An Analysis Methodology for Impact of New Technology In Complex Sociotechnical Systems

R. Oosthuizen
CSIR (DPSS)
PhD student, University of Pretoria
Pretoria, South Africa
roosthuizen@csir.co.za

L. Pretorius
Professor, University of Pretoria
Pretoria, South Africa
Leon.pretorius@up.ac.za

***Abstract*— Systems Engineering techniques and approaches are applied to design and develop solutions for complex problems. Information and Communication Technology systems can be complex to develop where the impact of new technology is not always understood as humans can apply them different than intended. This necessitates the application of a Sociotechnical System framework to analyze the possible impact of a new technology. A rigorous and valid experimentation approach is required to analyze system behaviors in support of Systems Engineering efforts, which is difficult with complex Sociotechnical Systems. Cognitive Work Analysis and System Dynamics are two complementary approaches that can be applied within this context. The products of these methods assist in defining the hypothesis required for experimenting with the new technology.**

Keywords*— *System; Command and Control; complex; Sociotechnical; Cognitive Work Analysis; System Dynamics

I. INTRODUCTION

Command and Control (C2) is a complex Sociotechnical System (STS) as it consist of humans interacting within a structure (organization) to make sense of the environment in support of decisions on actions required [1]. Humans apply technology to perform work in pursuit of the purpose of the STS. Within the dynamic military operational environment, with uncertainty and risk, the STS required for C2 becomes very complex due to non-linear and interacting human decision makers [2]. The introduction of new technology within this environment may have positive or negative consequences. It may fail to achieve the intended results or lead to new and unforeseen innovative uses [3].

A Systems Engineering approach for development or improvement of a STS with a new technology, having new capabilities, requires careful analysis. This can be achieved through experimentation with the STS in the operational context as supported by models describing system concepts, architecture (structure and interfaces) and behavior [4]. The success of experiments with complex systems is dependent on a well-defined hypothesis that addresses the cause and effect leading to Measures of Effectiveness [5]. This is difficult to achieve where elements of a STS have many unpredicted and nonlinear interactions within a complex and constrained environment [6][7].

Cognitive Work Analysis (CWA) and System Dynamics (SD) are combined to support the analysis of complex STS. CWA is a framework used to analyze work performed by humans in a complex STS within the context and constraints of a complex environment. The output of CWA is a number of useful constructs that support modeling [8][9]. However, complex STS also present dynamic system behavior through nonlinear interaction within itself as well as with the environment. SD seeks to understand the system behavior as a result of the underlying system structure. This support forecasting the possible effects of introducing new artifacts into the STS [10][11]. These system models will assist in defining and planning experiments. Concept models will help identifying the "Cause and Effect" of the artifacts. The experiments will benefit from the CWA which develop system models and the SD that help understand the effects as a result of new artifacts. This paper will describe and demonstrate the methodology.

II. COMPLEX SOCIOTECHNICAL SYSTEM

The term "Sociotechnical" refers to the interaction between "social" humans and "technical" systems, as seen in Fig. 1 [1]. This concept originated from the work of Fred Emery and Eric Trist during the 1950s. The sociotechnical approach was in contrast to the existing Taylorist based mechanistic (scientific) management paradigm. STS centered on the relationship between perception and action to create an environment for shared values and collaborative decision-making [12][13].

