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Abstract

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Keywords

Systems, dynamics, modelling, human, information, aspects, network, centric, configurations

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SYSTEMS DYNAMICS MODELLING OF HUMAN AND INFORMATION ASPECTS OF NETWORK-CENTRIC CONFIGURATIONS

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Abstract. This paper is based on the definition of a network-centric structure as one which enables members of an organisation to create and leverage information to increase competitive advantage through the joint efforts of creative individuals and independent teams. While the technical components of this environment are enabling, the organisational and behavioural components generate value as traditionally competitive workers strive to cooperate in self-directed, distributed teams. Many organisations are now complex hybrids of hierarchical and network-centric configurations and there is a need to increase our understanding of their human and informational aspects. Due to its suitability for managing complexity without reducing it to a simpler form, this paper concerns the use of the holistic and dynamic technique of systems modelling for research in this area. The use of stock and flow systems modelling is described and examples of its application to realistic network-centric phenomena, incorporating human and informational elements, are presented. Development of these models is not easy, neither is it an exact science. This approach does however have the potential to visualise and manipulate an interconnected set of human and informational elements to enhance understanding of the complex network-centric paradigm.

INTRODUCTION

The original concept of network-centrism is reflected in the following dictionary definition of the term Network-Centric Warfare (NCW) as "computerized warfare**:** relating to warfare that employs instantaneous electronic cooperation among air, ground, and naval forces, smart munitions, spy planes, drones, and commandos equipped with computers and laser-guided weapons, all coordinated to orchestrate highly accurate attacks" [1]. In contrast, recent Australian-based research describes a network-centric structure more broadly as one which enables members of an organisation to create and leverage information to increase competitive advantage through the joint efforts of creative individuals and independent teams [2]. As these authors say, the capability to do this, results from developments of Information and Communications Technology (ICT), however this view of network-centrism is more about people and culture than technology. While the technical component enables, the organisational and behavioural components generate value. From this perspective the network-centric environment implies new ways of operating that authorises workers to make strategic cooperative decisions throughout the enterprise through the sharing of knowledge so that centralised command and control is no longer the norm. According to Warne et al [3], the need to cooperate in self-directed, distributed teams is fundamental to network centric configurations. Here cooperative activity comprises multimodal communication for collective onsite decisions leading to local action.
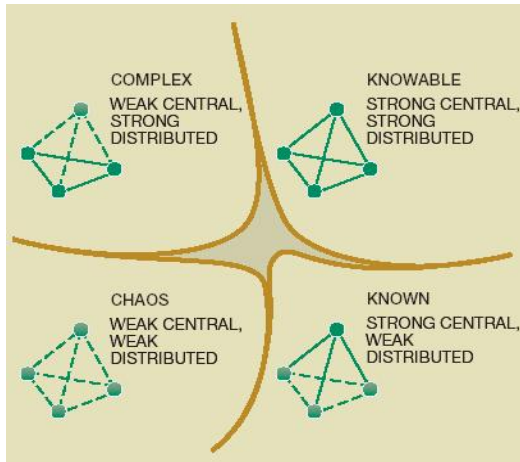
In order to increase our understanding of these critical human and informational aspects of network-centrism, this paper proposes the use of the holistic and dynamic technique of systems modelling. The case for this approach will be based on its suitability for managing complexity without reducing the multiple elements and relationships of complex situations to a simpler and more abstract form. The use of stock and flow systems modelling will be described and examples of its application to realistic network-centric phenomena, incorporating human and informational elements, will be presented and discussed.
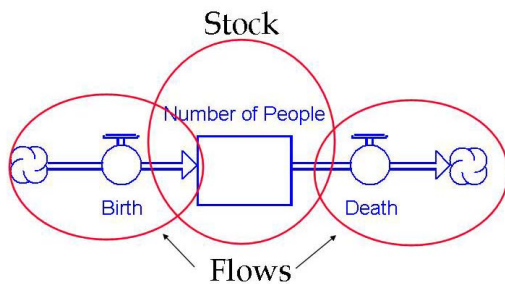
COMPLEXITY AND SYSTEMS THINKING

