the focus of the analysis of the WDA. The elements utilised in the command and control system for border safeguarding, and affected by the environment to restrict successful execution are:

i) Effectors or Assets. The elements available take action such as attending to suspicious activity or intercepting and apprehending criminals. They are required to be transported to a point of contact by foot, road or air.

ii) Sensors. Electronic, optical or human sensors record activities in the operating environment.

iii) Communication Systems. Communication systems and infrastructure are required to distribute information between all the assets and participants in the mission. Different communication technologies may have different advantages or limitations.

iv) Supporting Infrastructure. Normally communication and sensor systems require infrastructure to support operation such as power or towers.

v) Criminal or Military Activities. Criminals or opposing forces may destroy or steal deployed systems as well as supporting infrastructure.

vi) Natural Effects. This includes weather conditions or geographical features that limit the range or effectiveness of sensors and communication systems.

6.3 Assessment of the Work Domain Analysis

6.3.1 Analysis of Object Related Functions

For the purpose of determining the effect of an underdeveloped, degraded or denied environment on requirements for a C2 system suited for border safeguarding, the Physical Objects and their functions is first analysed. The other object related functions of Information Display and Processing are often embedded in the C2 physical system, being supported and protected in shelters during deployment. However, the Information Reporting and Distribution tend to be remotely deployed and dependant on the external environment, making them more vulnerable. They are affected by the following:

a) Criminal or Military Action. The ability to report or distribute information can be limited or removed through theft or destruction of relevant systems. The information that is available may also be altered through Information Warfare activities.

b) Effects of Nature. The ability to collect and report information is affected through limitation of detection ranges due to atmospheric conditions (fog, smog or sand). This is in addition to geographical features limiting the line of sight ranges. The ability to distribute the information can also be affected through loss of sensors, communication equipment or supporting infrastructure (*i.e.* masts) due to flooding or high winds.

c) Serviceability and Availability of Communication System, Infrastructure, Sensors and Effectors. The sensors, communication equipment may become unserviceable due to the harsh operational environment at any moment, without prior notice. This aspect includes the unavailability of infrastructure such as a power grid, optical fibre networks or masts for antennas. Nations or private companies owning satellites can stop the use of their facilities for communication. As with the other two factors above, the object related functions of information reporting and distribution will be hampered.

6.3.2 Analysis of Purpose Related Functions

The affected object related functions of Information Reporting and Distribution are required for the purpose related functions of Information Gathering, Issue of Orders and Liaison between Participating Departments as seen in Figure 4. These purpose related functions affect all of the listed values and priority measures, resulting in a high priority concern for the C2 system. From this assessment it should be clear that a failure in the communication system will result in failure to build a situation picture for sense making in support of the planning purposes (incomplete information) as well as the inability to control and coordinate with assets and other departments. Even if all the other assets (*i.e*. sensors and effectors) were available, the lack of an effective communication network will render the C2 system almost useless.

