Modelling a Network of Decision Makers[1]

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Abstract

New information technologies introduced into military operations provide the impetus to explore alternative operating procedures and command structures. New concepts such as network-centric operations and distributed, decentralised command and control, have been suggested as technologically enabled replacements for platform-centric operations and centralised command and control. As attractive as these innovations may seem, it is important that responsible military planners test these concepts before their adoption. To do this it is necessary to build models and simulations and to conduct experiments and exercises.

The authors assess the flow of information within three alternative Command and Control (C2) structures using a series of quantitative measures of performance of command and control effectiveness. In terms of the categorisation developed by Alberts,[2] these metrics bridge between the information domain and the cognitive domain.

The quantitative assessment of information flows within alternative C2 structures is part of a larger programme of work considering the structure of future headquarters for UK armed forces. Outputs are being compared with high level combat models outputs in order to assess the quantitative linkage between our measures of C2 effectiveness and metrics of benefit at the campaign level, measures of force effectiveness.

This addresses a key challenge identified in the NATO Code of Best Practice for Command and Control Assessment.

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[2] D.S. Alberts et al, '*Understanding Information Age Warfare'*. CCRP, DoD, Washington DC, USA, 2001.

Introduction

Network Centric Warfare and Network Enabled Capability

Network Centric Warfare (NCW) continues to develop through an on-going dialogue among an increasingly diverse group of proponents. In the United Kingdom, the counterpart to NCW is Network Enabled Capability (NEC). NEC shares the tenets of NCW, but it is more limited in scope in that it is not a doctrine or a vision. Nor is the network placed at the centre of capability in the doctrinal way implied by NCW. Rather, NEC is mainly concerned with evolving capability by bringing together decision-makers, sensors and weapons systems, enabling them to pool their information by "networking" in order to achieve an enhanced capability.

The key objective of NEC is to allow platforms and C2 capabilities to exploit shared awareness and collaborative planning to communicate and understand command intent and to enable seamless battlespace management.[3] Despite the differences already identified, the logic of Network Enabled Capability is essentially the same as the logic of Network Centric Warfare which is summed up in the following diagram.

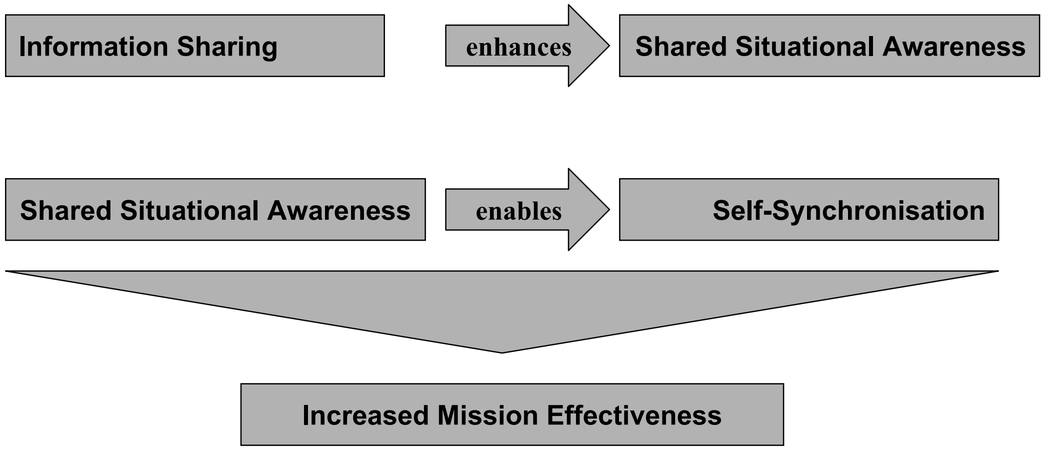

Figure 1. Adapted from "Tenets of NCW."

The work presented in this paper assesses and furthermore even quantifies the enhancing and enabling indicated in the diagram. This is a huge challenge, and the work is still in progress. Nevertheless, building on the well established Theory of Information Entropy and the Rapid Planning Process[4], researchers from RAND and Dstl have produced metrics for C2 Effectiveness (Command and Control Effectiveness) which seek to capture the benefit of NEC. These metrics have been incorporated into the *Collaboration Metric Model* (CMM). Some simple alternatives

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[3] Lt Gen Rob Fulton, high level mission statement for NEC.