According to Senge [4] Systems Thinking is a body of knowledge and tools that has been developed over the past fifty years, in conjunction with General Systems Theory [5] and Checkland's Soft Systems Methodology [6]. A *system* is by definition an assemblage or combination of elements or parts forming a complex inter-related whole that is "more than the sum of its parts". The adjectives holistic, integrated, dynamic and, in particular, purposeful describe systems of which there are many instances such as biological systems, ecology systems, urban systems, organisational systems and information systems, among others. In his seminal work on learning organisations, Peter Senge [4] notes that all human endeavour is becoming more complex, dynamic, and globally competitive. He makes a case for Systems Thinking as the discipline that will give a better understanding of this complex world. He writes; "from a very early age, we are taught to break apart problems, to fragment the world. This apparently makes complex tasks and subjects more manageable, but we pay a hidden, enormous price. We can no longer see the consequences of our actions; we lose our intrinsic sense of connection to a larger whole."

There is a current interest and growing understanding of how to work with complex systems, which involve a number of elements, arranged in structure(s) which go through processes of change that are not describable by a single rule nor are reducible to only one level of explanation. These levels often include features whose emergence cannot be predicted from their current specifications. Previously, when studying a subject, researchers tended to use a reductionist approach which attempted to summarise the dynamics, processes, and change that occurred in terms of lowest common denominators and the simplest, yet most widely provable and applicable elegant explanations. Since the advent of powerful computers, which can handle huge amounts of data, make rapid computations and provide direct manipulated screen modelling capability, researchers can study the complexity of factors involved in a subject and see what insights that complexity yields without simplification or reduction.

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Figure 1. The four perspectives on organisations, knowledge, information and systems depicted in the Cynefin framework [7] showing the connection strengths of the domains [8].

Figure 2. The symbols representing Stocks and Flows in the computerised Stella Systems Dynamics modelling tool.

Snowden [7] states that in complex situations it is not possible to predict or determine outcomes in advance, and cause and effect is only seen in hindsight. Complexity itself is characterised by a number of important characteristics such as self-organisation, non-linearity and emergence. Snowden proposes the Cynefin model which utilises the self-organising capabilities of informal communities to understand how to manage knowledge both as a thing and a flow. As shown in Figure 1 the Cynefin model is a knowledge space with four domains which set the context for collective decision making: two domains of order, the known and the knowable, the domain of complexity and the domain of chaos. Each has a different mode of community behaviour and each implies a different form of management and a different leadership style with the adoption of different tools, practices and conceptual understanding. Snowden's understanding of the characteristics of self-determination, emergence and organic forms that apply in the Complex quadrant are of particular interest to the philosophy of Systems Thinking as applied in our research

SYSTEMS DYNAMICS AND STOCK-FLOW MODELS

Hitchins [9] describes Systems Thinking as a way of managing complexity by conceiving of and testing ways of changing behaviour *in vitro*, with a view to implementing similar changes *in vivo*. The models that it engenders are, in general, nonlinear because the world they represent is

nonlinear. Richmond [10] defines Systems Thinking as "the art and science of making reliable inferences about behaviour by developing an increasingly deep understanding of underlying structure". It is therefore both a way of looking at a problem and a set of tools to address it. Such tools occupy the realm of Systems Dynamics which include computer-based modelling and simulation. While Systems Thinking provides a way of studying complex phenomena in a holistic and dynamic manner, systems dynamics is a formal quantitative analysis of the structures and typical behaviours of systems.

Techniques such as casual loop diagrams as well as stock and flow based models are often used for both research and practice (see for example [11]). Now, computer-based packages with direct manipulation graphical user interfaces make this type of analysis visual and interactive. The techniques of systems modelling and simulation can play a significant role in analysing the operational characteristics of a system for supporting strategic thinking and decision making. The behaviour of a system as it evolves over time can be studied by developing a simulation model. Once developed and validated, a model can be used to investigate a wide variety of "what-if" questions about the real-world system. Potential changes to the system can first be simulated in order to predict their impact on system performance.