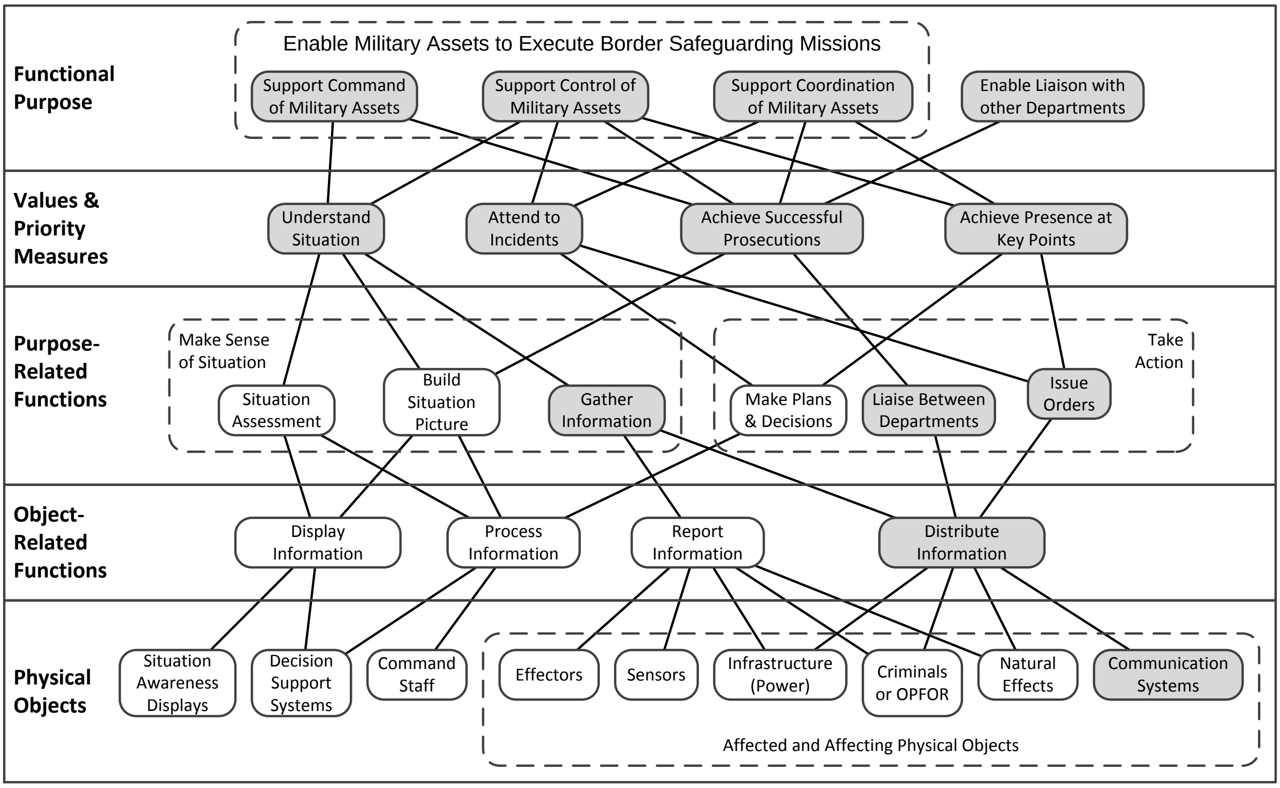

Figure 4: Affected Abstraction Decomposition Space

Regardless of specific causes and sources of loss of the object related functions through the physical objects, there will be inadequate or even no information available in the C2 system in an underdeveloped, degraded or denied environment. This may occur without the immediate awareness by the commanders or their supporting staff, making it difficult to execute the Purpose Related Functions as identified in the WDA. The communication system is a problem because of the following reasons:

a) Infrastructure required to support the communication system is not always available.
b) Infrastructure and communication systems may be attacked.
c) Limited information transmission capability can hamper the amount of information available for sense making and situation awareness.
d) Limit the ability to distribute orders to assets.
e) Limit the ability to control assets.
f) Limit the ability to liaise with other departments or entities participating in the operation.
g) Lack of knowledge on the state of the communication system.

Each means-to-ends relationship can be investigated in detail to determine which processes are affected and which purpose functions may suffer from loss of communications. For this analysis the focus will be on the purpose related functions of Information Gathering, Issue of Orders and Liaison between Participating Departments. The designers may investigate different or alternative methods to achieve these functions without information available of being able to distribute orders. The knowledge gained from the analysis will assist in defining requirements for a C2 system.

As confirmed by the analysis, the Communication System is crucial to the C2 of military operations as well as being very vulnerable. However, how changes in the communication system will influence the behaviour of whole C2 system in supporting border safeguarding operations in not clear. SD will now be used to conceptually simulate some effects of communication on the behaviour of the system.