[4] J Moffat "*Command and Control in the Information Age: Representing its Impact*", The Stationery Office, London UK 2002

for information sharing are then examined in this paper using the model to demonstrate its potential utility.

Combining C2 metrics with high level combat modelling, in ongoing work we are investigating the connection between measure of C2 effectiveness and measures of force effectiveness. In this way the work attempts to link across the Physical Domain, the Information Domain and the Cognitive Domain.

The combat model chosen for this work is HiLOCA – High Level Operations with Command Agents using Cellular Automata.[5] HiLOCA is a research tool which represents HQ processes explicitly. It simulates the dynamic interaction between manoeuvre, firepower and support assets and the collection and processing of sensor-derived information.

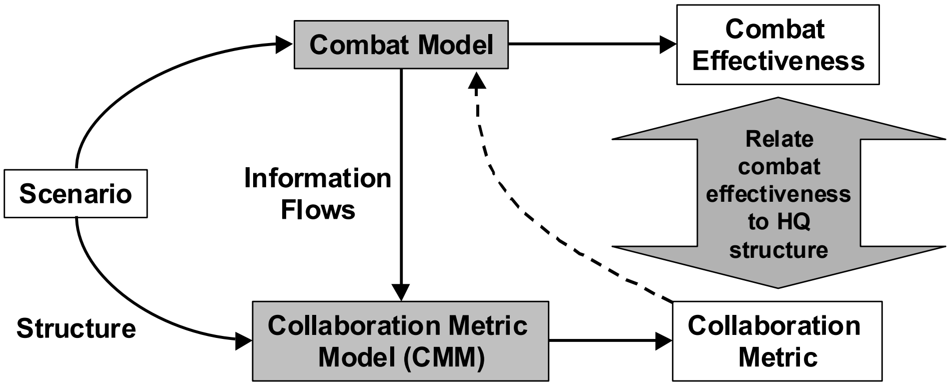

Figure 2. The relationship between the CMM and Combat Models.

The Collaboration Metric Model

Decisions in a Network

This approach brings together two sets of ideas, which have been developed thus far from rather different perspectives. The first is the Rapid Planning Process developed by Moffat[6] which represents the decision-making of military commanders working under stressful, fast changing circumstances. The second comes from the work by Perry[7] who modelled the effects of network-centric warfare carried out recently at RAND for the U.S. Navy. This examines the effects of collaboration across alternative information network structures in prosecuting a time-critical task. By combining these two approaches, metrics can be developed which measure the overall benefit to decision making of sharing information across an information network.[8]

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[5] The HiLOCA tool is owned by QinetiQ Ltd, but was developed by the Defence Evaluation and Research Agency, the predecessor organisation of Dstl.

[6] J Moffat '*Command and Control in the Information Age; Representing its Impact'*. The Stationery Office, London, UK, 2002.

[7] W Perry et al '*Measures of Effectiveness for the Information-Age Navy*' . RAND National Defense Research Institute, MR-1449-NAVY. RAND, Santa Monica, CA, USA, 2002.

[8] W Perry and J Moffat '*Information Sharing among Military Headquarters; The Impact on Decision Making'* Draft Accepted for Publication. Joint RAND/DSTL publication DRR-2965-UK, (2004).

New technologies allow militaries to leverage information superiority by integrating improved command and control capabilities with weapon systems and forces through a network-centric information environment. This provides a significant improvement in awareness, shared awareness and collaboration which in turn affect the quality of the decision making process and the decision itself. These decisions ultimately lead to actions that change the battlespace.

Here, we are concerned with the quality of the decisions. Decisions are made based on the information available from three sources: information resident at the decision node, information from collection assets and information processing facilities elsewhere in the network, and information from other local decision makers with whom they are connected and with whom they share information.

Rapid Planning Process

In most cases, decision makers must make decisions, without full understanding of the values of the critical information elements needed to support the decisions. The decision taken depends upon the current values of these critical information elements, which are dependent on the scenario. That dependency is modelled using the Rapid Planning Process. The critical information elements form a frame of reference for the commander's conceptual space. In the basic formulation of the Rapid Planning Process, a Dynamic Linear Model is used to represent the decision maker's understanding of the values of these elements over time. This understanding is then compared with one or more of the fixed patterns within the commander's conceptual space leading to a decision.