STELLA © [12] is one computer-based modelling and simulation program that enables the user to investigate time-based systemic problems and what-if analyses, recognising mathematical relations through pictures and patterns. It uses the basic structures shown in Figure 2 where:

- a Stock is a state variable that corresponds to the amount of stuff in various parts of a system, and

- A Flow is an input or output expression corresponding to the rate of change due to movement of the relevant stuff in and out of a stock.

The particular approach to stimulation using systems thinking with stocks and flows is recommended by Sterman [13] who reported that system dynamics modelling is important tool for complex real world systems. He recommends that systems modellers use stock-flow networks in systems with the computer simulation application Stella ©[12]. Using Stella software is a computer-aided way for effectively constructing effective models and simulation activities. Stella provides a easy to use graphical interface for constructing dynamic models that visualise and communicate how a system work through a stock flow diagrams. In the Stella language the stocks are nouns and are presented by rectangles, while flows which occur in and out of stocks are verbs that represent actions and activities. The other elements in the Stella language are converters, represented as circles, that are used to modify the verb productivity and connectors that link converters to stocks, flows or other converters. With this basic understanding the Stella model presented here should not be difficult to interpret.

While Stella has traditionally been used to represent stocks and flows of physical materials, it can also be used for non-material entities such as information, understanding and knowledge. Such entities are used in our models but it is important to note that there is one significant difference where they are concerned. When something physical such as water flows it leaves one stock and moves to another. When

something like information flows it does not diminish the source in the same way, for example if I tell you some piece of information I do not lose it when you gain it. This has implications for stock-flow models in that, while separate stocks have inflows and outflows the relationship between these is not a simple flow from one to the other as one might intuitively think. The following descriptions of models should be viewed with this in mind.

Our NCW studies use collected data, together with insights from the literature, to simulate information, decision and action flows in relevant situations, using systems modelling to explore and display the issues in a dynamic and holistic way in order to gain a greater understanding of the communication processes, decision-making and subsequent actions. Systems dynamics models are developed using Stella software in an evolutionary fashion. The models become a means of presenting this understanding to all stakeholders whose feedback informs further improvements to the models which can in turn inform practice. To illustrate this models of three network-centric phenomena are now presented. In each case there is a brief description of the origin and purpose of the model, followed by an explanation of the stocks, flows and other components of the system. While most models are conceptual, some have been implemented as simulations with estimated variables as shown in Figure 5a and 5b.

KNOWLEDGE IN HYBRID ENVIRONEMNTS

Many organisations are now hybrids of a traditional hierarchy, with a limited command and control structure, allowing the emergence of self-directed groups in a network-centric configuration. For example, the case-study research of Peltokorpi and Tsuyuki [14] depicts a project-based organisation which is in fact a hybrid of a formal corporation and a dynamic network-centric organisation whose loosely-coupled nodes are self-organising work units. The domain of network-centrism now encompasses the organisational, social and cultural, as well as the technical, aspects of working in these changing, hybrid environments. Where organisations are adopting network-centric practices within a hierarchical bureaucracy, they face the challenge of imposing culture change much more rapidly than it would normally occur. Managers are having to relinquish some of their traditional control to small self directed teams while workers must increase their situational awareness in order to take on more decision-making responsibilities within a small less formal group setting. In these hybrid environments organisational work and knowledge, requires sense-making at three different levels of aggregation: that of the individual actor, that of the group or unit within which the actor works and the organisational context for the work activity. Understanding the dynamic situation at each of these levels is complex enough but a holistic view of how the three levels interact lends itself to simulation using a systems dynamics modelling approach. The Stella conceptual model of Figure 3 is based on literature that promotes the coexistence of the three levels of organisational knowledge [15] and sense making [16].

The Stocks in this model are knowledge with respect to an individual **IndividualK**, to a group **CollectiveK** and that of the organisations, **OrganisationK**. Flows in are based on learning (Learning, CollectiveLearning and OrgLearning). Individuals loss knowledge through forgetting or getting rusty, organisations also forget while groups are behave

dynamically as links are formed and broken. Assumptions are made as follows: culture is influenced by collective and organisational knowledge and in turn influences the learning process at each level; individual knowledge contributes to organisational learning through intellectual capital; collective knowledge contributes to organisational learning through social capital.

