Applying the FINC (Force, Intelligence, Networking and C2) Methodology to the Land Environment

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ABSTRACT

In this paper we re-examine the FINC (Force, Intelligence, Networking and C2) methodology for analysing C4ISR architectures, studying its applicability to hierarchical organisational structures in the Land environment. For this study we utilise a search-and-manoeuvre experimental scenario, implemented using an agent-based simulation written in Java. The FINC methodology allows the calculation of three metrics or coefficients for every C4ISR architecture: the information flow coefficient, the coordination coefficient, and the intelligence coefficient. Our experiment shows that the FINC intelligence coefficient alone was able to predict 95% of the variance in performance. Consequently, the intelligence coefficient can be used to compare C4ISR architectures, and predict with moderate accuracy which one will give the best performance. A brief study of some US Civil War battles confirms the usefulness of the intelligence coefficient.

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Executive Summary

In responding to the Revolution in Military Affairs and rapid change in the modern strategic environment, it is important to utilise the best possible C4ISR architectures for the Australian Defence Force. Consequently, it is extremely important to evaluate the effectiveness of different C4ISR architectures. This can be done using the regular series of military exercises. However, these are not capable of examining the impact of technologies not yet in service. Wargaming is capable of examining such technologies, but both wargaming and real exercises have a substantial cost, and therefore there is considerable benefit in a low-cost methodology for evaluating C4ISR architectures, and selecting for further experimentation those that the methodology identifies as the best candidates. The **FINC** (Force, Intelligence, Networking and C2) methodology satisfies this goal.

The FINC methodology allows the calculation of three metrics for every C4ISR architecture: the **information flow coefficient** measuring tempo superiority, the **coordination coefficient** measuring coordination superiority, and the **intelligence coefficient** measuring information superiority.

Like all methodologies, the FINC methodology requires validation, and this report describes the second step in validating it, with specific emphasis on the Land military environment. For this study we utilised a search-and-manoeuvre experimental scenario, implemented using an agent-based simulation written in Java. Our simulation approach is complementary to agent-based "distillations" such as Project Albert, concentrating more heavily on C4ISR architectures and organisational structures.

In our previous study (DSTO-GD-0313), we demonstrated the usefulness of the FINC methodology, and in this paper we build on that work by specifically addressing some issues relating to land operations:

- Land forces traditionally employ a hierarchical organisation. This is because land operations usually involve problems which are too complex for centralised optimisation, and so benefit from being hierarchically subdivided.

- More complex problems require a hierarchical decomposition, just as larger organisations require a hierarchical structure; centralised architectures are less appropriate.

- Land operations are often of longer duration, and involve conditions changing over time and thus require adjustments to centralised planning.

- Network capability often varies as conditions change and units move, with consequent variation in performance.

In this second simulation study, we have addressed these issues within a scenario involving a larger number of units and a hierarchical command structure. We also specifically addressed variation in performance with varying network capability.

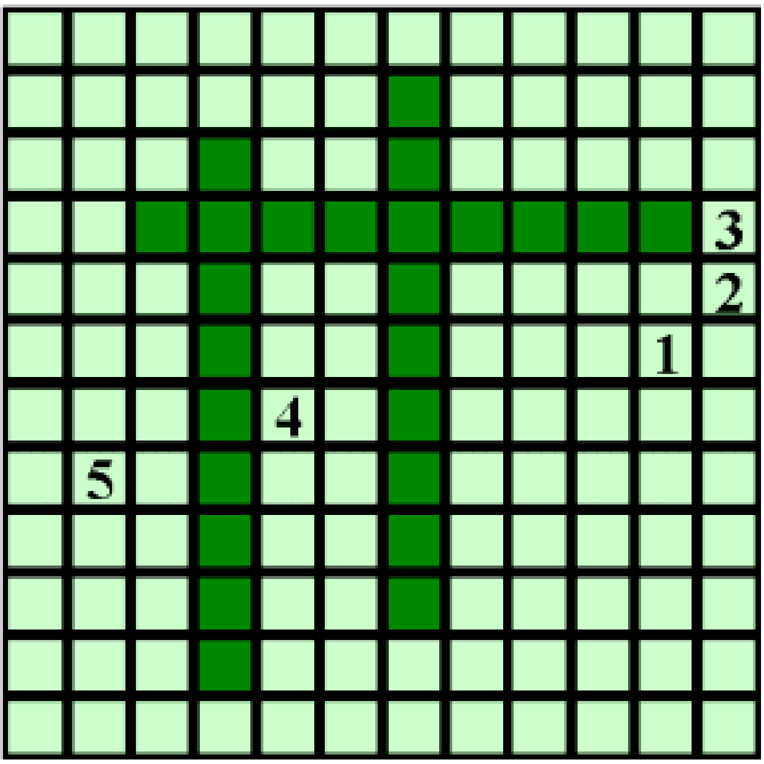

Figure (i): Example Micro-World with Five Targets and Three Randomly Placed Walls

The scenario involved manoeuvring a brigade consisting of 16 companies through a micro-world such as that shown in Figure (*i*), in order to reach an end-state where own forces are positioned at five randomly-positioned **targets**.

The experiment tested three planning strategies, seven levels of communication delay, and four C4ISR architectures. The architectures tested were **Command Hierarchy** (a simple hierarchy); **Situation Awareness Hierarchy** (situation awareness information is passed up and down the hierarchy); **Situation Awareness Networking** (situation awareness information is passed sideways via a simulated radio network); and **Command Networking** (some units can bypass the command hierarchy, issuing orders from below).

Best performance was obtained with the **Situation Awareness Networking** architecture, where situation awareness information was passed sideways, but C2 was handled hierarchically.

Statistical analysis showed that one of the FINC metrics, the **intelligence coefficient**, was capable of integrating information about architectural differences, quality of intelligence, and communication delays. Consequently, the intelligence coefficient was able to predict 95% of the variance in performance, where performance was calculated based on the time taken to locate targets and manoeuvre own forces towards them. The close fit of the data points to the red line in Figure (*ii*) illustrates the quality of the prediction:

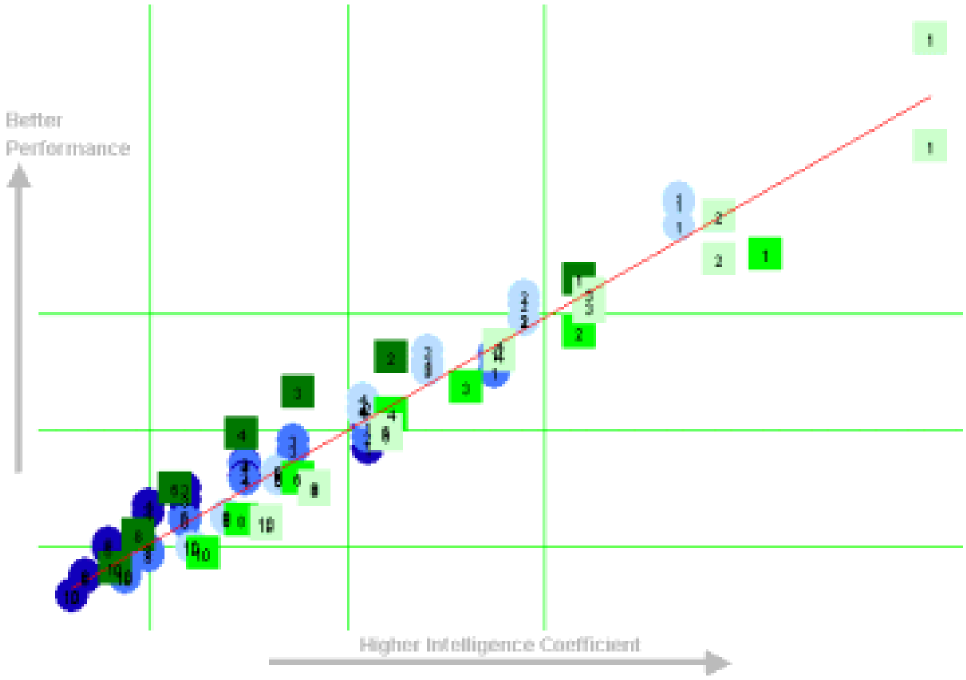

Figure (ii): Prediction of Performance by Intelligence Coefficient for Micro-World Experiment

A brief survey of twelve real-world battles from the first two and a half years of the US Civil War provided tentative confirmation that the intelligence coefficient is also useful in predicting real-world performance. These battles demonstrated wide variation in the ability to collect good intelligence, process it quickly, and transform it into unambiguous orders rapidly disseminated to subordinates. This is the quality which the intelligence coefficient is intended to measure. In the US Civil War, both sides shared similar culture, technology, and tactics, which reduces (but does not eliminate) the impact of other variables on the outcome of the battles. The US Civil War was also very well-documented. These factors make it a useful test of the applicability of the intelligence coefficient in the real world.

The moderate fit of the data points to the red line in Figure (*iii*) demonstrates the ability of the intelligence coefficient to approximately predict relative casualty rates. Moving from left to right, Union casualties generally decrease (relative to Confederate casualties) as the Union intelligence coefficient increases (relative to the Confederate coefficient). The first outlying point is the Battle of Fredericksburg, where the incompetence of General Ambrose Burnside (which went well beyond his failure to process information) led to Union casualties being more than double those of the Confederacy. The second outlying point is the Battle of Chickamauga, where the Confederacy had higher casualties in spite of handling information approximately as well as Union forces.

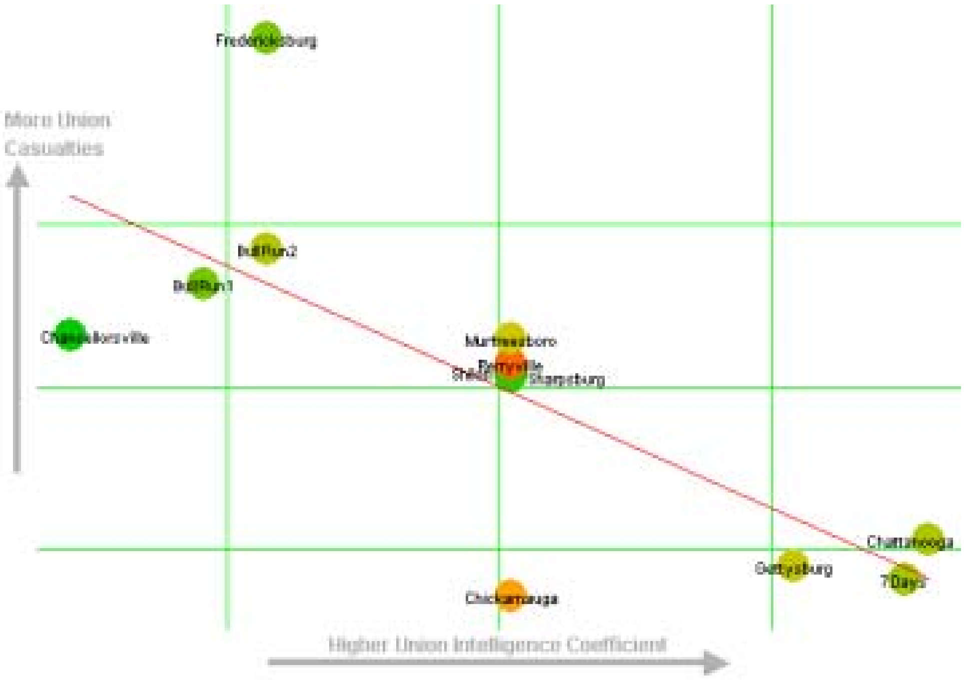

Figure (iii): Prediction of Casualty Rates by Intelligence Coefficient for 12 Civil War Battles

The combination of *in-silico* experiment and historical study presented in this paper provides preliminary confirmation of the usefulness of the FINC intelligent coefficient in comparing C4ISR architectures, particularly in the Land environment. This preliminary confirmation justifies more detailed future studies to refine and improve the FINC methodology. Future work will also use the FINC methodology to assess **joint** and **coalition** architectures.