A probabilistic information entropy model is used to represent the uncertainty associated with the critical information elements needed for the decision. Through the Rapid Planning Process, information from collection assets or from collaborating elements in the network serves to reduce uncertainty and therefore increase understanding.

Knowledge

We are principally concerned with the information and cognitive domains. Information derived from sensors or other information gathering, resides in the information domain. This is transformed into awareness and knowledge in the cognitive domain and forms the basis of decision-making. Our metrics quantify this process through the use of information entropy and knowledge measures.

Information sharing among nodes ideally tends to lower information entropy (and hence increase knowledge) due to the build up of correlations among the critical information elements, and through filling in gaps. Thus, for example, information can be gained about one critical information element (for example, missile type) from another (for example, missile speed). Such cross coupling gives the correlation and this is a key aspect for investigation.

Knowledge derived from entropy is a quantity that reflects the degree to which the local decision maker understands the values of the information elements. It is represented as a number between 0 and 1 with the former representing poor or no understanding and 1 representing good or perfect understanding. From this knowledge, decision-makers can then assess whether or not they are in their ‘comfort zone’ that is, whether the values of the key information elements support the decision they wish to take (such as to launch the next attack mission.) Networks provide an opportunity for participating entities to share information as part of a collaborative process. Here we focus on the synergistic effects of collaboration that improve the quantity (the completeness of our information), and the quality (its precision and its accuracy) of the information needed to take decisions. We model the network as the combination of clusters of such entities. Each such cluster consists of a set of entities, which have full shared awareness - all entities in the cluster agree on the set of information elements, and their values at any given time.

The CMM is a mathematical model implemented as a spreadsheet. It can currently handle up to ten decision nodes, ten information elements, and ten information sources.[9] This allows a reasonable representation of a headquarters or a network of headquarters. Metrics for network redundancy and information overload have recently been added to the model. The Overall Network Performance (ONP) metric now incorporates 6 sub-metrics as listed below.

1. Precision
2. Accuracy
3. Information Completeness
4. Network Redundancy
5. Information Overload – Unneeded Information
6. Information Overload – Redundant, Needed Information

Through observations of the battlespace, sensors and other information sources generate estimates for the information elements deemed critical to the decision. The uncertainty associated with the information elements is expressed in terms of probability distributions. The means of these distributions are estimates of the ground truth values. From these we derive estimates of *precision* and *accuracy.* These are then combined with a measure of *information completeness* to arrive at a single metric to assess the beneficial effects of collaboration across a cluster of information sharing entities. *Network redundancy* deals with receiving multiple reports of required information from several sources which will increase the reliability of the estimates of information elements in the model. When too much information is provided to a decisionmaker, the collaboration metric is also reduced. There are two types of such *information overload* in the model. One is when nodes receive information that is not needed. The other is when they receive too much needed information. In each case, the additional information penalises the overall collaboration metric.

The 6 metrics can be roughly broken into ‘Information’ based metrics (Precision, Accuracy) and ‘Structure’ based metrics (Completeness, Network Redundancy, Information Overload). Two things are needed to run the CMM— a network topology and information elements. Both could potentially be provided by operational data collected post-conflict, or real-time data during an exercise, or from a combat model.

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[9] It would not be difficult to extend the model to cope with more than 10 nodes, elements or sources.

The Overall Network Performance metric (ONP) then combines all the measures of benefit of a particular clustering of information sharing entities (e.g. headquarters or parts of a headquarters) across the information network. The approach thus allows the exploration of alternative ways of forming information sharing clusters of decision makers, and a comparison of their likely effectiveness. From this we can form hypotheses for experimentation, or compare with the results of simulations to gain additional insight.

This work has focussed on producing a synergy between the CMM and combat models which produce the necessary input data. This study used the combat model HiLOCA. We now detail the relationship between the combat model and the CMM.

CMM – Some Early Results

Impetus

There are two central questions we wish to develop in this paper:

How do we instantiate different models of decision making and network structures in the CMM? We have chosen to concentrate on two modes of decision making associated to logistics. This is intended to represent extremes of logistics decision making: *supply led* and *demand driven* logistics. The metrics developed in the CMM should be sufficiently robust to differentiate among the corresponding networks. The overall performance of the network should distinguish between the extremes.