PROFESSIONAL COMMUNICATON UNDER STRESS

Wolstenhome [17] and Derrick et al [11] have used stock-flow modelling techniques in the UK health services and these studies, together with the models of Hitchins [9 p400] on work flows and Richmond [10 p 8] on the learning process, have strongly influenced our research in the realm of communication between healthcare professional and the public. This section describes how a stock-flow model was developed using Stella software to represent the communication between the staff of Intensive Care Units (ICU) and patient's families. The researchers used the literature review and data gathered from the three groups of stakeholders to create and improve the model through a series of iterations.

Key STOCKS were identified with appropriate in and out flows as shown in Figure 4. For the family members the Stock was the UNDERSTANDING of what was happening to their loved one while for the clinicians it was RELEVANT MEDICAL KNOWLEDGE generated by, and applicable to, the case at hand. Both these stocks mediated, and were mediated by, the patient's condition which is represented by the stock PATIENT CRISIS LEVEL.

Using these three stocks as the foundation, an integrated conceptual model was created and improved over several iterations with feedback from researchers and stakeholders. The current version of the model is depicted in Figure 4 and its components are explained below. We found that the issues that influenced in the stocks and flows were:
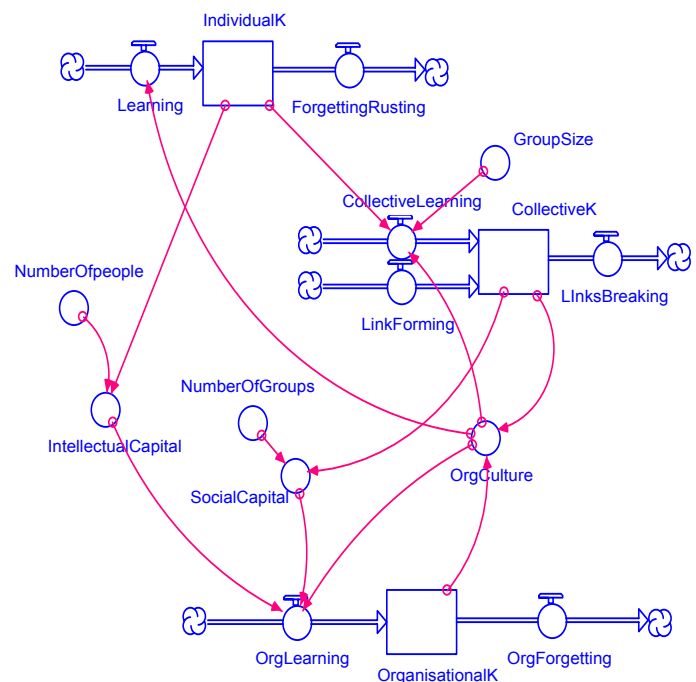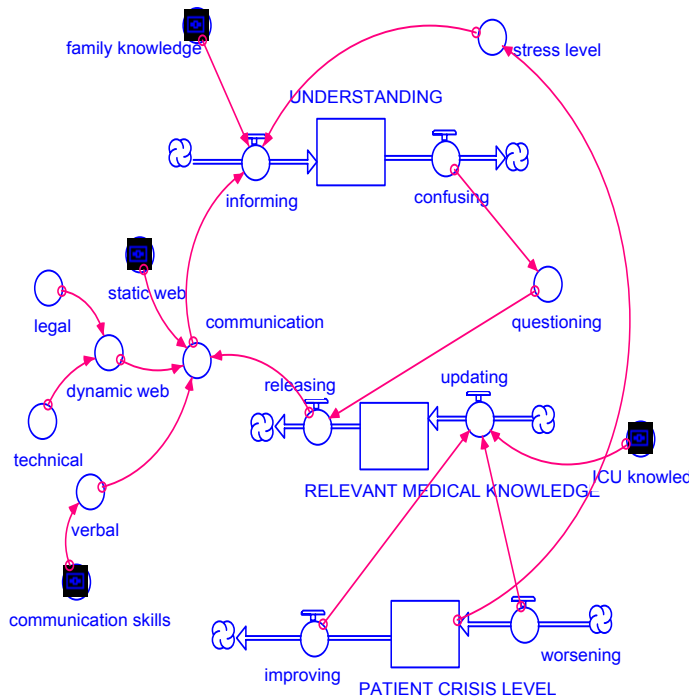

Figure 3.   Stella model of 3 levels of organisations.