Contents

1. Introduction

In this paper we investigate the applicability of the FINC methodology [3, 19] to the Land military environment. FINC (Force, Intelligence, Networking and C2) is a methodology for evaluating C4ISR (Command, Control, Communications, Computers and Intelligence, Surveillance & Reconnaissance) architectures [8].

The FINC methodology is based on techniques drawn from Social Network Analysis [1, 2, 20] and graph theory [9, 10]. Social Network Analysis is an approach to analysing organisations focusing on the linkages between people and/or groups as the most important aspect. We have constructed a Java-based tool called CAVALIER [18] to implement the FINC methodology as well as other forms of Social Network Analysis.

The investigation reported here examines a search-and-manoeuvre scenario implemented using an agent-based simulation written in Java. We believe that such relatively simple experimental testbeds will over time allow us to gain an understanding of the fundamental principles of organisational design, in much the same way that early experiments with fruit flies [4] eventually led to modern successes in genetic engineering.

Our simulation approach is complementary to agent-based “distillations” such as Project Albert [7, 15, 17], which have a slightly different focus. Project Albert is a US Marine Corps activity using low-resolution agent-based simulations (or “distillations”) to investigate mostly tactical issues such as firepower, mobility, situational awareness, and tactical doctrine. Since these are variables which interact in complex ways, there is a requirement for modelling which is sufficiently simple to allow many combinations of variables to be explored. Existing software includes ISAAC, ARCHIMEDES, and EINSTein. Our simulation approach can also be described as a “distillation,” but has a reduced focus on tactical variables, concentrating instead on C4ISR architectures and organisational structures. We hope eventually to integrate our simulation techniques into versions of the Project Albert software, producing a unified environment capable of examining interactions between tactical and C4ISR architecture issues. In particular, we use map-aware agents, and the need for these within Project Albert has already been recognised by the development of the MANA (Map Aware Nonuniform Automata) tool by the New Zealand Defence Technology Agency [17].

This paper is divided into four main parts: the first discusses our experimental testbed and the results of experimentation, the second describes the FINC methodology, the third applies the FINC methodology to our experimental results, and the final part contains a brief look at the FINC methodology in an historical case study. The experiments reported here have demonstrated that the FINC methodology is just as successful in predicting performance in a land-based scenario as it was in previous work [19].

1.1 Previous Work

In our previous work [19], we described the FINC (Force, Intelligence, Networking and C2) methodology [3], which provides metrics for evaluating C4ISR architectures [8]. We also applied the methodology to a “SCUD Hunt” simulation experiment, and showed that the FINC metrics could predict the performance of different organisational architectures. In particular, in that simulation experiment, 61% of performance was due to battlefield conditions (tempo of target movement) and an additional 33% could be explained using the FINC metrics (the remaining 6% was due to nonlinearities and other factors). More detailed examination of the relationship between the FINC metrics and performance showed that there were four performance regions as shown in Table 1:

Table 1: Performance Regions in Previous Work

	Poor sensors	**Fair to Good sensors**
Slow tempo	**Region A**: ***Information superiority most important*** (rapid access to available information & information sharing are important)	**Region B**: ***Balance information superiority and coordination superiority*** (centralised organisational architecture performed best)
Moderate tempo		**Region C**: ***Balance all three kinds of superiority*** (network centric warfare performed best)
Fast tempo	**Region D**: ***Balance information superiority and tempo superiority*** (rapid access to information is most important)	

However, that study suffered from some limitations:

- The study did not adequately address issues in land operations. In particular, it did not fully do justice to the kind of hierarchical organisation traditionally employed in land force structure. Land operations usually involve problems which are too complex for centralised optimisation, and so benefit from being hierarchically subdivided [16].

- The scenario was not sufficiently complex to require a hierarchical decomposition, nor was the organisation sufficiently large to require a hierarchical structure, and so centralised architectures performed well in the simulation experiment.

- The scenario did not involve conditions changing over time, and the adjustments to central planning this would require.

- The study did not address variation in performance as network capability was varied.

In this second simulation study, we address these issues by further testing the validity of the FINC methodology in a land-based scenario, which we have developed. This new scenario involves a larger number of units and hence requires a hierarchical command structure. We also specifically address variation in performance with varying network capability.

It remains the case that a purely hierarchical organisation is sub-optimal when communication delays are large compared with battlefield tempo. For example, in the Gulf War ground campaign, Norman Schwarzkopf acted as both CINC and ground component commander. There were two levels of command (3rd Army and VII and XVIII Corps) between him and the US Army divisions on the ground, although a single level may have been more appropriate. General (Ret) Fred Franks (who commanded VII Corps) in his assisted autobiography [12] records a number of ways in which the multiple levels of hierarchy caused delays and misunderstandings which partially compromised the success of this high-tempo campaign. In the words of Clausewitz, cited in [16]:

> *"There is no denying that the supreme command of an army... is markedly simpler if orders only need to be given to three or four other men; yet a general has to pay dearly for that convenience... an order progressively loses speed, vigor and precision the longer the chain of command it has to travel, which is the case where there are corps commanders placed between the divisional commanders and the general."*

To examine these issues, our second simulation study compares the purely hierarchical structure with a number of network-centric modifications.

1.2 Outline of the Paper

In the first part of this paper (Section 2), we introduce our experimental testbed for studying C4ISR architectures in the land environment. Section 3 describes the experimental results and indicates which of the C4ISR architectures studied performed best. The FINC methodology will shed additional light on these results, and we describe the FINC methodology next (Section 4). In Section 5, we apply the FINC methodology to our experimental data, and show how the methodology can be used to predict the observed results. Finally (Section 6), we apply the FINC methodology to a series of battles from the US Civil War, in order to confirm the usefulness of the methodology in a real-world example.

2. The Experimental Testbed

The scenario for the study reported here involves a search-and-manoeuvre activity. This takes place within a micro-world which is a 12×12 grid divided by randomly positioned horizontal and vertical walls as shown in Figure 1:

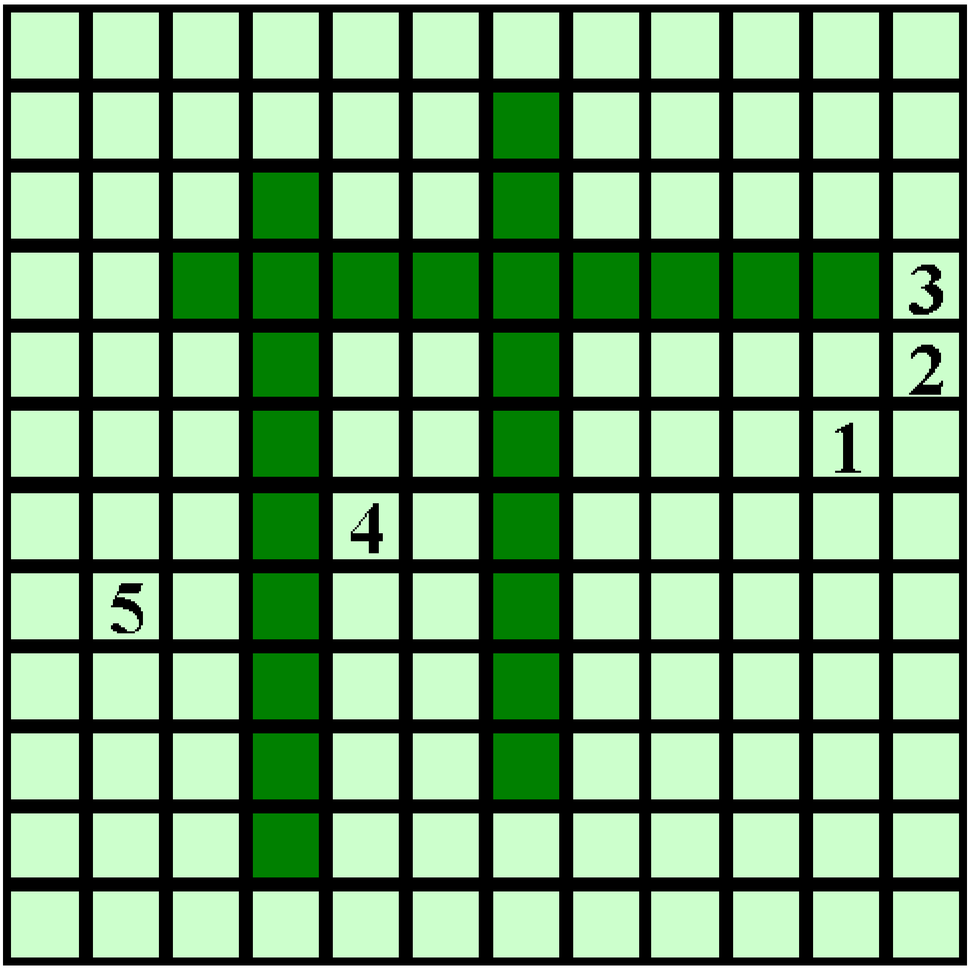

Figure 1: Example Micro-World with Targets and Randomly Placed Walls

Only horizontal and vertical movement is permitted, and the walls present an obstacle to progress. The micro-world contains five **targets**, which can represent either hostile forces to attack, displaced persons to be evacuated, or victims of a natural disaster who require humanitarian assistance. Our study is relevant to all three possibilities.

The operation that we model consists of three phases:

Phase 1: locate the targets.
Phase 2: manoeuvre own forces towards the targets.
Phase 3: respond to the targets.

The experiment addresses only Phases 1 and 2. Phase 3 (i.e. attacking, evacuating, or rendering assistance as appropriate) is not simulated. Own forces in this experiment consist of a brigade divided into four battalions of four companies each. The command and control (C2) hierarchy is shown in Figure 2:

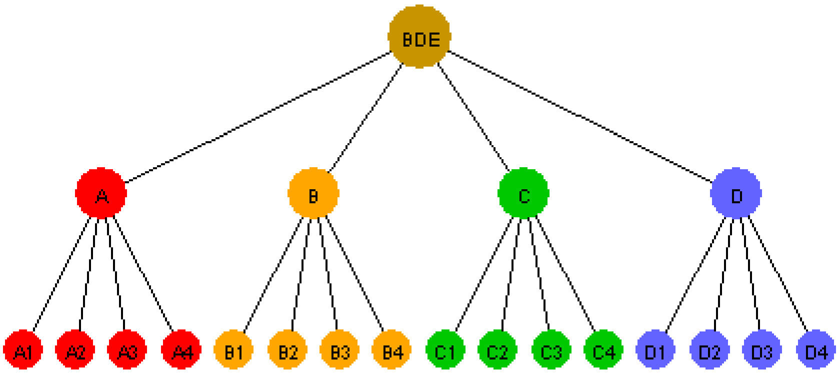

Figure 2: Command and Control Hierarchy for Simulation Experiment

The required end-state of the experiment is the manoeuvre of forces to the following position:

- At target 1, one detached company present.
- At target 2, two companies present under the control of a battalion headquarters.
- At target 3, three companies present under the control of a battalion headquarters.
- At target 4, four companies present under the control of a battalion headquarters.
- At target 5, five companies present under the control of a battalion headquarters.

Since there are a total of 16 companies, one will be surplus at the end of the simulation. Also, at least two companies must be detached from their original battalion.

Own forces begin in the top left of the micro-world. Units have access to the map of the micro-world, and are capable of calculating the shortest path between two grid squares (travelling around the walls as required). Units communicate by sending **messages**, such as “I am here,” “I have found a target” or “I need additional support.” Consequently, units are able to maintain (possibly inaccurate) positional information for both targets and other agents.