Given a specific network topology, how does the level of clustering change the various information and structure metrics developed in the CMM? We wish to analyse the effects of different levels of information sharing on the metrics produced in the CMM. We do this by splitting the demand driven mode into two cases: one where each node works in isolation, and one where some nodes are clustered and work with the knowledge of their peers.

Vignette

The vignette we used to provide the network topology and information elements was a red-on-blue engagement taking place over 24 hours. The vignette is extracted from a larger well-established scenario used in policy planning. It covers the period at the start of a ground war as a Blue division moves against screening elements of a Red Division followed by an engagement against a second Red Division that advances in response to the Blue attack.

There are 10 units associated with the logistics function. The use of materiel by these units was aggregated to 10 minute increments which produced 144 data points for each asset over the course of the day. The use of 30mm ammunition provides a starting point for the analysis. Figure 3 shows the use over time for three of the logistics units.

Various materiel can potentially be analysed in this example. The HiLOCA combat model provides details on a host of materiel, supplies, and other logistics infrastructure. In the example described here, we focus on the consumption of 30mm ammunition.

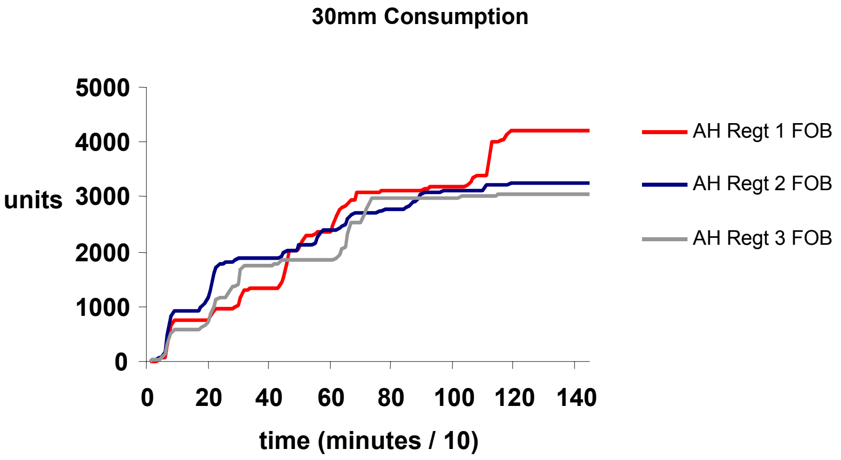

Figure 3. Aggregated use of 30mm ammunition by three logistics units of the blue force over 24 hours of the simulation. A consumption unit of 30mm ammunition is 30 shells.

Descriptions of the Structures

Three structures have been assessed in the CMM with data coming from the combat model. These are shown in Figure 4. The three cases are:

- (S) Supply: Information on consumption is sent to the second and third line logistics units but the amount supplied to those units is based on a set expectation of use.
- (D10) Demand: Each first and second line unit (10 units total) sends the demand for an asset which is met by their resource manager. The managers do not have access to all demands, but rather deal with each demand separately.
- (D3) Demand: The three second line logistics units are clustered with the subordinates into an information network. The superior units used their knowledge of all of their subordinates' information elements to update their perception of the current status and needs of each unit.

The first two are extremes in logistic decision making. The first case uses doctrine to push materiel to the units, regardless of what happens during the scenario. The amount being pushed to the units is decided a priori and is not updated over time. The second case uses a daily update of what was consumed to re-supply stocks to previous levels. The first two modes of logistics (S and D10) have been implemented in HiLOCA to analyse the effect of different logistics methods on combat effectiveness.

The third is a variant on the second case but with additional clustering of information. This case uses three clusters which contain the 10 decision nodes (denoted D3).

In each of the three cases, S, D10 and D3, the information elements being tracked are the consumption of 30mm ammunition over time from each logistics unit. All of the units are expected to use some 30mm ammunition, however, due to the stochastic nature of the combat model, it depends on the run of the model which of the units are engaged during the 24 hours of the simulation. Consequently the outputs from the CMM will not only be scenario dependent, but also dependent on the exact circumstances of the particular run of the stochastic simulation.