6.4 Application of System Dynamics

6.4.1 Initial Hypothesis and Boundary

An effective communication system is crucial for C2 and is required to distribute information from sensors to the commanders as well as orders from the commanders to the effectors. If there is no communication system that distributes all available information, all elements will operate blind and in isolation without any form of control. However, there should always be some form of communication available, from digital wideband high speed systems to analogue HF radios that are good for voice but with limited digital capability. For a given level of communication capability, certain policies can (doctrine) support effective C2.

Modelling and simulation in SD, with Vensim PLE™, of the C2 system is supported by the constructs and understanding gained by the CWA. This SD analysis addresses the key variable communication system (capability), as derived from the CWA. The aim of this SD analysis is to explore what the effect of different policies (doctrine) will be on C2, considering the expected problems with communication within an underdeveloped, degraded or denied environment. The models will focus on the effect of the communication system of the execution of C2 and not how the communication system is being affected. The effect of the C2 system on the information available for sense making and the distribution of orders will be included in the model.

6.4.2 Causal Loop Diagrams

The CLD, as seen in Figure 5, is derived from the WDA constructs for the enemy action system. This diagram identifies the control loops and is used to construct the stock and flow diagram to be used in simulations.

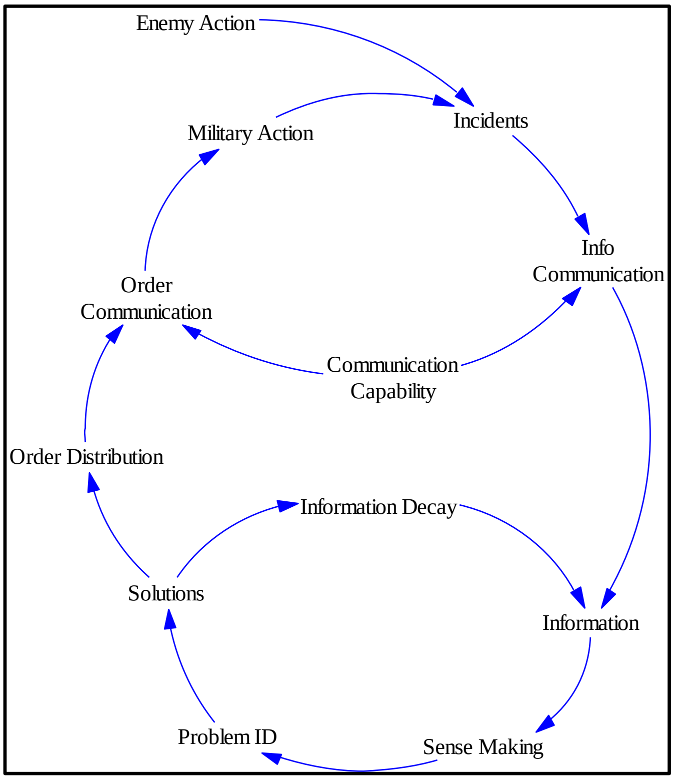

Figure 5: Causal Loop Diagram

6.4.3 Stock and Flow Diagram

The CWA provides the structure and interdependencies of the problems facing a C2 system for border safeguarding. The construction of the stock and flow model, as seen in Figure 6, is as follows:

a) Incidents. The incidents are accumulated through enemy action and are depleted through military action. This may include any cross-border or related criminal activity that requires attention from available assets. Military action is in response to an incident or enemy action. It requires orders to assign assets to attend to the incident. The rate of military action, as influenced by the communication system, will determine the level of incidents left in the system.

b) Information. The total information is the sum of the information reported from the incidents. Reporting consist of information on incidents reported through the communication system. The level of the information available for sense making is limited by the time value of the information. The main factor influencing it is the information utilised in generating solutions and related orders.

c) <u>Solutions</u>. Every problem identified through the amount of information available is analysed, solved and a plan generated. As soon as the information reaches a certain level in value, a problem or possible incident can be identified. As soon as an incident or problem is identified and a solution planned, orders are sent to implement the plan. This will involve action by effectors or other assets (including liaison with departments other than the military participating in the operation. The level of solutions is depleted through the distribution of orders.

d) <u>Communication Capability Variable</u>. The distribution of information for sense making and orders to control military action is affected by the communication system. The main influence of the communication system is the delay of information. This is as a result of the level of technology and related supporting infrastructure available.