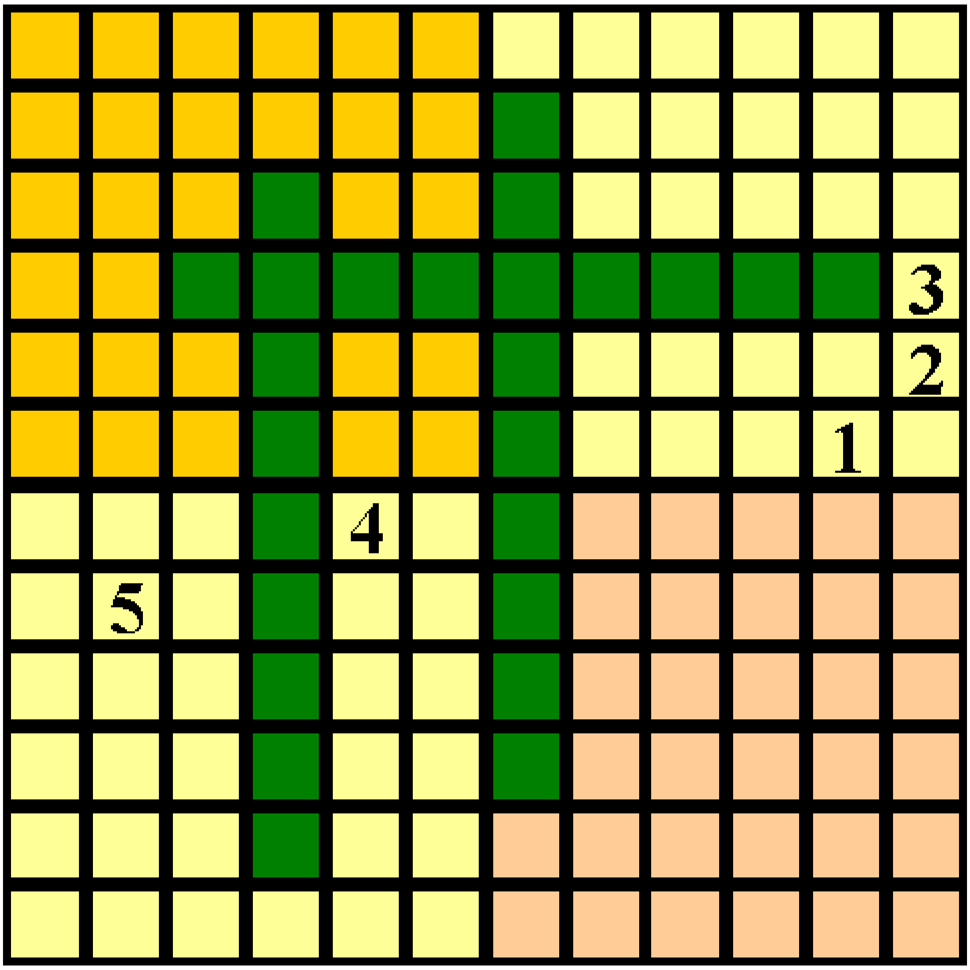

Figure 3: Quadrant-Based Brigade Plan for Example Micro-World

The operation begins with a **brigade plan**, which essentially consists of the division of the micro-world into four regions, to be searched by the four battalions. Three different search plans are investigated in this experiment:

Quadrant-based search:	The micro-world is divided into four equal square regions. These are shown coloured in Figure 3. Note that the upper left region is divided into two disconnected parts by walls.
Terrain-based search:	The micro-world is divided into four approximately equal regions, with the division made at wall boundaries, so as to minimise obstacles within a battalion search area (see Figure 4).

Intelligence-based search: This assumes a source of additional intelligence, which provides an approximate position for each target, and distinguishes the high-effort targets (target 3, 4 and 5) from the low effort targets (targets 1 and 2). Battalions are then assigned (possibly overlapping) search areas, which are rectangles around each reported position. Figure 5 shows an example of five rectangular search areas. In this diagram, bold numbers represent the actual target positions, and faint numbers the (approximate) reported positions. The overlap between the search areas is indicated by a checkerboard pattern. Three battalions will search the high-effort target areas, and the remaining battalion will search the areas around targets 1 and 2. For this plan, much of the micro-world need not be searched.

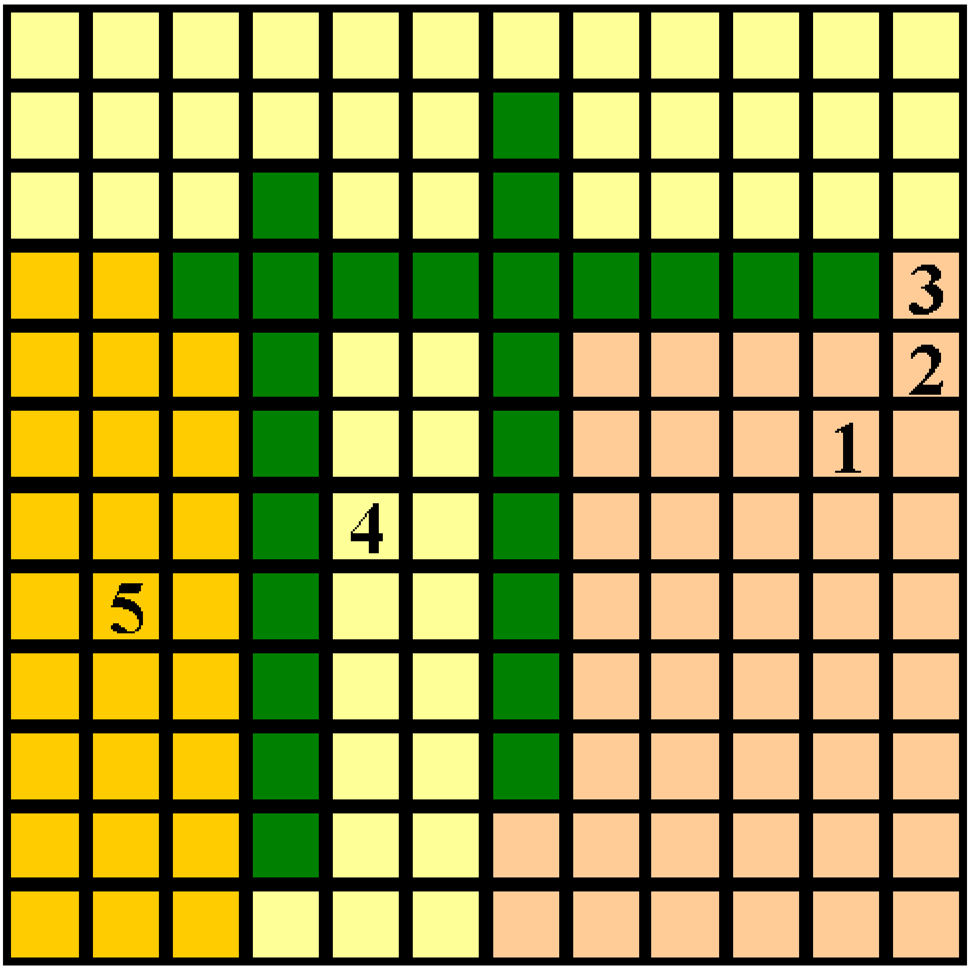

Figure 4: Terrain-Based Brigade Plan for Example Micro-World

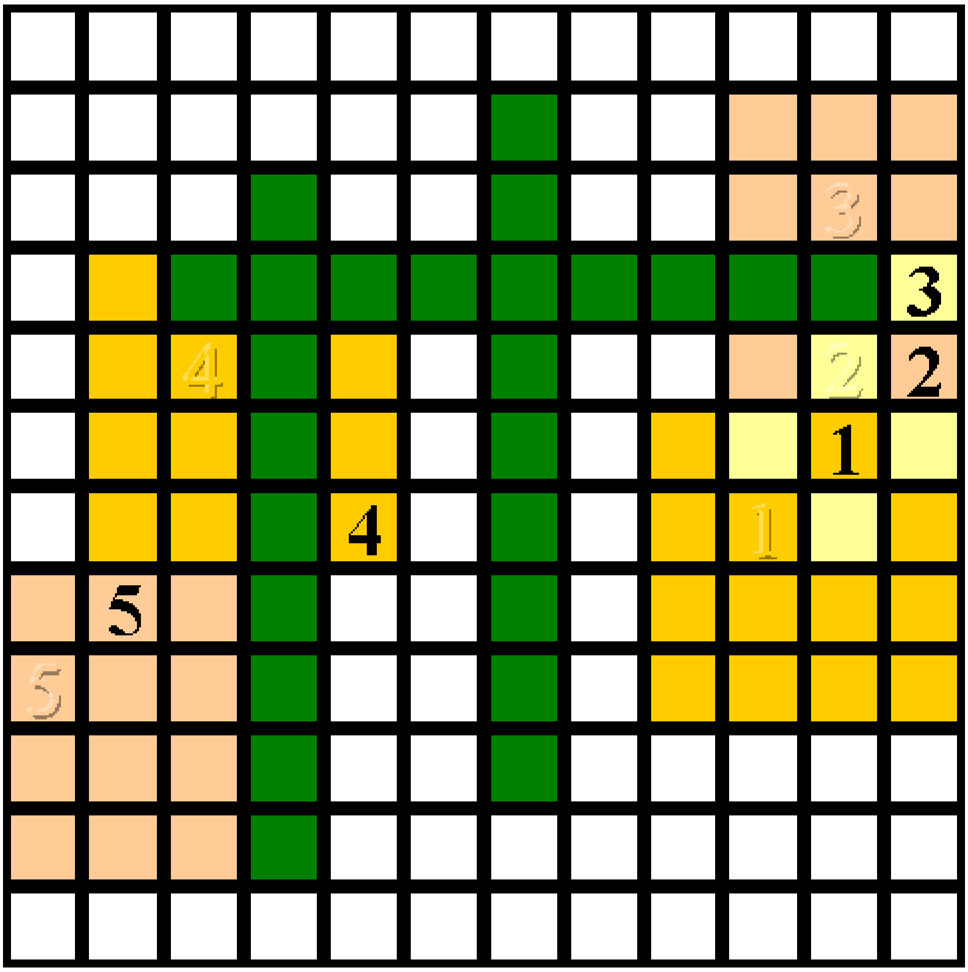

Figure 5: Intelligence-Based Brigade Plan for Example Micro-World

Battalion planning simply subdivides the battalion search area into four company search areas. Company planning consists of finding the shortest path to the designated company search areas, and then formulating a search plan. Figure 6 shows the subdivision of one battalion search area (the lower right part of a quadrant-based brigade plan) and the planned movement of companies from the starting position to their designated company search areas. Note that companies do not necessarily travel together. We assume that initial brigade, battalion and company planning takes 20 **time steps**, and that movement takes 1 time step per grid square travelled.