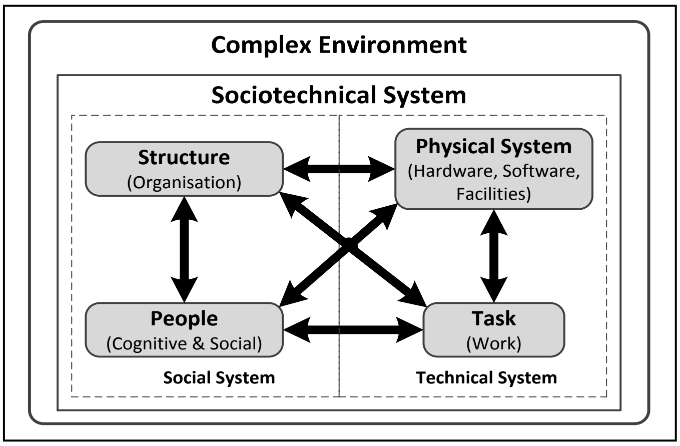

Fig. 1. Complex Sociotechnical System

STS theory highlights the importance of social humans in the organization instead of only relying of technical solutions to complex issues. This is achieved through knowledge sharing, learning and innovation with a human focus based on shared awareness, agility and self-synchronization [1]. The interaction between the social and technical aspects of an organization may be both linear (designed cause and effect) and non-linear (unexpected and unpredictable complex relationships). Improving a work system to cope with complexity in a dynamic environment with new technology, both the social and technical factors require analysis and adjustment [1]. Changes in technology, structure of the organization or context of the work affect how the people interact.

STS approaches have become a focus for information systems development. Modern communication and knowledge management systems create new opportunities for flow of information, operation and management within enterprises. People interact with the physical system and each other to distribute information through a Human Machine Interfaces. The contributors to system complexity include the dynamic and context-dependent nature of cognitive work and the dynamic nature of sociotechnical work settings. Analysis of the STS requires a simultaneous focus on all these elements to describe the total system with the non-deterministic behavior of the humans. A new technology or artifact affords new ways for humans to operate and organize in achieving a goal, requiring a formative development approach [14].

III. COMMAND AND CONTROL SYSTEMS

C2 is a STS as it is composed of personnel performing work with organizational structures, procedures and technical equipment (assets, sensors, communications, decision support and situation awareness displays) [1]. The C2 system support commanders to make sense of complex situations and manage the risks of mission execution. Making sense of all the information available is difficult with structures and processes developed for industrial age war. Human interpretation will always be required to make sense of complex situations [2][16]. 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 [17]. Different human decision makers in the hierarchy may have different levels of responsibility, decision cycles, timelines, agendas, culture and methods of decision making [15].

The output of C2 is a plan implemented through distribution of orders. Control is supported through feedback of actions and information from sensors and other assets. The quality of sense making is determined by the degree of shared awareness, social climate and interaction between the people in the C2 system. 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 modeling to understand all the implications [18][19].

The environment of military operations is complex as the opposing forces influence successful execution of plans. To control combat as a system, the variety of states within combat itself must be similar to the controller of the combat system [20]. C2 system performance is highly dependent on the context and environment of the task (mission) being performed. The C2 system requires agility to continue functioning under adverse circumstances. Agility is the capability to cope with changes in the situation or environment. It consists of responsiveness, versatility, flexibility, resilience, innovativeness and adaptability [21]. C2 system development requires consideration of the human in relation to the three levels of design: Purpose, Function and Form [16]. These levels relate to the means-to-ends relationships of why, what and how.

IV. ANALYSIS APPROACH FOR COMPLEX SOCIOTECHNICAL SYSTEMS

A. Analysis of Systems

Systems Thinking aims to understand the part in the context of the whole, while it interacts with and adapt to the environment. This evolved as modeling of system behavior to investigate the dynamic and non-linear interaction between different systems to identify possible future outcomes [4]. Models represent the structure and behavior of the problem and system design (solution) for communication of ideas and concepts [22]. Behavior is caused by the dynamic interaction between the system elements (structure) as well as the effect of the environment. The dynamic patterns of behavior of the system support learning about the underlying structure and other latent behaviors. The structure of a system consists of interlocking stocks, flows, and feedback loops [11]. Models can be utilized to continuously experiment with knowledge on the problem and to develop an understanding of the implication of different solutions. Experiments are used to explore different “what ifs’” to identify elements that cause complexity and other counterintuitive effects [4].

Analysis is required to understand the problem to be solved through Systems Engineering. The need for system analysis may be as a result of changes in the system, such as introduction of a new technology, or environment affecting performance [11][22][24]. Classic Systems Engineering approaches, which see the human as outside of the system, may not be suited for complex STS [14]. 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 utilized in the C2 system design. CWA and SD can 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. Analysis of systems within the military and C2 environment is often conducted in the form of a series, or campaign, of experiments.