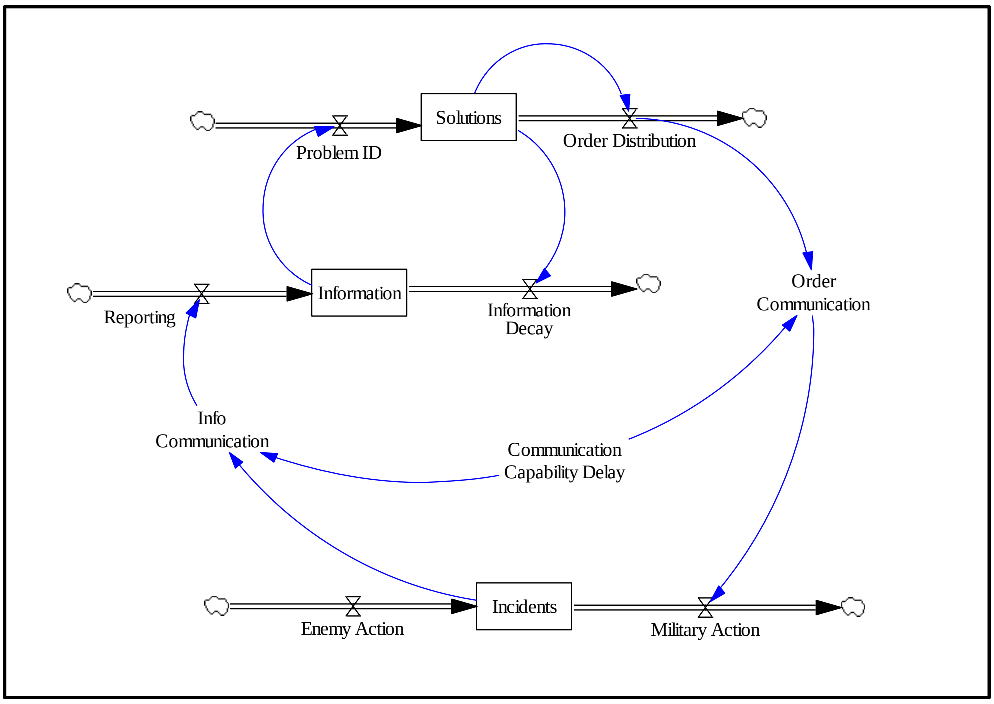

Figure 6: Systems Dynamic Stock and Flow Model

6.4.4 Simulation Results

The SD model from Figure 6 was used to investigate the effect of communication delays on the C2 system and supporting processes. On face value the model has two loops with delays embedded, resulting in a second order differential equation. This may lead to instabilities and oscillation under certain conditions. The level of information on the incidents over time as a function of different values for the Communication Capability Delay is shown in Figure 7.

The simulation was conducted over a period of 24 hours to measure the level of information on the incidents to support successful action of own assets. The blue line (0 hour delay) presented a near smooth curve before the level of information stabilises. A delay of 1 hour, as seen with the red line, results in a slight overshoot before the dynamic behaviour of the system stabilises. The green line with a 2 hour delay presents an oscillating behaviour indicating instabilities in the system.

The value of the SD simulation is highlighting the importance of the communication system and its effect on the dynamic behaviour of the system under the effect of delays. This awareness can lead to the identification of technology, processes and interfaces to prevent instabilities in the real world implementation of the C2 system with communication delays. This simulation presents only a very basic initial investigation into the dynamics of a C2 system and can be more detailed by incorporating various other variables, processes and influences.