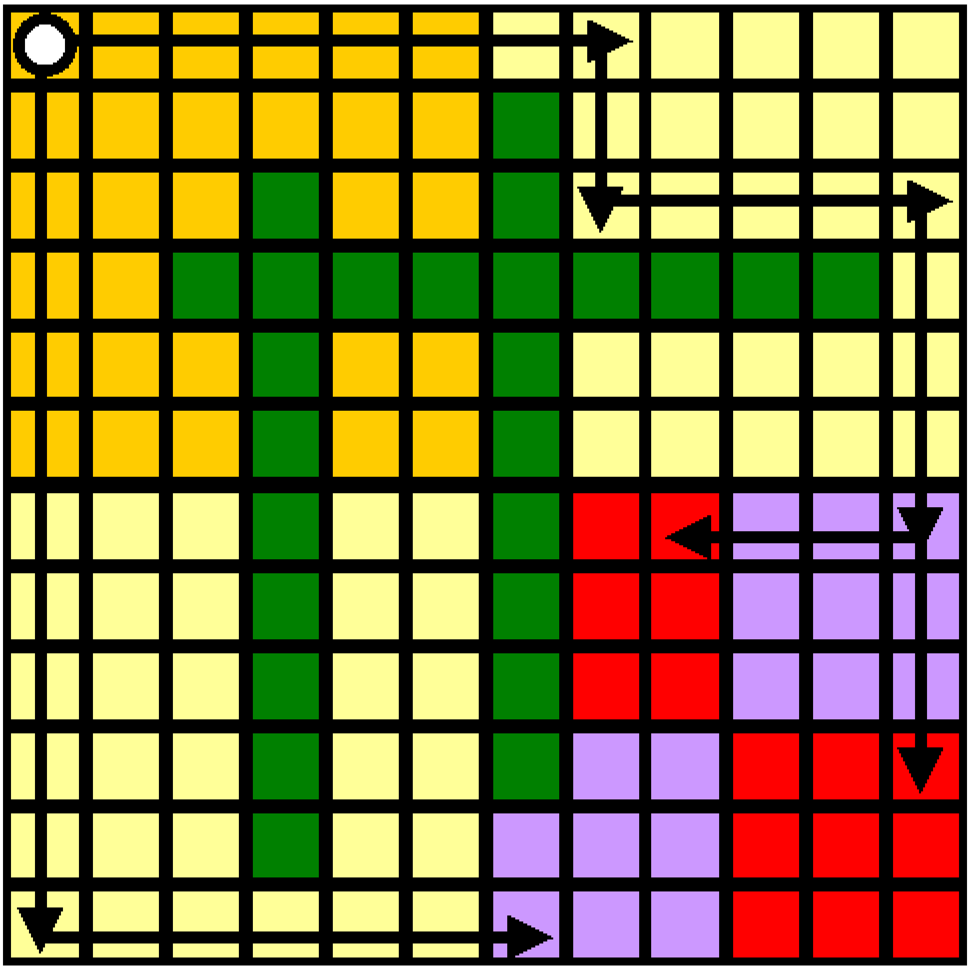

Figure 6: Battalion Movement Plan for Example Micro-World

Figure 7 shows the operational instruction for one of the companies in Figure 6:

a. You will travel to grid region 10–12 by 7–9 to conduct search operations. On completing search of this region with negative results, you will expand your search to adjacent squares. You will provide regular situation reports as you do so.

b. On reaching a target requiring military action, you will orient your forces appropriately, and report contact to your superior headquarters.

c. On receiving orders to travel to a specified grid square, you will do so by the shortest route. If your presence at that grid square is not in fact required, you will resume search operations.

Figure 7: Example Company Operational Instruction

Figure 8 shows the operational instruction for the battalion in Figure 6. These operational instructions are implemented as Java code within the agent-based simulation.

a. You will travel to grid region 7–12 by 7–12, and instruct your assigned companies to search that area.

b. You will provide regular summaries of company situation reports to Brigade HQ.

c. On finding a target requiring military action, you will assign appropriate units, including the Battalion HQ if required. You will report contact to Brigade HQ, and request additional support if necessary.

d. On receiving orders to transfer the Battalion HQ to a specified grid square, you will do so by the shortest route. If your presence at that grid square is not in fact required, you will await further contacts.

Figure 8: Example Battalion Operational Instruction

2.1 C4ISR Architectures Examined

For each of the three brigade plans, four C4ISR architectures are tested:

Command Hierarchy (CH):	This is as described above.
Situation Awareness Hierarchy (SH):	In addition, situation awareness information (including a summary of grid squares which have already been searched) is passed **down** from superior headquarters to subordinate units.
Situation Awareness Networking (SN):	Situation awareness information is instead passed **sideways** via a simulated radio network. Sideways radio connection is assumed to exist between physically close units (whose Euclidean distance is less than 3.75). It is assumed to have the same communication delays as messages travelling up and down the hierarchy.
Command Networking (CN):	As for the situation awareness network, but the first company on the scene at a target can bypass the command hierarchy, taking control of nearby units and assigning them to the target.

The last three architectures represent progressively more extreme forms of Network Centric Warfare [13]. Network Centric Warfare (NCW) includes the use of networks to share information between units (as in the SH and SN architectures), but it realises its full potential where units can negotiate tasks with each other (self-synchronisation) in response to rapidly changing situations without first contacting higher command. In the words of David Alberts et al [13]:

> *"NCW offers the opportunity not only to be able to develop and execute highly synchronized operations, but also to explore C2 approaches based upon horizontal coordination, or self-synchronization, of actor entities. In fact, the Marines have adopted Command and Coordination as their preferred term for command and control in future operations."*

However, the extreme form of Network Centric Warfare which we call command networking (CN) may go too far in terms of bypassing the command hierarchy. This is one of the questions that we will examine in this simulation experiment.

For each of the three brigade plans and four C4ISR architectures, we also examine the effect of varying communication delays between units. The time required to send a message from one unit to another is varied from 1 to 10 time steps. One time step of processing time is also required when a message transits through a headquarters.

This delay represents the actual transmission time plus the average time between transmissions, which in real life depends on bandwidth, availability, set-up time, and standard operating procedures.

We implement this scenario as an agent-based simulation written in Java. To produce statistically valid results, for each combination of C4ISR architecture, brigade plan and communication delay, we average the performance of 1,000 experimental runs, each of which uses a different randomly generated micro-world. We measure the number of time steps required to reach the desired end-state.

3. Experimental Results

Table 12 in Appendix A shows the average time required to reach the desired end-state, for each combination of C4ISR architecture, brigade plan and communication delay, averaged over 1,000 experimental runs. In general, the best performance is obtained by combining intelligence-based search and situation awareness networking (SN), and keeping communication delay as low as possible.

Table 2 shows the average time required to reach the desired end-state, for each of the three brigade search plans. A separate experiment shows that, even if exact target positions are known, an average of 19.8 time steps is needed simply to travel to the target position. We can thus partition the total time taken into planning time, minimum travel time, and the time taken for search and manoeuvre. Only the final component varies between alternative brigade search plans:

Table 2: Average Time Taken to Reach End State for Three Brigade Search Plans

	Quadrant-based search	**Terrain-based search**	**Intelligence-based search**
Total planning time	20	20	20
Minimum travel time	19.8	19.8	19.8
Search/manoeuvre time	64.4	65.8	55.9
Total time taken	**104.2**	**105.6**	**95.7**

Since only the search / manoeuvre time varies between alternative brigade search plans, we can use it as a measure of performance. By dividing 100 by the search / manoeuvre time, we obtain a **performance measure** which increases as performance improves, as shown in Table 3. In Section 5 we will show how this performance measure can be predicted by the FINC intelligence coefficient, which we shall introduce in Section 4.

Quadrant-based search and terrain-based search perform about equally well (terrain-based search is slightly worse than quadrant-based search). This is because of a balance between two factors. On the one hand, the absence of walls which cross battalion search areas in the terrain-based search reduces travel time within the search area. On the other hand, the uneven sizes of battalion search areas increases search time for the largest area. Performance with intelligence-based search is significantly better, since the presence of even approximate intelligence on target positions significantly reduces the amount of searching required (see Figure 5):

Table 3: Average Performance Measures for Three Brigade Search Plans

	Quadrant-based search	**Terrain-based search**	**Intelligence-based search**
Search/manoeuvre time	64.4	65.8	55.9
Performance measure	1.552	1.520	1.790

Table 4 shows the average performance for the four C4ISR architectures. The situation awareness hierarchy (SH) outperforms the command hierarchy (CH), since passing situation awareness information (about areas already searched) down the hierarchy reduces search time. This is because areas which another unit has already travelled through need not be searched again. Situation awareness networking (SN) is even better, since situation awareness information can be passed more rapidly to nearby companies that need it, in one message (by radio) instead of two (via battalion headquarters) or four (via brigade headquarters).

As anticipated, the extreme form of Network Centric Warfare which we call command networking (CN) generally reduces performance. This is because conflict in orders and confusion arises when the first company at a target bypasses the command hierarchy and takes control of nearby units. However, Table 12 shows that there is a slight performance improvement for CN with good intelligence and slow communication.

Table 4: Average Performance Measures for Four C4ISR Architectures

	Command hierarchy (CH)	**Situation awareness hierarchy (SH)**	**Situation awareness networking (SN)**	**Command networking (CN)**
Search/manoeuvre time	71.9	65.3	54.8	56.0
Performance measure	1.390	1.530	1.825	1.785

Table 5 shows the search / manoeuvre time (averaged over all search plans and C4ISR architectures) and performance measure for the communication delay values used:

Table 5: Average Performance Measures for Communication Delay Values

Communication Delay:	**1**	**2**	**3**	**4**	**6**	**8**	**10**
Search/manoeuvre time	41.6	48.4	53.1	57.8	68.3	78.1	86.9
Performance measure	2.404	2.066	1.883	1.730	1.464	1.280	1.151

Linear regression shows that the average search / manoeuvre time is approximately:

$$\mathbf{37.8 + 5.0}\ \boldsymbol{d}$$

where $\boldsymbol{d}$ is the communication delay (the correlation is 0.87, $r^2 = 0.76$, $p < 0.0000000001$). In other words, an average of five messages periods pass before the desired end-state is reached. The first two of these are the dissemination of brigade and battalion plans down the hierarchy. The remaining three messages (on average) include contact reports on finding a target (0 required for a company that finds the target itself, 2 required if a company in the same battalion finds the target, 4 or more otherwise).

Before we discuss our experimental results further, we will introduce the FINC methodology. Our presentation is a modified version of that in [19]. Readers already familiar with the FINC methodology may prefer to skip to Section 5.

4. The FINC Methodology

In this section we describe the FINC (Force, Intelligence, Networking and C2) methodology [3], using a simple military structure (Figure 9) as an illustrative example (our presentation is a modified version of that in [19]). In this example, two brigade-level units (BDE 1 and BDE 2) are controlled by a divisional-level headquarters (DIV HQ), which in turn is controlled by a joint headquarters (JNT HQ) which also controls strategic intelligence and air assets. We provide this example structure purely in order to describe the FINC methodology, and are not suggesting that it is appropriate for any specific purpose. In the next section of this paper we provide an application of the FINC methodology to our simulation experiment.

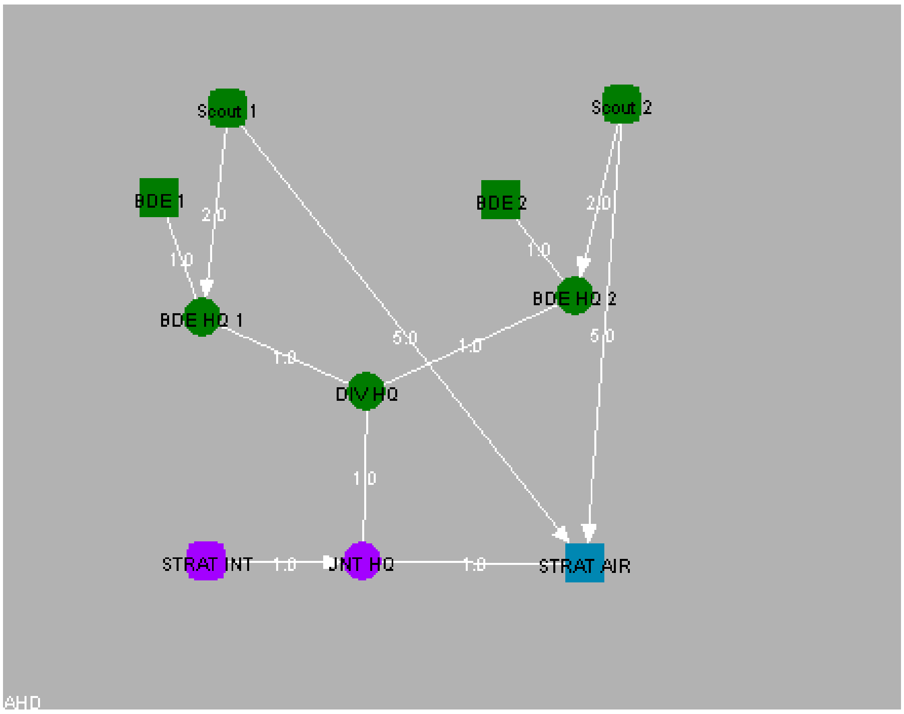

Figure 9: A Simple Military Organisational Structure

The FINC methodology analyses an organisational structure relatively simply in terms of **force**, **intelligence**, **networking**, and **C2** assets. Force assets are those which carry out any kind of military task, and are indicated by square boxes in Figure 9. Intelligence assets collect any kind of information, and are indicated by rounded boxes in Figure 9. Networking provides communication between assets, indicated by lines or arrows in Figure 9 (depending on whether information flow is unidirectional or bidirectional). C2 (command and control) assets make decisions, and are indicated by circles in Figure 9. The force and intelligence assets are often themselves organisations that can be subdivided in a similar way, if necessary. Having divided an organisation in this way, the FINC methodology provides a number of **metrics**, for evaluating the efficiency of the organisational structure.