Figure 4.   **Stella model of communication in an ICU.**

- The amount of UNDERSTANDING acquired from information provided to the families was affected by their level of medical knowledge, the quality of the communication and their level of stress due to the patient's condition. These are supported both by the literature and our research and are represented in the model by the three converters *family knowledge*, *communication* and *stress level* respectively.

- The stock of working RELEVANT MEDICAL KNOWLEDGE is required by the ICU staff at any time both to treat the patient and to inform the family. Its *updating* is triggered by changes to the patient's condition (*improving* and *worsening*) and *questioning* from the family. It is also influenced by the medical capability of the ICU clinicians and the quality of both their general medical knowledge and their knowledge of things specific to the ICU (converter *ICU Knowledge*).

- The converter *communication* on the left-hand side of the model is critical and the results of the research have been used extensively to incorporate various parameters into this section of the model as follows:

  o The quality of traditional *verbal* communication affected by converter *communication* skills

  o The role of a *static web*-based information service as is currently the case in the study.

  o The possible role of a *dynamic web*-based information service as many stakeholders reported that is this is important to meet users' needs for specific and query-able information about their patient. However the web-site owners indicated that this would be affected by factors represented by converters *legal* and *technical*. .
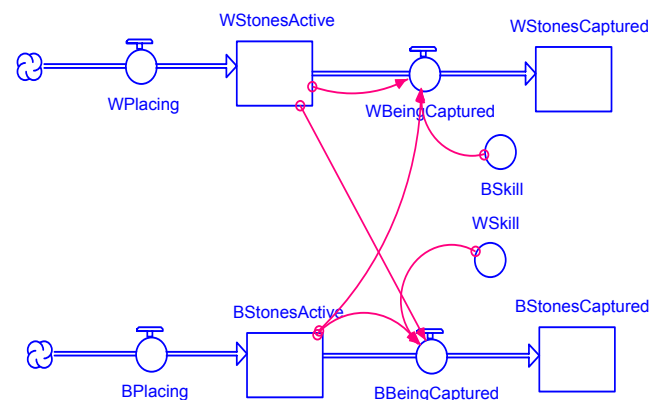
We consider that this model is generalisable to non-healthcare situations where experts must communication to

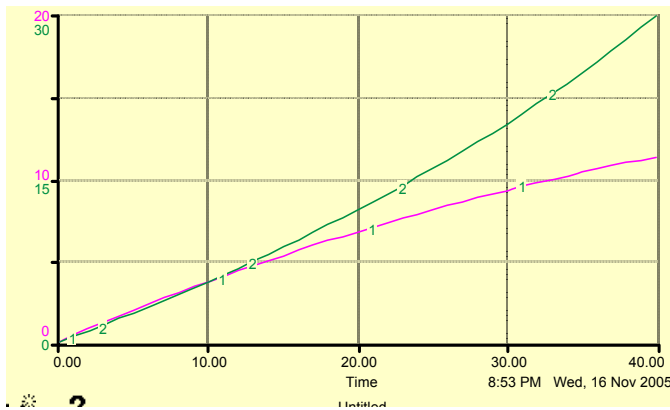others under conditions of stress with a mix of face-to-face and computer-mediate modes.