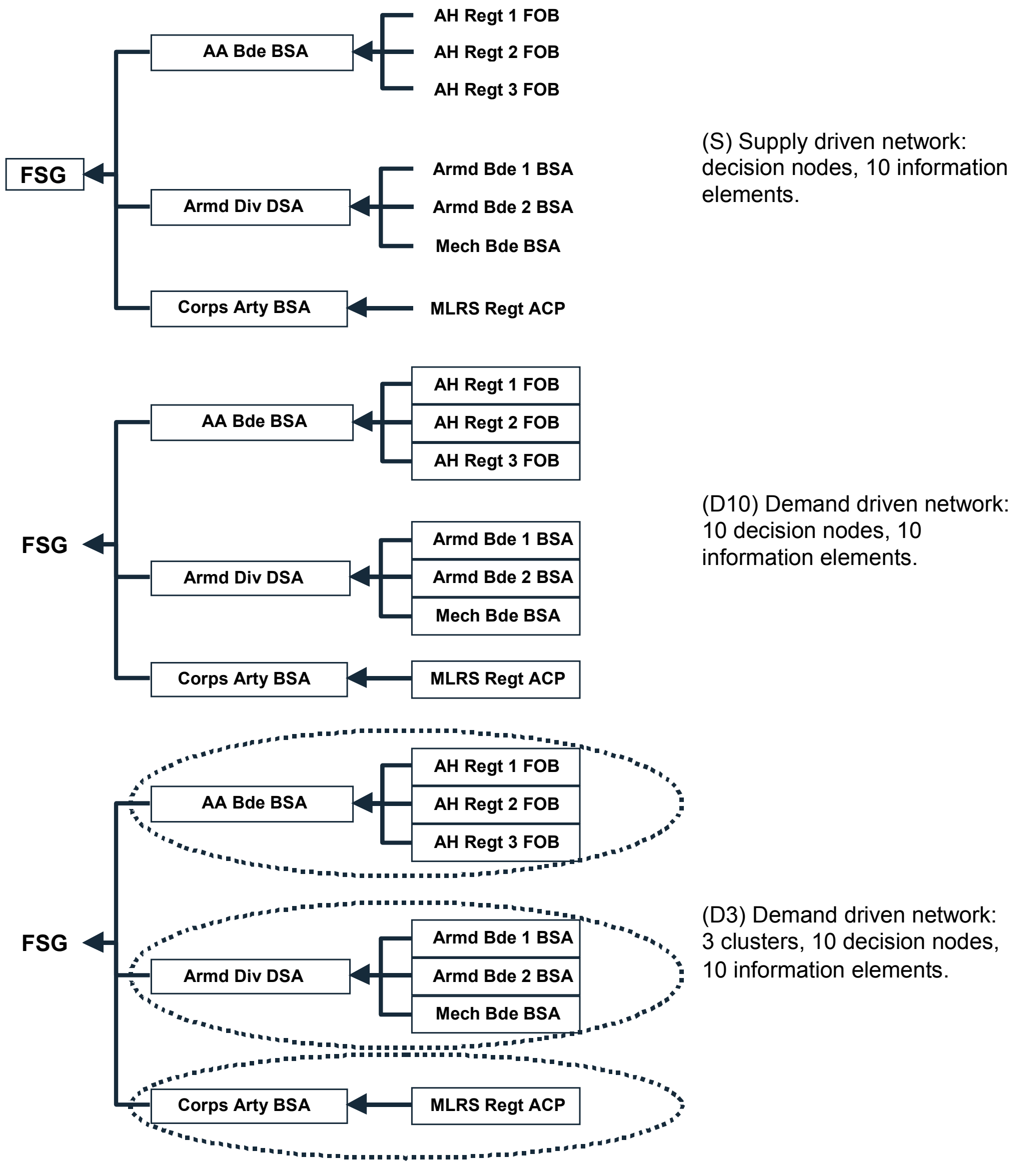

Figure 4. Three networks are shown. Decision nodes are shown as rectangles. Each second and third line logistics unit produces an information element. The dashed lines denote clusters of nodes that share a common perception.

Analysing Modes of Decision Making for Logistics

To answer the first question, we need to ensure that the modes of logistics decision making can be captured within the combat model as well as the Collaboration Metric Model. The combat model was able to work under two principles of logistics decision making – that of supply and demand-driven logistics. In the supply case, the first line logistics units send demand for fuel to the second line, and are met with a re-supply at the expected doctrinal level.