The FINC methodology is also applicable to business organisations. For example, the force assets which carry out tasks could include the sales force and business units; intelligence assets could include research and development, market research, and recorded sales figures; and C2 assets could include management and decision-makers.

Each force and intelligence asset has an associated **area of operations**, which in this illustrative example is assumed to be approximately circular. In Figure 9 these assets are:

```
Scout unit 1 (Intelligence), radius = 100 (in arbitrary units)
Scout unit 2 (Intelligence), radius = 100
Brigade BDE 1 (Force), radius = 100
Brigade BDE 2 (Force), radius = 100
Strategic air (STRAT AIR) assets (Force), radius = 400
Strategic intelligence (STRAT INT) assets (Intelligence), radius = 400
```

In cases where the areas of operation for intelligence and force assets overlap, there is benefit in providing a flow of information from the intelligence asset to the force asset. In Figure 9, candidate information flows are:

```
Scout unit 1 to Brigade BDE 1
Scout unit 2 to Brigade BDE 2
Strategic intelligence (STRAT INT) to Brigade BDE 1
Strategic intelligence (STRAT INT) to Brigade BDE 2
Scout unit 1 to Strategic air (STRAT AIR)
Scout unit 2 to Strategic air (STRAT AIR)
Strategic intelligence (STRAT INT) to Strategic air (STRAT AIR)
```

Note that intelligence from Scout units is only useful to their associated Brigade units, since in this example, the areas of operation of the two brigades do not overlap. However, the strategic intelligence and air assets (with radius = 400) overlap with both brigades.

Intelligence assets differ in the kind of information they provide. Although such differences can be quite complex, for simplicity we model this by associating a **mode** or **band** with each intelligence asset. If a single asset produces different kinds of information, we simply model it as multiple co-located assets. We assume that two intelligence assets in different bands are complementary, while intelligence assets in the same band provide duplicate information. Intelligence assets also differ in the **quality** of information they provide. We model this using a numerical quality score for each intelligence asset. Given two intelligence assets in the same band, we prefer the highest quality information, and can discard the lower quality information. For Figure 9, intelligence assets are assumed to be in the same band, and quality (in arbitrary units) is taken to be:

```
Scout unit 1 (Intelligence), quality = 0.5
Scout unit 2 (Intelligence), quality = 0.5
Strategic intelligence (STRAT INT) assets (Intelligence) quality = 0.2
```

In other words, the strategic intelligence assets in this example provide information which overlaps with the information provided by scout units, and which is lower-quality but available over a wider area (we emphasise that this example is not realistic, and is provided merely to illustrate the methodology). The issue of how actual sensor characteristics are translated to numerical quality scores is outside the scope of the present paper, and we intend to address this in future work.

Each communication link in the network has varying reliability and bandwidth characteristics which for simplicity we model as an average **delay factor** for the transfer of information across the link. The key idea here is not the message transmission time, but the time to get across an **understanding** of reports or instructions. This may require multiple exchanges and clearly takes longer with low-bandwidth communication while face-to-face communication reaches understanding more rapidly. Delays (in arbitrary units) are indicated on the links in Figure 9. The delay factors are estimated based on a formula which is simple, but still of value in predicting performance:

delay factor = actual delay * misunderstanding factor / amount of information

Here the actual delay is the time required to actually send the block of information, i.e. the transmission time plus the average time between transmissions. This will depend on communications bandwidth, availability of the communications technology involved, set-up time, and standard operating procedures.

The amount of information per transmission is measured in bits (in the sense of information theory [32], equivalent to assuming the best possible compression technology is used). Increasing the amount of information per transmission means that understanding is achieved sooner, and hence the delay factor decreases.

The misunderstanding factor is usually taken to be 1.0, but for organisations which involve multiple cultures, the misunderstanding factor will be greater than 1.0 for cross-cultural links. Such cross-cultural links include communication between different services (such as between the US Army, Air Force, and Marines in the Gulf War [11, 12]), or communication between units from different countries. Links like these involve a greater delay before understanding is achieved.

Further work is still needed to assess the suitability of this calculation of the delay factor. In cases where this formula cannot be applied, we utilise a rule of thumb based on the “SCUDHunt” experiment reported in [21]. In this experiment, performance increased by 79% (from 1.36 to 2.44) when a communications technology (a voice or text chat facility or a shared visualisation tool) was introduced. Performance increased by a further 7% (to 2.61) when both chat and visualisation facilities were available. Our rule of thumb is then to halve the delay factor when significant new communications capability is introduced and to cut it by 10% for incremental improvements.

Each C2 node in the architecture processes intelligence information and passes it on (as well as many other C2 functions). This introduces an additional delay factor which is added to the delay factor for communication links (currently we do not model the headquarters process in detail, but in future work we intend to do so, using techniques such as those in [5] and [6]). In Figure 9, all delays for C2 nodes are assumed to be 1.0 (in the same arbitrary units as for links).

The FINC methodology uses the information in this model to conduct three kinds of analysis: **delay analysis**, **centrality analysis** (not discussed here), and **intelligence analysis**.

4.1 Delay Analysis 1: the information flow coefficient

In delay analysis, we consider the combined delay (i.e. the combination of communication delays and C2 delays) for each candidate information flow. Where multiple communication paths exist, we take the one with the shortest delay. For Figure 9, the delays for the candidate information flows are:

```
Scout unit 1 to Brigade BDE 1, delay = 2.0 + 1.0 + 1.0 = 4.0
Scout unit 2 to Brigade BDE 2, delay = 2.0 + 1.0 + 1.0 = 4.0
Strategic intelligence (STRAT INT) to Brigade BDE 1, delay = 7.0
Strategic intelligence (STRAT INT) to Brigade BDE 2, delay = 7.0
Scout unit 1 to Strategic air (STRAT AIR), delay = 5.0
Scout unit 2 to Strategic air (STRAT AIR), delay = 5.0
Strategic intelligence (STRAT INT) to Strategic air (STRAT AIR), delay = 3.0
```

The first metric we use for assessing C4ISR architectures is simply the average of these delay values, which we call the **information flow coefficient**. It provides a measure of how effectively the military organisation can mobilise information to carry out a task. For the example in Figure 9, this coefficient is 5.0. For this metric, low values are desirable.

The numerical value of 5.0 for this coefficient is in arbitrary units. However, it can be used for comparing C4ISR architectures, since (all other things being equal), the architecture with the lowest information flow coefficient will be the best.

The information flow coefficient thus provides one simple way of assessing changes to the military structure. For example, eliminating the direct links between scout units and strategic air assets in Figure 9 reduces the effectiveness of information flow, and increases the information flow coefficient to 5.86. Since it measures the delay between obtaining information and acting on it, the information flow coefficient provides an indication of **tempo superiority**, i.e. the ability to react more rapidly than an adversary.

4.2 Delay Analysis 2: the coordination coefficient

The second metric we use for assessing C4ISR architectures is the **coordination coefficient**. It provides a measure of how effectively the military organisation can coordinate activities. This metric is calculated by averaging the delays along paths connecting force assets. This is very similar to the information flow coefficient, but the information flow coefficient considers paths from relevant intelligence assets to force assets, while the coordination coefficient considers paths between force assets. For the example in Figure 9, these paths are:

```
Brigade BDE 1 to Brigade BDE 2 and vice versa, delay = 7.0
Brigade BDE 1 to Strategic air (STRAT AIR) and vice versa, delay = 7.0
Brigade BDE 2 to Strategic air (STRAT AIR) and vice versa, delay = 7.0
```

Consequently, the coordination coefficient is 7.0. For this metric, low values are also desirable. It provides an indication of **coordination superiority**, i.e. the ability to “orchestrate” (in the words of General Sir John Monash) multiple actions more effectively than an adversary.

4.3 Intelligence Analysis: the intelligence coefficient

Our third form of analysis measures the degree to which intelligence is used. For each candidate information flow from an intelligence asset to a force asset (which uses the intelligence), we estimate the **effective intelligence quality** to be the intelligence quality discussed above divided by the delay factor for the path, to allow for the decrease in value of information as it ages. This is a somewhat crude calculation, since some information retains its value even after considerable time has passed, while other information becomes useless almost immediately. However, this calculation provides a simple approximation to the way that information loses value over time. For the example in Figure 9 we have:

```
Scout unit 1 to BDE 1, delay = 4.0, quality = 0.5, effective quality = 0.125
Scout unit 2 to BDE 2, delay = 4.0, quality = 0.5, effective quality = 0.125
STRAT INT to BDE 1, delay = 7.0, quality = 0.2, effective quality = 0.029
STRAT INT to BDE 2, delay = 7.0, quality = 0.2, effective quality = 0.029
Scout unit 1 to STRAT AIR, delay = 5.0, quality = 0.5, effective quality = 0.1
Scout unit 2 to STRAT AIR, delay = 5.0, quality = 0.5, effective quality = 0.1
STRAT INT to STRAT AIR, delay = 3.0, quality = 0.2, effective quality = 0.067
```

These calculations are repeated for each intelligence band or mode.

For each force asset and intelligence band, we calculate an **intelligence volume** which is the product of effective intelligence quality and relative area (within the area of operations of the force asset) covered by the intelligence information. In cases where the areas of operations of intelligence and force assets only partially overlap, we assume that there is sufficient flexibility of position to make this overlap total when needed.

For example, for the strategic air (STRAT AIR) asset in Figure 9, strategic intelligence covers the entire area of operations (radius = 400) with effective intelligence quality = 0.067, while the two scout units cover smaller areas (radius = 100) with slightly higher effective intelligence quality = 0.1 of the same kind of information. Figure 10 illustrates this:

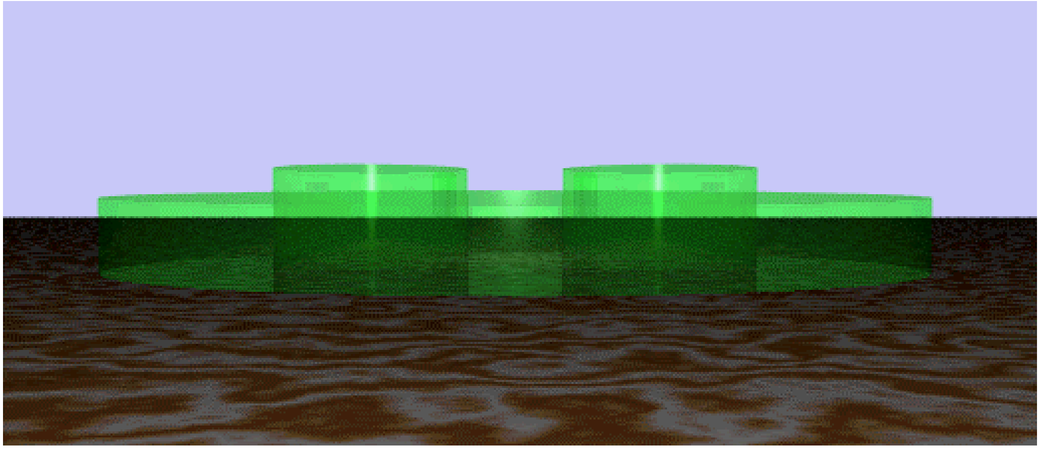

Figure 10: Intelligence Volume for Strategic Air Asset

In this diagram, transparent green cylinders indicate the intelligence assets relevant to STRAT AIR. The area of each cylinder indicates the physical area covered by the intelligence asset. The height of each cylinder indicates the corresponding effective intelligence quality, so that the two cylinders representing scout units stand out above the slightly lower effective intelligence quality of the strategic intelligence (STRAT INT) asset. The **intelligence volume** for the strategic air asset is simply the total volume of the combined shape (divided by pi for simplicity):

```
intelligence volume for STRAT AIR
= 0.067 * 400 * 400 + (0.1 - 0.067) * 100 * 100 + (0.1 - 0.067) * 100 * 100
= 10720 + 330 + 330
= 11380
```

Note that this is a “virtual” volume, representing a combination of effective intelligence quality and area. It does not represent a “physical” volume of any kind.