B. Experiments

Experiments are undertaken to discover something not yet known or to demonstrate something known in order to grow the body of knowledge and enable the development of new capabilities [25]. The main difference between experimentation and other research methods is that something is manipulated to see what happens [5]. Experiments require credible results to be of value for decision makers through rigor, which implies experiment validity. Validity relies on the ability to use the potential cause and to observe an effect that is related to the cause. There must be no plausible alternative explanation for the effect other than the cause [5].

Experimentation requires a "scientific method" from Fig. 2, based on systematic process of observation, experimentation and analysis [5]. During the Discovery phase problems and future requirements need to be clarified using operational lessons learned, wargames 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.

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. An experiment fails when no sufficient evidence exist to determine whether the manipulated variable caused the effect. Experimentation must be anchored in a well define conceptual model that guides the thinking and planning of experiments [5]. A clear identification of the cause (new technology) and an effect (system behavior) need to form the foundation of experiment planning. The models for hypothesis formulation must capture all the attributes of the system and environmental influences, including human behavior in STS with dynamic behavior as a result of delays and feedbacks.

C. Cognitive Work Analysis

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. It supports the development of cognitive systems that allow human decision makers to perform their work effectively and flexible with technology and supporting organizational structures. CWA develops formative (how work can be done) designs for decision support systems. It considers the ecological constraints that may shape the execution of tasks as well as the cognitive approaches of the users of the system [8][9][26][27][28][29].

The CWA framework organizes and presents information and knowledge about a system. Subject Matter Experts are used for their operational experience to provide insight on mental models and heuristics. The initial phase of CWA, the Work Domain Analysis (Fig. 3) identifies the purpose and boundaries of the analysis as well as how the constructs will be used in relation to the ecological constraints. It provides an event-independent foundation for a complex STS analysis and design through understanding the effect the environment has on achieving the purpose [9].

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. Means-to-ends relationships are used to analyze the propagation of effects of decisions and actions throughout the system on the fulfillment 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 [9].

The resulting constructs can be applied in planning C2 system tests during simulated and field exercises. However, it still doesn't provide information on the dynamic behavior 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 behavior of the system.

D. System Dynamics

The concept of SD was developed to analyze feedback, one of the main causes of complexity, in social systems. Dynamic complexity may exist in simple systems, 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, making controlled experiments difficult and expensive [30][31]. SD utilizes Causal Loop Diagrams and Stock and Flow Diagrams to model and support simulation of complex systems. A disciplined scientific process must be applied to support effective learning and prevent typical simulation pitfalls [11][32].

The behavior of a system is defined as its observed dynamics over time in terms of growth, decline, oscillation, randomness and evolution. Behavior is as a result of the structure of the system and can be analyzed through simulating a series of events in virtual worlds. The structure of a system consists of its stocks, flows and feedback loops that are interlocked. Virtual worlds are used as low cost laboratories to exercise decision making skills, conduct experiments and test assumptions.

SD can be used to support the high level analysis of C2 systems in terms of volume and timing of information to understand the social and technical interaction in a dynamic environment [32]. SD explores what would happen in a system within a number of scenarios and not necessarily to predict the future behavior of a system to learn about possible behavior. Therefore, the validity of a model is not reliant on how realistic the driving scenarios are, but whether the system responds with a behavior represented by realistic patterns [11].

E. Measures of Effectiveness

Measures of Effectiveness measure how well a system performs its higher-level functions within a given operational environment. Measures of Effectiveness refer to the effectiveness of a STS, regardless of how it is physically implemented. Defining the relevant Measures of Effectiveness for a complex STS, such as C2 systems, is a difficult task [6][7]. The problem is that these systems are difficult to isolate from the environment as they are often integrated within a higher order system to support a mission. The Measures of Effectiveness of C2 are integrated into the parent military system which require synergy, and other emergent properties, for a successful mission execution.

Determining Measures of Effectiveness requires an identification of system properties in a top-down approach, starting with 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 to support the accomplishment of the set objective of a mission. These normally involve cognitive aspects of humans that are almost impossible to measure [7]. These elements should be present in the products of a CWA and SD.