SHARED SITUATION AWARENESS AND COLLECTIVE DECISION-MAKING

As described elsewhere [18.19], Go*Team is an online team-based version of the ancient strategy game of GO. It is a tool that is used to study, train and profile the capability of individuals and teams to make strategic decisions and act cooperatively where there is stress, uncertainty and complexity and a need to share information in a network-centric environment. The playing of Go*Team can lead to a better understanding of the collective processes and behaviour of people in organisations. Of particular interest are human or group related factors that may impede or even prevent the successful achievement of team coordination, cooperation, information sharing and consequently knowledge sharing [18].When designing a Go*Team episode a significant set of variables can be manipulated, including the experience of individual players, the composition of teams, the type of communication channels between team members, the tempo of the play, the size of the board values and so one. The number of possible permutations of these variables is too large to attempt to collect enough live data to see the effect of them all. Simulation provides a means of manipulating some of these factors to determine their likely affect in a much more timely fashion. The following demonstrates how this might be done through increasingly complex systems dynamics "stock and flow" modelling, in this case using Stella software.
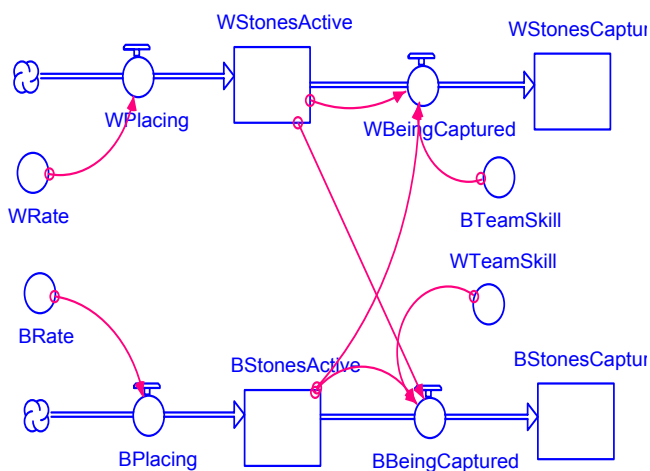
In the traditional game of Go two individuals play, White against Black, each player taking turns to play stones to capture territory and stones of the opponent so that the players' skill is the main determinant of the outcome. In the Stella model of Figure 5a white skill is rate higher than black and so over time captures more black stones. This is reflected in the graph of a simulated run shown in Figure 5b.
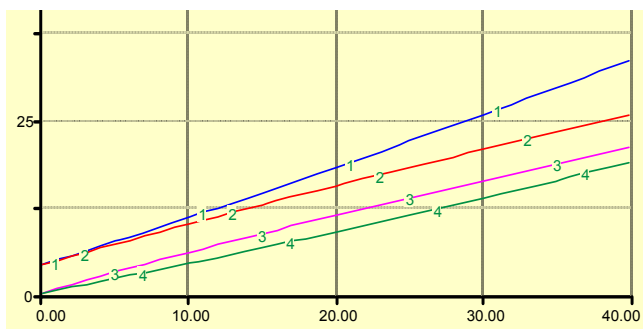

Figure 5a.   **Stella model of traditional Go where two individuals of different skill-levels play, taking turns.**

Figure 5b. A simulation of Model 5a in arbitrary units where 1 is White Stones Capture, and 2 Black Stones Captured over time.

Figure 6a. Stella model of Go*Team with added complexity to the Go model of Figure 5a.

Figure 6b. A simulation of Model 6a in arbitrary units where 1 is Black Stones Active, 2 is White Stones Active, 3 is Black Stones Capture, and 4 is White Stones Captured over time.

A simple example of the extra complexity of Go*Team over traditional Go is shown in Figure 6a. In Go*Team players do not take turns but can place a stone whenever they like after a "relaxation time" which can vary for each team and over the course of the game. Even if this is fixed, one team may actually take longer to make the decision to play than the other team. In the Go*Team simulation below the time variables (WRate and BRate) are set to offset the skills (WTeamSkill and BTeamSkill). So, although White is more skilful. they play at a slower rate. The time-series graph of
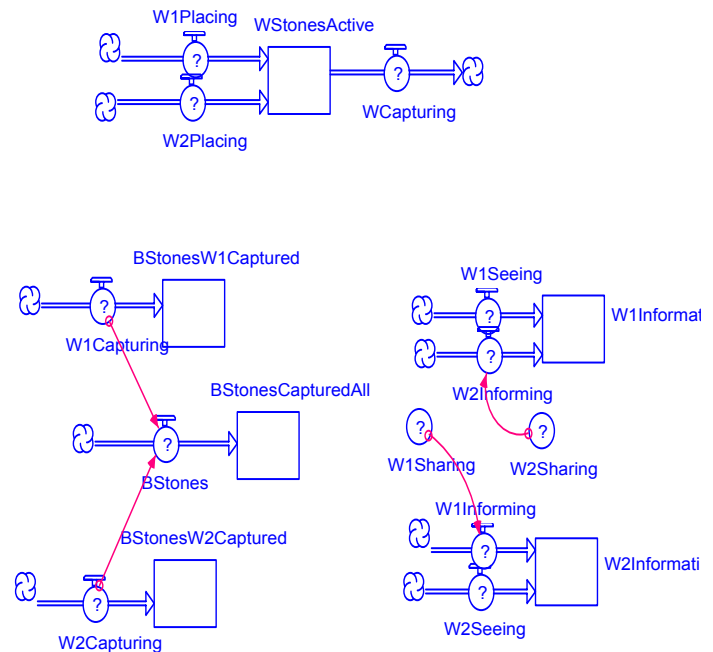
Figure 6b shows more black stones on the board but also more captured.