The intelligence volume for each brigade ignores strategic intelligence assets, since for this example we assume that the scout units provide exactly the same kind of intelligence and they have a higher effective intelligence quality of 0.125:

```
intelligence volume for BDE 1 or BDE 2
= 0.125 * 100 * 100
= 1250
```

The **intelligence coefficient** of the architecture is simply the total of the intelligence volumes for each force asset and intelligence band. For Figure 9 this is 11380 + 1250 + 1250 = 13800, approximately. For this metric, large values are desirable.

The intelligence coefficient can be improved either by improving the quality of individual intelligence assets, decreasing the delay on communication paths, or by adding intelligence assets (on new bands) which complement existing assets. We believe this metric provides a reasonable way of assessing the impact of such changes. Essentially this metric provides an indication of **information superiority**, i.e. the ability to obtain and utilise information more effectively than an adversary.

5. Modelling the Testbed with the FINC Methodology

For the purposes of the FINC methodology, we model each company, battalion, and brigade headquarters as a C2 node. Figure 11 illustrates this for the situation awareness hierarchy (SH) architecture. We set the FINC delay factors to 1 for each headquarters, and ***d*** (the communications delay) for each link, since these are the delays used in the Java-based simulation.

Note that this scenario is significantly more complex than that reported in [19], and hence the FINC modelling process involves a greater degree of estimation. The resulting three coefficients calculated by the methodology will therefore be an imperfect reflection of reality. However, as we will see, regression analysis shows that the FINC coefficients still predict performance extremely well.

We assume that an intelligence node is attached to the brigade headquarters, with quality factor 1, and with delay factor 0, since the link is internal to the headquarters. This intelligence node is assumed to provide information about the location of obstacles in the world. For the case of intelligence-based search (where information about target location is also provided) we double the quality factor on the intelligence node to allow for this.

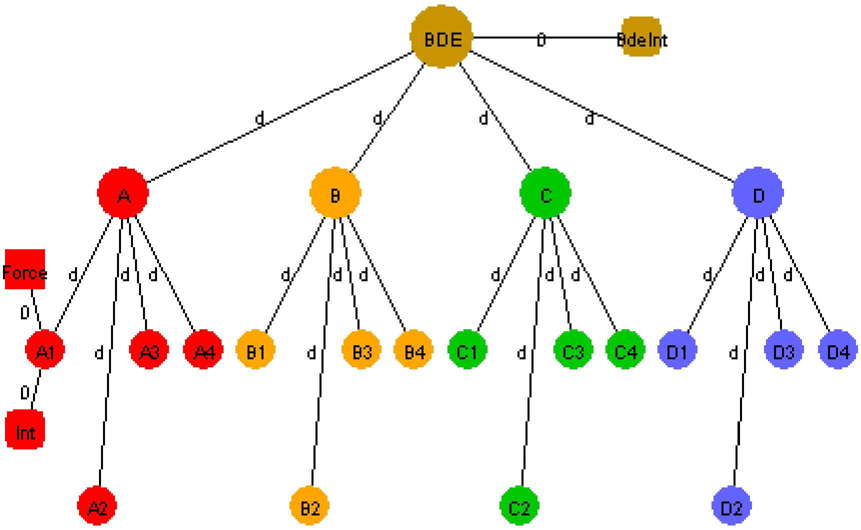

Figure 11: FINC Modelling for the Situation Awareness Hierarchy (SH) Architecture

We also assume that attached to each company headquarters is an intelligence node representing information collected by the company, with quality factor 1 and delay factor 0 (since the links are internal to the headquarters). Similarly, a force node representing activities carried out by the company is also attached, again with delay factor 0. Figure 11 shows these nodes attached to company A1 only.

For the command hierarchy (CH) architecture, situation awareness information is not propagated from one company to another. In accordance with our rule of thumb for the FINC delay factor, we double the delay factor ***d*** on communication links to compensate for the reduced amount of information transferred (see Figure 12). This is justified by the fact that situation awareness information is still transferred implicitly (since it is implied by orders given), but this transfer is much slower than a direct transfer of situation awareness information would have been.

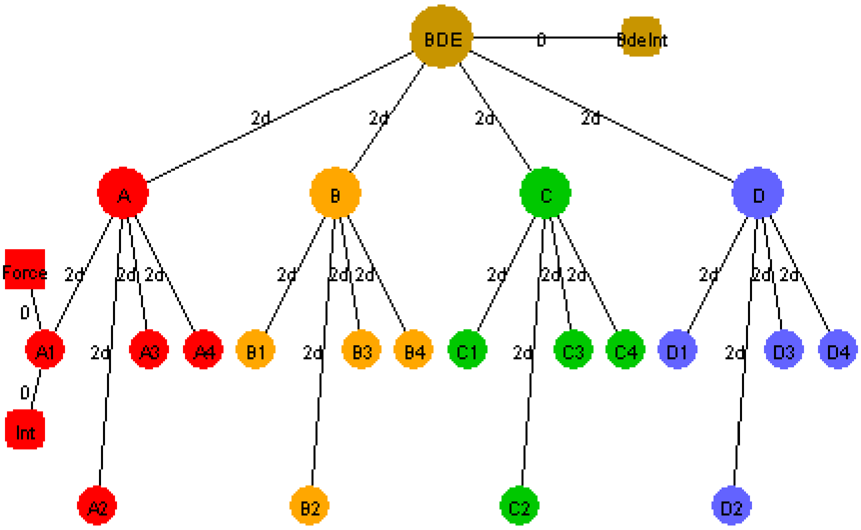

Figure 12: FINC Modelling for the Command Hierarchy (CH) Architecture

5.1 The Information Flow Coefficient

For the calculation of the information flow coefficient, we must use a substantial degree of estimation as to the area of operations of units, since units travel through the entire world. Based on our observations of the simulation in action, we estimate the key area of operations for each company to be 12 grid squares, 4 of which have intelligence provided by the company itself, 2 of which have intelligence provided by another company in the same battalion, and 6 of which have intelligence provided by three other companies in different battalions. Figures 11 and 12 illustrate these sources of intelligence from the point of view of company A1. We assume that intelligence from brigade headquarters applies to all 12 grid squares (and is in a different intelligence band, indicating that it is complementary to other sources of intelligence).

For the situation awareness hierarchy (SH) case, the candidate information flows to A1 are then A1 to itself (delay factor 1), A2 to A1 (delay factor $3 + 2\,\boldsymbol{d}$), B2, C2, and D2 to A1 (delay factor $5 + 4\,\boldsymbol{d}$ each), and brigade headquarters to A1 (delay factor $3 + 2\,\boldsymbol{d}$). The average of these is $(22 + 16\,\boldsymbol{d})/6$, which is the information flow coefficient. The information flow coefficients for the other C4ISR architectures are calculated similarly, and are shown in Table 6. For the situation awareness networking (SN) and command networking (CN) cases, we assume that the companies providing intelligence are within radio range, and hence can be reached in a single step (delay factor $2 + \boldsymbol{d}$). Figure 13 illustrates this from the point of view of company A1.

Table 6: Information Flow Coefficients for Four C4ISR Architectures

	Information Flow Coefficient
Command hierarchy (CH)	$(22 + 32\,d)/6$
Situation awareness hierarchy (SH)	$(22 + 16\,d)/6$
Situation awareness networking (SN)	$2 + d$
Command networking (CN)	$2 + d$

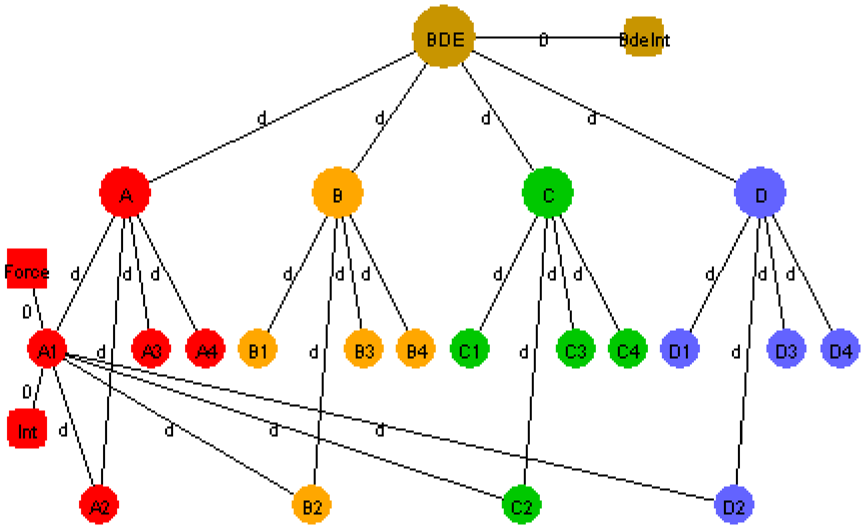

Figure 13: FINC Modelling for the Two Networking Architectures

5.2 The Coordination Coefficient

To calculate the coordination coefficient, we note that there are 120 possible pairs of companies, 24 of which are within the same battalion. The average delay factor between force nodes can then be calculated easily for the command hierarchy (CH) and situation awareness hierarchy (SH) cases.

For the situation awareness networking (SN) and command networking (CN) cases, we assume that, of the 120 pairs of companies, 48 are a single step away from each other by radio (for a delay factor of $2 + \boldsymbol{d}$), 48 are two steps away from each other (for a delay factor of $3 + 2\,\boldsymbol{d}$), and 24 are four steps away (for a delay factor of $5 + 4\,\boldsymbol{d}$). The average of these is $3 + 2\,\boldsymbol{d}$, which is the coordination coefficient. Table 7 shows the estimated coordination coefficients for the four C4ISR architectures:

Table 7: Coordination Coefficients for Four C4ISR Architectures

	Coordination Coefficient
Command hierarchy (CH)	$(23 + 36\,d)\,/\,5$
Situation awareness hierarchy (SH)	$(23 + 18\,d)\,/\,5$
Situation awareness networking (SN)	$3 + 2\,d$
Command networking (CN)	$3 + 2\,d$

5.3 The Intelligence Coefficient

The calculation of the intelligence coefficient is similar to that of the information flow coefficient, but we multiply intelligence quality by applicable area, and divide by the delay factor. As a consequence, the intelligence coefficient is higher for the case of intelligence-based search, as shown in Table 8:

Table 8: Intelligence Coefficients for C4ISR Architectures and Brigade Search Plans

	Intelligence Coefficient (Quadrant & terrain-based search)	**Intelligence Coefficient (Intelligence-based search)**
Command hierarchy (CH)	$32\,(2 + 7\,/\,(3 + 4\,d) + 3\,/\,(5 + 8\,d))$	$32(2 + 13\,/\,(3 + 4d) + 3\,/\,(5 + 8d))$
Situation awareness hierarchy (SH)	$32\,(2 + 7\,/\,(3 + 2\,d) + 3\,/\,(5 + 4\,d))$	$32(2 + 13\,/\,(3 + 2d) + 3\,/\,(5 + 4d))$
Situation awareness networking (SN)	$32\,(2 + 6\,/\,(3 + 2\,d) + 4\,/\,(2 + d))$	$32\,(2 + 12\,/\,(3 + 2\,d) + 4\,/\,(2 + d))$
Command networking (CN)	$32\,(2 + 6\,/\,(3 + 2\,d) + 4\,/\,(2 + d))$	$32\,(2 + 12\,/\,(3 + 2\,d) + 4\,/\,(2 + d))$

The process of modelling the experimental architectures by choosing delay values for each headquarters and link (which we have just described) has been largely based on informed estimation. For a real-life scenario, a similar estimation process would be necessary. However, once the estimated delay values have been chosen, we can calculate the information flow coefficient, coordination coefficient and intelligence coefficient using the procedures outlined in the previous section. In general, the three coefficients calculated by the FINC methodology (being based on an estimation process) will be a reflection of reality, but not a perfect one. However, although the FINC coefficients are imperfect, regression analysis shows that they predict performance extremely well (both for this simulation scenario, and for the one in [19]).