F. Complex Sociotechnical System Analysis

The elements in this section are combined to support the analysis and development of complex STS. The basis for analysis is the scientific method used for experimentation. The CWA and SD are added to this framework to support analysis, as seen in Fig. 2. These two methods mainly support the problem discovery and hypothesis formulation phase of the process. The CWA present the current information on the system and operational requirements within the context of the problem. All available information from documents (doctrine) and SME are captured in constructs with means-to-ends relationships. This leads 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 organization and the environment to achieve organizational objectives.

The C2 system models are used to support hypothesis generation through identification of specific cases to produce desired effects. SD modeling can then be applied to analyze different cause and effect relationships within the complex dynamic context. This step helps to identify possible deficiencies in the hypothesis before expending time, effort and funds on experiments. The C2 system models and expected behavior also leads to identification and refinement of Measures of Effectiveness. This serves as input to the experiment design and data analysis.

V. NEW COLLABORATIVE TECHNOLOGY

A. Scenario

The use of a Web-Based Collaboration Tool, through mobile devices (Smartphone), for border safeguarding C2 will be used to demonstrate the proposed analysis framework. The proposed analysis methodology is applied to assist in defining field experiments with the technology. The aim of this assessment is to determine what effect the Collaboration Tool will have on the ability to effectively collaborate for success of

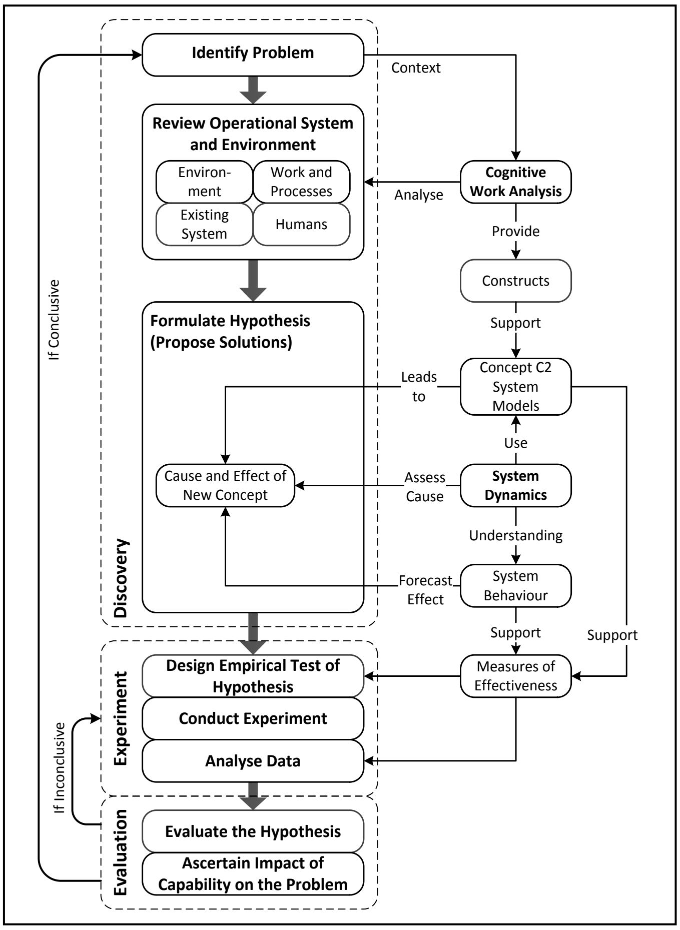

Fig. 2. Experimentation Process for Air Defence Control

an operation. Real time situation awareness in a border safeguarding environment is critical. It includes awareness of own forces location and status, right down to the lowest level of command.

B. Web-Based Collaboration Tool

The purpose of the new Web-Based Collaboration Tool is to provide situation awareness and global track management for decision support. Mobile applications in smart devices can be used to observe the environment (take pictures, record voice and video, get GPS coordinates, compass and accelerometer readings). A centralized server integrates and distributes all the information from the mobile devices into a situation awareness picture. The mobile applications receive feedback and orders from the base station through visual display or voice messages. Several software applications can be used to analyze information to improve situational awareness and provide decision support. The applications of the Collaboration Tool are immediate environment display, blue force tracking, target positioning, information gathering and a search engine.