The Overall Network Performance (ONP) metric for the three cases is shown in Figure 5. The ONP is an overall measure given for a network to show how good the network is at providing for quality decisions. It is bounded between 0 and 1 and takes into consideration measures such as the accuracy, precision, and completeness of the underlying data. The nearer to 1, the 'better' the quality of decision being made. Shown in the figure are the averages and ranges over the 24 hour period of the metric for all three cases.

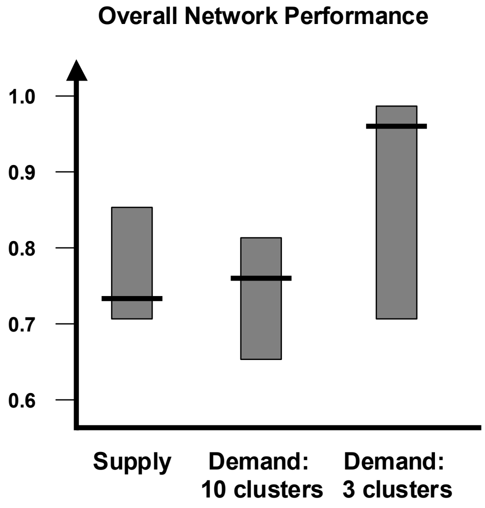

Figure 5. Overall network performance metric for the three cases. The shaded region defines the minimum and maximum of the value over the 24-hour scenario; the black bar shows the average over time.

The three cases are differentiated based on both the level and the range of the estimates. The levels indicate a better network in the 3 cluster demand-driven case relative to the other two cases. The two lower level cases are quite similar in average and spread, whereas the spread of the 3D case is much larger.

It is expected that the ONP of the demand cases should be better than that of the supply case. However, the overall network performance of the S and D10 cases are quite similar. The actual ONP for the supply case starts high, and tails off during the course of the scenario. The network is well suited at first to providing logistics decision making, and only after many minutes of combat fighting does the network begin to provide a poorer performance. The doctrine that provided the initial estimates of consumption in the supply case were reasonable overall, but as the simulation progressed, the planned average consumption rates did not accurately respond to the surging demands of troops during combat. The D10 case shows a similar spread of values to the S case, however, with a slight increase in the average value over time, and without the temporal characteristics.[10]

A large difference arises when the decision nodes are clustered. The cases D10 and D3 have the same information elements and number of decision nodes but they differ crucially in the number of clusters sharing information. In the former case, each logistics unit is introduced to one information element, and develops an understanding of the logistics consumption based on that information. In the latter, the decision nodes are able to access other information from neighbouring units which helps to build a better understanding of the situation. Even though both demand cases seem to have a much better understanding of the information elements over time compared with the supply driven case, it is only when the information is shared among decision nodes that the increase in Overall Network Performance becomes evident. In this example, the sharing of information provides a greater increase to the overall ability of the network to perform compared with the location of the decision making.

Analysing Levels of Clustering

The second question deals with different levels of clustering among similar decision modes. In this example, we looked at two levels of clustering within the demand driven logistics example. The differences between the D10 and the D3 case is the addition of three clusters in the latter which allows the nodes in the structure to access information produced by their peers. For example, in D10, the 1st Attack Helicopter Regiment logistics unit is supplied based on its demand alone. In D3, it is supplied based on knowledge of what the 2nd and 3rd Regiments use. The information produced by the 3rd can be seen and furthermore, can be compared with the 2nd Regiment and 3rd Regiment. If the elements are correlated to some extent, (which, in this case, they are as witnessed by the similarities shown in Figure 3), the knowledge of one unit can be used to reduce the uncertainty of the estimates for the others.

Operationally, it makes sense that possession of information of the three first line logistics units would provide a better picture to the decision maker at the second line. Previously it has been difficult to describe exactly what effects that information produces. The CMM now provides a series of metrics that account for the correlation between information elements within a network structure and topology.

An example metric is the combination of Accuracy and Knowledge produced by the CMM.[11] Figure 6 below plots the Accuracy and Knowledge metric over time for the three cases run in the study.