5.4 Regression Analysis

Recall that by dividing 100 by the search / manoeuvre time, we obtained a performance measure which increased as performance improved (Section 3). Regression analysis of this performance measure against the FINC coefficients showed that performance could be predicted extremely well by the intelligence coefficient alone, and that the information flow and coordination coefficients did not improve the prediction of performance.

As in our earlier work [19], the square root of the intelligence coefficient was a slightly better predictor than the intelligence coefficient alone. Prediction of performance using the square root of the intelligence coefficient was extremely good: 95% of the variance was explained (a correlation of 0.97, $p < 0.0000000001$). The equation of best fit was:

$$\boldsymbol{performance} = \mathbf{0.4400}\ \sqrt{\boldsymbol{i}} - \mathbf{2.666}$$

where $\boldsymbol{i}$ is the intelligence coefficient.

Figure 14 illustrates this. Green squares indicate intelligence-based search and blue circles indicate quadrant and terrain-based search. SN and CN are shown light, CH dark, and SH medium. The numbers indicate communication delay values ($\boldsymbol{d}$). Green lines show the average (plus or minus one standard deviation), and the best-fit line is red.

For this experiment, the information flow and coordination coefficients provide no additional ability to predict performance. Why is this so? The answer is that for hierarchical structures like the one examined here, all the FINC metrics tell a similar story. Table 9 shows the correlation matrix for the information flow and coordination coefficients and the reciprocal of the intelligence coefficient (the reciprocal is taken since the intelligence coefficient tends to increase as the others decrease). It can be seen that, for the hierarchical structure studied here, all three metrics produce similar numbers. However, as we have seen, the square root of the intelligence coefficient produces the best summary of the differences between alternate organisational structures. Information about architectural differences, availability of intelligence, and communication delays is successfully summarised by a single number which predicts 95% of the variance in performance.

Table 9: Correlation Matrix for FINC Metrics

	Information Flow Coefficient	**Coordination Coefficient**	**Reciprocal of Intelligence Coefficient**
Information Flow Coefficient	1.00	0.99	0.79
Coordination Coefficient	0.99	1.00	0.82
Reciprocal of Intelligence Coefficient	0.79	0.82	1.00

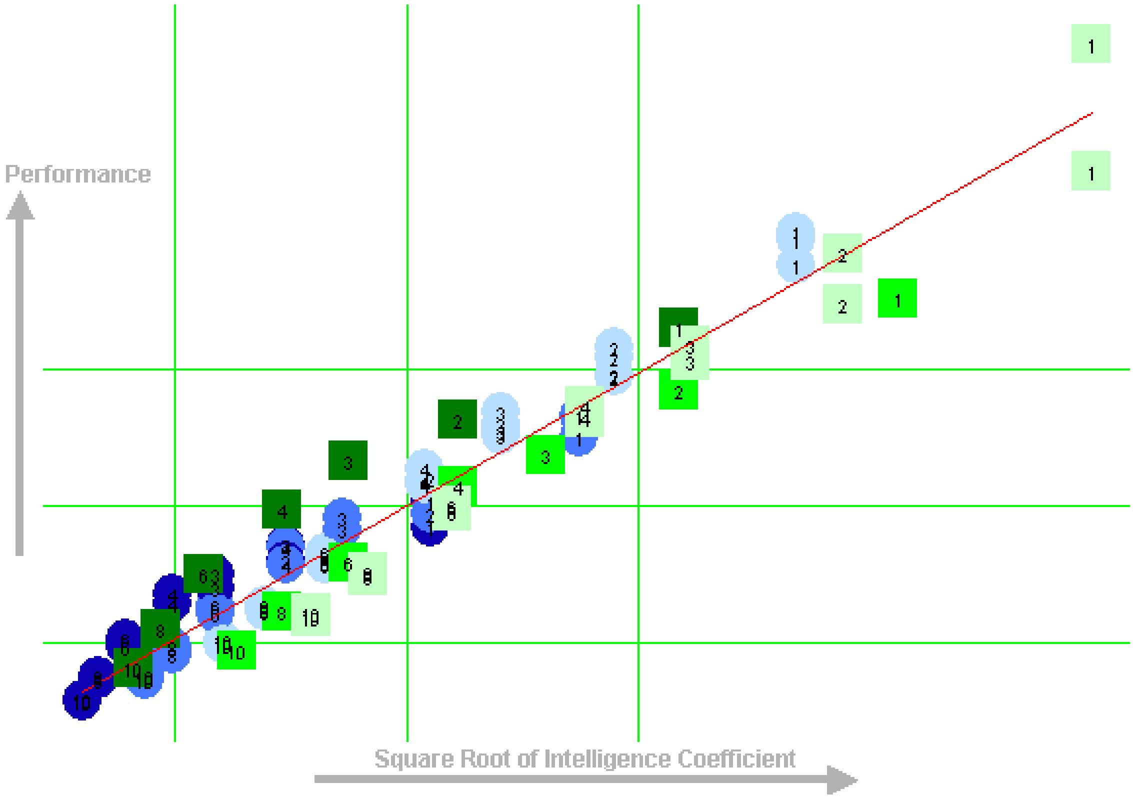

Figure 14: Performance against Square Root of Intelligence Coefficient

5.5 Sensitivity Analysis

We have seen that the process of FINC modelling has been largely based on estimation, and that for a real-life scenario, a similar estimation process would be necessary. Does the result above depend on the details of the estimation process? We examine this by varying some of our FINC modelling assumptions.

Recall that we assumed that the intelligence node attached to the brigade headquarters had its quality factor doubled for the case of intelligence-based search. We examine the effect of choosing a factor of 1.5 or 2.5 instead of 2. Recall also that we set the FINC delay factors to 1 for each headquarters, and ***d*** (the communications delay) for each link. We also examine the effect of choosing a delay factor for headquarters of 0.5 or 2 instead of 1 (this factor of 1 was in fact based on the actual delay incorporated into the Java-based simulation).

Table 10 shows the percentage of variance explained by the square root of the intelligence coefficient under these alternate assumptions. It can be seen that all of these variations produced a worse result, i.e. our initial estimates were the best possible (this is not surprising, given our knowledge of the testbed). However, most of the alternative estimates (seven out of eight) still resulted in being able to predict at least 91% of the variance in performance. For the one exception, 86% of the variance in performance could still be explained (a correlation of r = 0.93). Figure 15 shows the graph for that worst case. The graph shows that the performance of low-delay cases (1's and 2's) is underestimated (1's and 2's are mostly above the line of best fit), while the performance of intelligence-based search (green squares) is overestimated (green squares are mostly below the line of best fit).

Table 10: Percentage of Variance Explained under Different Assumptions

		Quality Factor for Intelligence-based search		
		1.5	**2**	**2.5**
Delay factor for HQ	**0.5**	93%	94%	92%
	1	94%	95% (original result)	91%
	2	93%	91%	86%

It can be seen that the success of the FINC methodology in predicting performance does depend on the estimation process, but not by too much.

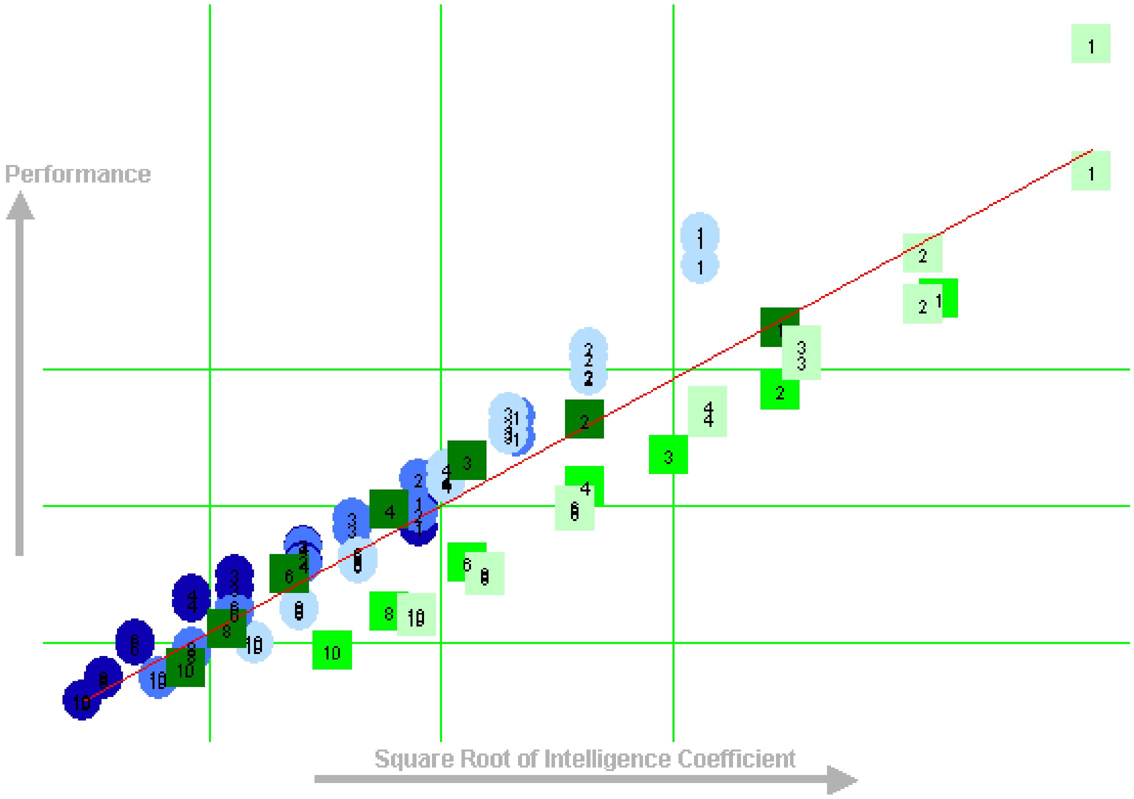

Figure 15: Performance against Square Root of Intelligence Coefficient for Worst Estimate

6. FINC in the Real World: The US Civil War

In this section we briefly examine an application of the FINC methodology to an historical case study. A series of twelve battles from the first two and a half years of the US Civil War [22] demonstrate wide variation in the ability to collect good intelligence, process it quickly, and transform it into unambiguous orders rapidly disseminated to subordinates. This is the quality which the intelligence coefficient is intended to measure. In the US Civil War, both sides shared similar culture, technology, and tactics, which reduces (but does not eliminate) the impact of other variables on the outcome of the battles. The US Civil War was also very well-documented. These factors make it a suitable test of the usefulness of the intelligence coefficient in the real world.