C. Analysis of New Technology Impact on Border Safeguarding Command and Control

1) Problem Identification. The hypothesis for this analysis states that a Collaboration Tool will assist the C2 system for border safeguarding to issue better orders faster to the correct elements for effective mission execution. Incidents have to be attended to as fast as possible to support successful prosecution of transgressors, despite the environmental constraints of risk, uncertainty and time pressure.

2) Cognitive Work Analysis. The CWA for C2 in border safeguarding with the Collaboration Tool is presented in Fig. 3. This analysis highlighted the effect of the complex dynamic environment on C2 functions. Building the situation picture (Perception) is affected by time pressure. Assessing the situation (Comprehension) is affected by uncertainty through lack or quality of information. The ability to make decisions on the best course of action is affected by the risk involved in doing the right thing balanced with the possible impact of making mistakes. The ability to collaborate with all entities may increase the time pressure as more information sources and decision makers are involved while reducing the effect of risk and uncertainty as more information and interpretations are involved in the decision making process.

3) System Dynamics. The Work Domain Analysis is used to develop a SD model for the Collaboration Tool analysis. The Causal Loop Diagram with feedback loops that relates the Values and Priority Measures with the Purpose Related Functions was compiled, as seen in Fig. 4. This lead to construction of a Stock and Flow diagram, as seen in Fig. 5. The object related functions are used to identify the structural aspects for SD modelling. The stocks and flows represent the perception, comprehension and projection phases of situation awareness as well as the Observe, Orientate Decide and Action (OODA) loop models for C2 [16]. Time pressure will limit the amount of information available, uncertainty will limit the quality situation assessment performed and the risk will limit the decisions being made.