The Accuracy and Knowledge metric (also a measure of C2 effectiveness) is bounded between 0 and 1 and relates the expectation and uncertainty of an information element with the actual information element. (The estimation of Accuracy and Knowledge is

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[10] The changes between the topology (4 decision nodes versus 10 decision nodes, for instance) may well lead to additional complexity in analysing the outputs of the metrics. Further exploration will provide context for these comparisons.

[11] Knowledge is a function of precision. The means of combining accuracy and knowledge is described in Moffat and Perry, ibid

done by means of a Dynamic Linear Model, which can be thought of as a type of Kalman Filter. [12])

The Supply case uses the doctrinally mandated expected use patterns as the baseline, whereas, the demand cases apply the actual use as the baseline. In each of the three cases, the baseline is compared with the system value which is calculated through a collection of dynamic linear models.

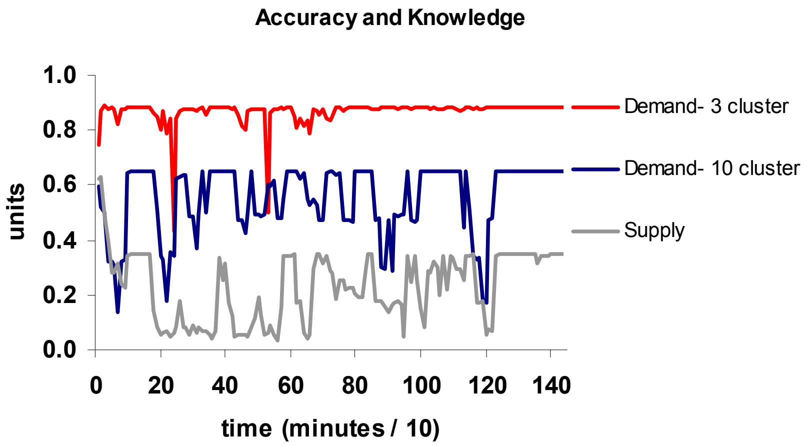

Figure 6. Accuracy and Knowledge metric for the three networks modelled.

There are two main differences among the three cases. The first is the variation within each data set. A cursory comparison of the three cases reveals that the upper trend has much less variation between adjacent points than the lower two trends. The additional clustering of the D3 example compared with the D10 example, has perhaps relieved the uncertainty of unexpected changes in the information elements. A reduced sensitivity to changes in the information elements is reflected in a less volatile and smoother line. The knowledge of three units engaged in a sudden change in their supply level will be more *understandable* or *palatable* to a commander than if only one unit experiences that change.

The second difference among the data is the level of Accuracy and Knowledge. The Supply case exhibits the lowest Accuracy and Knowledge metric, reflecting the large differences between the average doctrinal use of 30mm shells compared with the actual use during combat. The two Demand cases provide enhanced Accuracy and Knowledge compared with the Supply case; the baseline is much more closely related to the actual use. The difference between the two Demand cases, one having 10 isolated clusters each having a single node, and one with 3 clusters of aggregated nodes, provides the value of shared information between peers in this example. Recall that the information elements and baselines are the same in both Demand cases.

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[12] In fact this is part of the Rapid Planning Process. It addresses the uncertainty of a commander concerning where he thinks he is in the decision space described by the key information elements which drive his decision. The higher this metric, the less uncertain is the commander about the value of these key variables and the higher the quality of his decision in terms of selecting the correct fixed pattern within his decision space. These fixed patterns, held in the commander's long term memory, relate to his experience, training and personality.

However, the system values calculated through the dynamic linear models are much closer, and hence have enhanced Accuracy and Knowledge, in the case of the more collaborative network. In this example, the 3 cluster demand-driven network provides the clearest picture of the consumption of the subordinate units.

Summary

To assess the benefit of improved information sharing on military effectiveness is a formidable challenge. The analysis in this paper is a significant step towards meeting this challenge. The Collaboration Metric Model is a mathematical model which quantitatively measures the benefits of sharing across an information network and the effect this has on the quality of decisions made by commanders. This gives rise to a number of quantitative measures of C2 effectiveness. We are combining this with high level combat modelling in order to link the measures of C2 effectiveness with measures of force effectiveness. This is a developing method which lends insight into the benefits and pitfalls of sharing information across a network. This work addresses directly a key challenge identified in the NATO Code of Best Practice for C2 Assessment and represents what we believe to be a significant advance in dealing with the question: how does better information sharing relate to military effectiveness?