The model of Figure 7 shows Go*Team with two players per team. This model is not yet set up as an integrated simulation but indicates the potential to incorporate more Go*Team variables and constraints. The components of the model relevant to the white team are as follows:

The top grouping shows the stock of white stones active (ie on the board) growing due to stones place there by W1 and W2 and being reduced if a stone is captured. Black would have a similar grouping.

The left hand grouping shows the stocks of black stones captured: those by W1, those by W2 and the total captured. Black would similarly have white stones captured.

The right-hand groups show the information of the positions of white and black stones held by W1 and W2. W1 knows what he/she has seen plus what information has been gained through communication from W2 which could be affected by the willingness and ability of W2 to share. Similarly, W2 knows what he/she has seen plus what information has been gained through communication from W1. Information sharing is crucial in Go*Team to build up a shared situation awareness as each team member has only a partial view of the board.

Figure 7. Stella Model showing a Go*Team session with 2 players per team. Plays and information communicated for shared situation awareness are shown for both teams but not integrated.

DISCUSSION

The three sets of models presented above deal with critical human and informational aspects of network-centrism. Firstly, in Figure 3, there is a representation of the interaction of knowledge and learning at individual, group and organisational levels of a hybrid enterprise. The collective level is the site of the self-directed groups of a network-

centric configuration contributing to organisational learning through the accumulation of social capital.

Secondly, in Figure 4, there is a model of communication between two groups, one of medical professional and the other members of the public under the stressful situation when a family member is critically ill in an ICU. The purpose of this research was to foresee the impact that web-based information may have on the quality of this communication. It is widely understood that this could contribute to improved decision-making for the patient by responsible family members and better health outcomes This model could be adapted to situations where groups of different levels of expertise must communicate in condition of stress to increase their level of understanding for decision-making and action.

Thirdly, in Figure 5, 6 and 7, there are models of the Go*Team gaming environment where team members must share information to make decisions and act to achieve the goal of winning the game. Figure 7 is only a first step to an integrated model where the relationship between information exchanges and group performance are simulated. Many other factors could be introduced that could be assumed to affect the quality of the communication and the achievement of team goals representing collective behaviour in a true network-centric environment.

This use of the holistic and dynamic technique of systems modelling is suitability for studying hybrid environmental situations without reducing the complexity of the context. We have found the use of stock and flow modelling in Stella to enable the incorporation of human and informational elements into first conceptual models and then ones that can be simulated. Results of the latter were shown in Figures 5 and 6 although meaningful simulations are now being developed for the models of Figure 3 and 4. When producing exploratory dynamic simulations of models in Stella there are challenges to face in respect of the following:

- Finding suitable units to quantify the stocks and flows

- Establishing meaningful functional relationships or parameter values for the converters.

- Finding the most effective way to drive the model with some typical, random or cyclic behaviour of one or more elements.

Experience shows us that development of these models is not easy, neither is it an exact science when dealing with the softer human aspects of network-centric environments. This approach does however have the potential to visualise, through conceptual models, and perhaps manipulate, in a quantified simulation, an interconnected set of systems elements to enable enhanced understanding of the complex network-centric paradigm. While attempts to rigorously quantify the soft variables in these models may be problematic, it is argued that they do provide an opportunity to gain valuable insights into the human processes being studied.

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