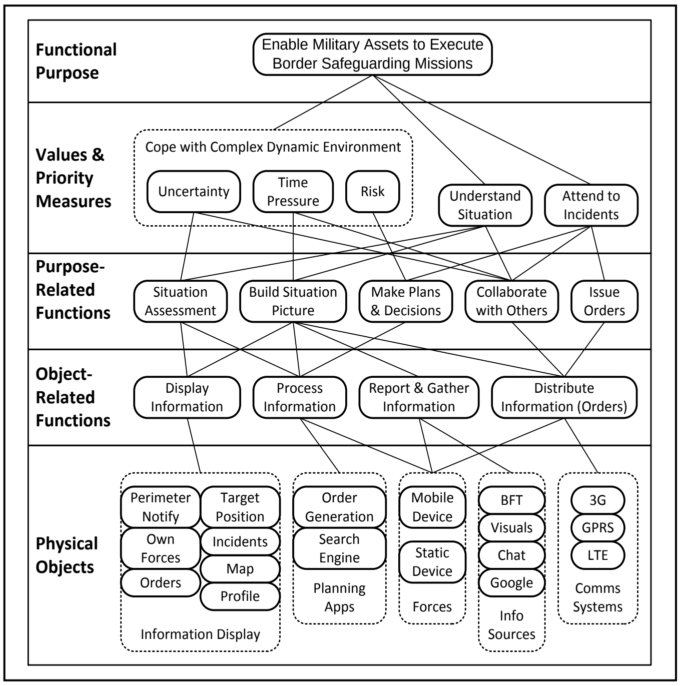

Fig. 3. Abstraction Decomposition Space for WBCT

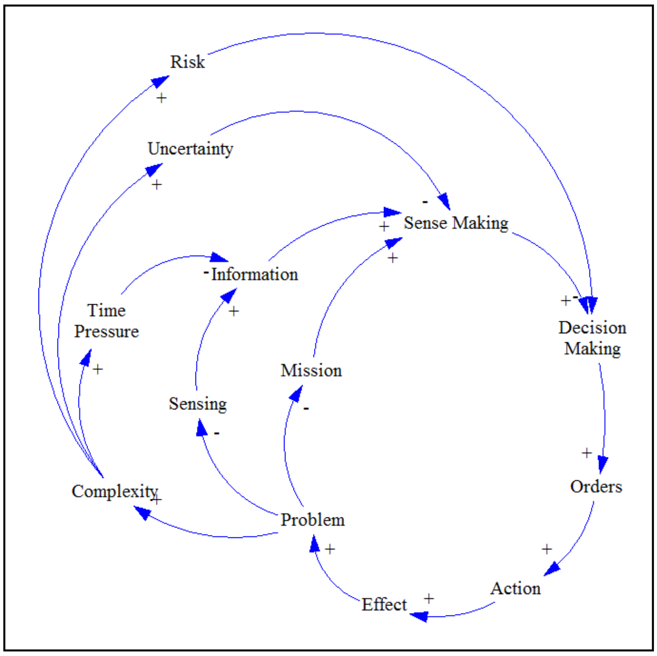

Fig. 4. Causal Loop Diagram for WBCT

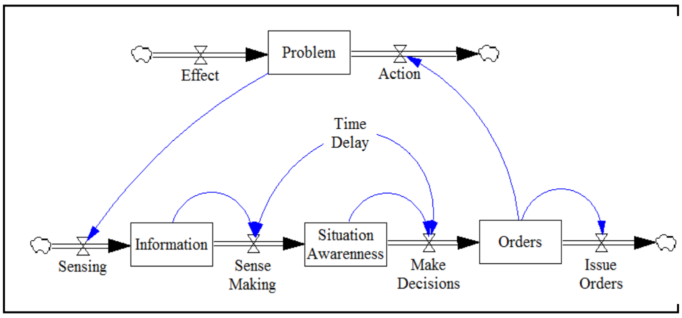

Fig. 5. Stock and Flow Diagram for WBCT

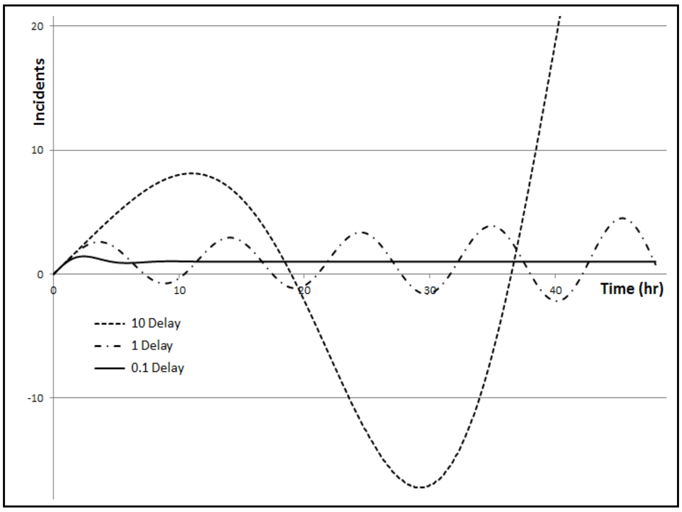

Fig. 6. Simulation Output Graph

4) Simulation. Simulations were used to assess the effect of collaboration in supporting gathering of information in support of the operation. Simple linear inputs were used to illustrate the effect of inherent delays due to feedback and stocks in the system for a 48 hour period, as seen in Fig. 6. The vertical axis indicates the number of incidents, which should converge to 1 in an ideal situation. The graph indicates that longer delays in the system case instability. This shows that efforts to reduce delays will increase stability in the system. The Collaboration Tool have to enable the decision makers to anticipate into the future for the best results.

5) Experimentation. The modelling and analysis in the previous steps support experimentation with a new technology in a complex STS. A hypothesis can be defined and validated within the structure and dynamic interaction of the STS. The areas where human operators can influence the process within the environmental constraints are identified and dynamic behavior of the system as a result of delays understood. The ability to anticipate future situations needs to be enhanced and its effect measured. A campaign of experiments can now be planned to support learning about the problem to improve the models.

VI. CONCLUSION

In complex STS the introduction of new technology will influence how work is performed and how the humans in the system interact. System analysis, through a set of experiments, is required to determine the impact of the new technology. Since complex STS are difficult to analyze and develop, a sound experimentation process based on a hypothesis s must be followed. CWA and SD are analysis and modeling frameworks capable of addressing complex STS. They address humans interacting and doing work with artifacts within the constraints of the environment. The effect of feedback loops with delays on behavior of the system is also considered. These methods assist in defining the cause and effect for a hypothesis for planning and execution of experiments. The results of the experiments should improve the knowledge on influence of different technologies on the STS. The systems engineering process requires this knowledge to define requirements for development of the system.

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