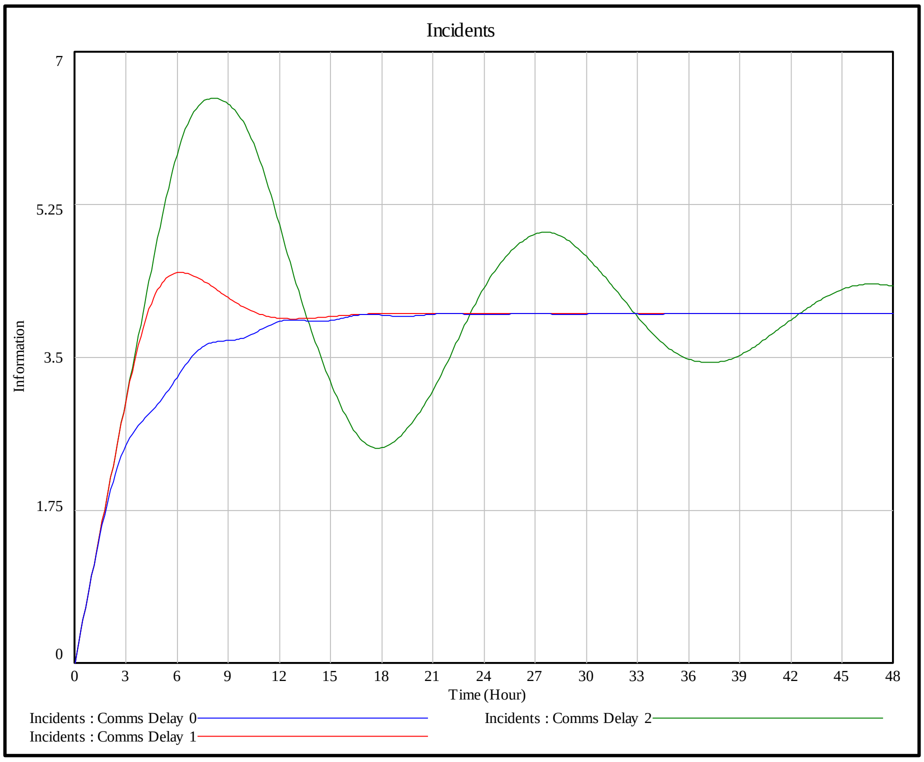

Figure 7: Effect of Communication on Handling Incidents

6.5 Contribution to Command and Control System Requirements

The designers of the C2 system need to be aware of the functions that cannot be supported if the physical objects are affected. CWA and WDA are very useful to identify the functionality that will be lost or reduced due to underdeveloped, degraded and denied environments. The dynamic effects thereof on the behaviour of the system are studied through SD. The combined analysis of the C2 system provided some useful inputs.

Although obvious, the analysis confirmed that the communication system is one of the main vulnerabilities of a C2 system. The evident, and often first solution, is to implement alternative communication technologies, being dependant on different or more robust infrastructures. However, they still need to be integrated and interoperable to cover each other according to a plan in the case of the main capability being lost. The following additional or alternative solutions also transpired:

a) Implement communication architectures that enable different routes for information to be distributed. Here the implementation of an edge network may be more advantageous than strict hierarchical information distribution that should reduce information flow delaus. This is echoed in the output of the SD simulation.

b) Commanders need to be aware of what they do not know. The C2 system may need to warn commanders and supporting staff of outdated or the unavailability of information due to problems in the communication system. They must be aware that they do not have an up to date situation awareness picture and that their orders to the effectors are not received. Commanders need to identify which function cannot be conducted when information is unavailable. They must be able to apply their cognitive and social skills to plan and implement alternative actions.

c) Identify alternative ways and means to perform C2 without or with limited information available. These may include the following:

    i) Establish a proper intent and long term vision for sub units of what the mission is to achieve. This will enable sub units to operate independently for extended periods.

    ii) Make the best possible use of available information for situation awareness. This may enable commanders to be able to predict the near future states, even when new information is not immediately available.

    iii) Commanders need to be aware of the age of information. They must assign the appropriate value to old information to prevent outdated sense making, as seen in the SD simulations.

    iv) Plan backup or alternative processes to support C2 in a degraded, denied or underdeveloped environment must be considered. Autonomous and procedural execution of tasks must be planned for fall-back modes of operation. As seen in the SD simulation an effective communication system will improve the ability to react to incidents.

d) Identify ways to execute border safeguarding missions without the ability to liaise with other participating departments. These may include the following:
   i) As stated above, commanders need to plan and implement backup or alternative processes to support liaison in a degraded, denied or underdeveloped environment. Autonomous and procedural execution of tasks must be planned for fall-back modes of operation.
   ii) The presence of a representative of the other department present in the command post or the team executing a task will assist with liaison. He may have a different way or technology to communicate with his department.

e) Identify ways to execute missions if orders cannot be issued to deployed elements. These may include the following:
   i) Again, the importance of commanders planning and implementing backup or alternative processes to support the execution of a mission is highlighted. Autonomous and procedural execution of tasks must be planned for fall-back modes of operation.
   ii) Continuous feedback from subordinates, deployed elements and teams will confirm with that they have received an order. This will also assist in maintaining an awareness of the status of the communication system.

6.6 Lessons

Because the analysis is formative and on a functional (purpose) level, it enables designers to focus on the work that needs to be performed in the system. This prevents a fixation on employing new technology in an attempt to solve operational problems. SD also provides a tool to assess the dynamic and behavioural effect of the factors on the C2 system. Despite this exercise providing some useful inputs for consideration in designing C2 systems for operation in underdeveloped, degraded or denied environment, it was performed at a superficial level and only scratching the surface. A thorough, more detailed and in-depth analysis may provide an even more profound appreciation of how a C2 system can be improved under the described conditions.

The output of the analysis still has to be tested in a representative environment during exercises and simulations. The output models, constructs and proposals of this process provide a foundation for detailed discussions with SMEs and other stakeholders. They will also be useful in helping to develop the exercise and guide the analysis of results. It is interesting to note the role the commanders and subordinates (cognitive and social) play in the proposed solutions, adding the sociotechnical system and associated complexity aspects to the C2 system. The other phases of the CWA will be useful in further analysing the cognitive strategies and social interaction during overcoming the environmental difficulties.

7 Conclusion

C2 is required to ensure the success of border safeguarding operations. However, it should maintain the capability to perform its purpose, even in complex operational environment where the capabilities of systems may be underdeveloped, degraded or denied. Furthermore, C2 is a complex sociotechnical system where the human operators may apply their cognitive and social capabilities to overcome environmental difficulties. Therefore, design and analysis of C2 systems have to consider the human element as part of the system.

CWA is one framework that can be applied for the analysis and design of C2 systems. CWA provides models and constructs to assess vulnerabilities in the C2 system. The initial phase of WDA, through the ADS, is useful in relating the purpose of the system to the technical means available. This can be used to identify risks and problems as a result of the complex operational environment. This paper performed the WDA on the C2 system for border safeguarding operation. From the analysis the vulnerability and importance of the communication system to support sense making and decision taking for the military operations transpired. This insight can allow designers to compensate for the foreseen deficiencies in design of the C2 system and supporting processes.

However, WDA with ADS alone are not sufficient. WDA however does help to identify the affected elements and processes. Analysts may need to delve deeper to more detail with additional tools and phases of the CWA. The typical decision and their information requirements must be identified to assist in the enhancement of communication architectures and supporting operational procedures. This can lead to the identification of physical elements and the context having an influence on these decisions. Assessing dynamic behaviour through SD, increases understanding of the possible problems. It was seen that CWA and SD compliments each other in assessing in C2 system. Using these methods in tandem with the support of field experiments should result in better complex sociotechnical systems.

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