The results in this section should be treated with some caution, since we use extremely crude and subjective estimates of the intelligence coefficient. However, they do provide tentative confirmation of the usefulness of the intelligence coefficient in the real world, and a justification for further studies. The estimation process in this section is simpler than that described in Section 4, and simply estimates the intelligence coefficient to be an estimated intelligence quality factor divided by an average delay factor (since the area of operations is the same for both sides). For details, see Appendix B.

We measure the outcome of each battle using the number of casualties on each side. This is not a perfect measure, since it has the disadvantage of not taking into account the tactical result. However, given the tragically high casualty rates (the results of mixing eighteenth-century tactics with more modern technology), the number of casualties does give a partial measure of the strategic outcome, and is an adequate measure of performance for this preliminary study.

6.1 The First Battle of Manassas (Bull Run), July 1861

Table 11(a) shows the data for this early Confederate victory [29]. The number of troops recorded here includes those at Manassas and at Winchester nearby. Both armies were rather disorganised, but effective use of telegraph communication between Confederate Generals Beauregard and Johnston allowed for the efficient transfer of troops from Winchester to Manassas (reflected by a lower estimated average delay for the Confederate side). Beauregard had good intelligence on the size and plans of the Union army, but the Union General Patterson at Winchester was unaware of the transfer of Johnston’s troops to Manassas (reflected by a lower estimated intelligence quality for the Union side). We estimate the intelligence coefficient to be the intelligence quality divided by the average delay.

We take ratios in order to compare numbers of troops and casualties as well as intelligence coefficients. Ratios ensure that only comparisons for the same battle are important, and we need not have a systematic way of comparing numbers between battles. In order to eliminate bias as to which way the ratio is calculated, we use the natural logarithm of the ratio (since inverting the ratio merely changes the sign of the result).

Table 11(a): Data for the First Battle of Manassas (Bull Run)

	Generals	**Troops**	**Casualties**	**Intell. Quality**	**Average Delay**	**Intelligence Coefficient**
Union	Irvin McDowell Robert Patterson	35,000 18,000	2,900	4	4	1
Confederate	P.G.T. Beauregard Joseph E. Johnston	22,000 12,000	2,000	5	3	1.67
Log Ratio		0.44	0.37			–0.51

6.2 The Battle of Shiloh, April 1862

Table 11(b) shows the data for this Pyrrhic Union victory [29]. Both armies were rather disorganised. Initially, Union forces were separated, and intelligence reports on Confederate movement were ignored. Similarly, Confederate intelligence reports often did not reach General Beauregard, who was often out of touch with his subordinates. We therefore estimate the intelligence coefficients to be equal.

Table 11(b): Data for the Battle of Shiloh

	Generals	**Troops**	**Casualties**	**Intell. Quality**	**Average Delay**	**Intelligence Coefficient**
Union	Ulysses S. Grant Don Carlos Buell	40,000 23,000	13,000	4	4	1
Confederate	Albert S. Johnston P.G.T. Beauregard	40,000	10,700	5	5	1
Log Ratio		0.45	0.19			0

6.3 The Seven Days Battle, June–July 1862

The famous Confederate General Robert E. Lee demonstrated both his natural talent and his poor organisational skills in this battle. Lee issued verbal orders which were often misunderstood (partly due to an inadequate headquarters staff [27]), did not always use cavalry effectively to gather intelligence on opposing forces, and had very poor information on the local topography. The Confederate General D. H. Hill (quoted in [22]) described this intelligence failure in these words:

> *"Throughout this campaign we attacked just when and where the enemy wished us to attack. This was owing to our ignorance of the country and lack of reconnaissance of the successive battlefields."*

Confederate General Richard Taylor (also quoted in [22]) used even stronger words:

> *"Indeed it may be confidently asserted that … there was nothing but a series of blunders, one after another, and all huge. The Confederate commanders knew no more about the topography of the country than they did about Central Africa."*

Conversely, Union General George McClellan made effective use of telegraph communication — his main failing was timidity. We therefore estimate the intelligence coefficient to be significantly higher for the Union side, as shown in Table 11(c):

Table 11(c): Data for the Seven Days Battle

	Generals	**Troops**	**Casualties**	**Intell. Quality**	**Average Delay**	**Intelligence Coefficient**
Union	George McClellan	115,000	16,000	4.5	2	2.25
Confederate	Robert E. Lee	85,000	20,000	3.5	3	1.17
Log Ratio		0.30	–0.22			0.66

6.4 The Second Battle of Manassas (Bull Run), August 1862

The Union Army of Virginia (commanded by John Pope) revisited the defeat of July 1861 here. Pope's forces were poorly coordinated, and he was often totally unaware of the state of the conflict. We therefore estimate the intelligence coefficient to be higher for the Confederate side, as shown in Table 11(d):

Table 11(d): Data for the Second Battle of Manassas (Bull Run)

	Generals	**Troops**	**Casualties**	**Intell. Quality**	**Average Delay**	**Intelligence Coefficient**
Union	John Pope	70,000	14,000	4	3	1.33
Confederate	Robert E. Lee	55,000	9,000	4	2	2
Log Ratio		0.24	0.44			–0.41

6.5 The Battle of Sharpsburg (Antietam), September 1862

A Union intelligence advantage in this battle (the capture of Robert E. Lee's Special Orders No. 191) was not taken rapid advantage of, and intelligence collected by Allan Pinkerton's espionage organisation systematically overestimated Lee's strength [25]. In addition, both sides were poorly coordinated. We therefore estimate the intelligence coefficients to be equal, as shown in Table 11(e):

Table 11(e): Data for the Battle of Sharpsburg (Antietam)

	Generals	**Troops**	**Casualties**	**Intell. Quality**	**Average Delay**	**Intelligence Coefficient**
Union	George McClellan	75,000	12,400	4.5	3	1.5
Confederate	Robert E. Lee	38,000	10,300	3	2	1.5
Log Ratio		0.68	0.19			0

6.6 The Battle of Perryville, October 1862

Confederate General Bragg's forces in this battle were poorly coordinated, and he had poor intelligence on Union positions. However, Union General Buell had equally poor intelligence on Confederate positions, and the battle was indeed the result of an accidental meeting of forces. Bragg did not realise his forces were engaged in combat until several hours had elapsed. We therefore estimate the intelligence coefficients to be equal, as shown in Table 11(f):

Table 11(f): Data for the Battle of Perryville

	Generals	Troops	Casualties	Intell. Quality	Average Delay	Intelligence Coefficient
Union	Don Carlos Buell	60,000	4,200	4	4	1
Confederate	Braxton Bragg Kirby Smith	70,000 20,000	3,400	4	4	1
Log Ratio		–0.41	0.21			0

6.7 The Battle of Fredericksburg, December 1862

In this battle, Robert E. Lee had a well-organised defence along a relatively short front, which simplified his communications. The incompetence of Union General Ambrose Burnside is, however, not fully reflected in our estimated intelligence coefficients. We estimate the intelligence coefficient to be higher for the Confederate side, as shown in Table 11(g):

Table 11(g): Data for the Battle of Fredericksburg

	Generals	Troops	Casualties	Intell. Quality	Average Delay	Intelligence Coefficient
Union	Ambrose Burnside	120,000	12,600	5	3	1.67
Confederate	Robert E. Lee	78,000	5,300	5	2	2.5
Log Ratio		0.43	0.87			–0.41

6.8 The Battle of Murfreesboro (Stones River), December 1862

This battle demonstrated incompetence on both sides. We therefore estimate the intelligence coefficients to be equal, as shown in Table 11(h):

Table 11(h): Data for the Battle of Murfreesboro (Stones River)

	Generals	Troops	Casualties	Intell. Quality	Average Delay	Intelligence Coefficient
Union	William Rosecrans	41,000	13,000	4	3	1.33
Confederate	Braxton Bragg	35,000	10,000	4	3	1.33
Log Ratio		0.16	0.26			0

6.9 The Battle of Chancellorsville, May 1863

Union General Joseph Hooker had four Corps which were initially well-coordinated, but intelligence on the Confederate attack by "Stonewall" Jackson was ignored. Later on, an injured and dazed Hooker failed to coordinate the battle. We therefore estimate the intelligence coefficient to be significantly higher for the Confederate side, as shown in Table 11(i):

Table 11(i): Data for the Battle of Chancellorsville

	Generals	Troops	Casualties	Intell. Quality	Average Delay	Intelligence Coefficient
Union	Joseph Hooker	134,000	17,000	3	2.5	1.2
Confederate	Robert E. Lee Thomas J. Jackson	60,000	13,000	5	2	2.5
Log Ratio		0.80	0.27			–0.73

6.10 The Battle of Gettysburg, July 1863

In this famous battle [28], Robert E. Lee was crippled by lack of intelligence and inadequate staff work. Initially, he did not have cavalry to locate Union forces, and later his artillery had no intelligence on the fall of shot. Some uncoordinated activity was evident on both sides, although the Union's defensive position facilitated signalling between units. We therefore estimate the intelligence coefficient to be higher for the Union side, as shown in Table 11(j):

Table 11(j): Data for the Battle of Gettysburg

	Generals	Troops	Casualties	Intell. Quality	Average Delay	Intelligence Coefficient
Union	George G. Meade	90,000	23,000	4	2	2
Confederate	Robert E. Lee	75,000	28,000	2.5	2	1.25
Log Ratio		0.18	–0.20			0.47

6.11 The Battle of Chickamauga, September 1863

In this battle (fought in wooded country) Union General William Rosecrans had poor intelligence on the state of Confederate forces, but Confederate forces also had poor intelligence, and were very poorly organised [26]. Rosecrans was later described by Abraham Lincoln as "confused and stunned, like a duck hit on the head." We therefore estimate the intelligence coefficients to be equal, as shown in Table 11(k):

Table 11(k): Data for the Battle of Chickamauga

	Generals	Troops	Casualties	Intell. Quality	Average Delay	Intelligence Coefficient
Union	William Rosecrans	57,000	16,200	2	4	0.5
Confederate	Braxton Bragg	67,000	21,000	2	4	0.5
Log Ratio		–0.16	–0.26			0

6.12 The Battle of Chattanooga, November 1863

Union General Ulysses S. Grant, taking over from Rosecrans, coordinated his forces significantly better (see his *Memoirs* [24] for his own account). One of Grant's important qualities was his ability to communicate, both verbally and in writing. Meade's chief of staff (quoted in [31]) describes the clarity of his orders as follows:

> *"There is one striking feature of Grant's orders; no matter how hurriedly he may write them on the field, no one ever has the slightest doubt as to their meaning, or even has to read them over a second time to understand them."*

The Confederates, on the other hand, suffered from conflicts between senior generals [26]. We therefore estimate the intelligence coefficient to be significantly higher for the Union side, as shown in Table 11(l):

Table 11(l): Data for the Battle of Chattanooga

	Generals	**Troops**	**Casualties**	**Intell. Quality**	**Average Delay**	**Intelligence Coefficient**
Union	Ulysses S. Grant	60,000	5,800	5	1	5
Confederate	Braxton Bragg	46,000	6,700	5	2	2.5
Log Ratio		0.27	–0.14			0.69

6.13 Analysis

Statistical analysis of these results shows that there is no correlation between log ratio for the number of troops involved and log ratio for the number of casualties, i.e. the number of casualties suffered bore no relationship to the size of the armies involved.

However, the log ratio of the intelligence coefficients predicted a significant 55% of the variance in casualty log ratio (a correlation of –0.74, $p = 0.006$), even with our simplistic estimates. Figure 16 illustrates this. The remaining 45% of the variance is presumably due to tactical factors, terrain, and other aspects of command skills. In other words, although other factors are also important, fewer casualties were attained by the use of good intelligence, processed quickly, and transformed into unambiguous orders rapidly disseminated to subordinates. Robert E. Lee is an example of an otherwise talented general who often failed to do this.

Battles marked in green in Figure 16 had a Union advantage in the number of troops, while battles marked in orange had a Confederate advantage in the number of troops. As indicated above, having an advantage in the number of troops did not in general affect the outcome.

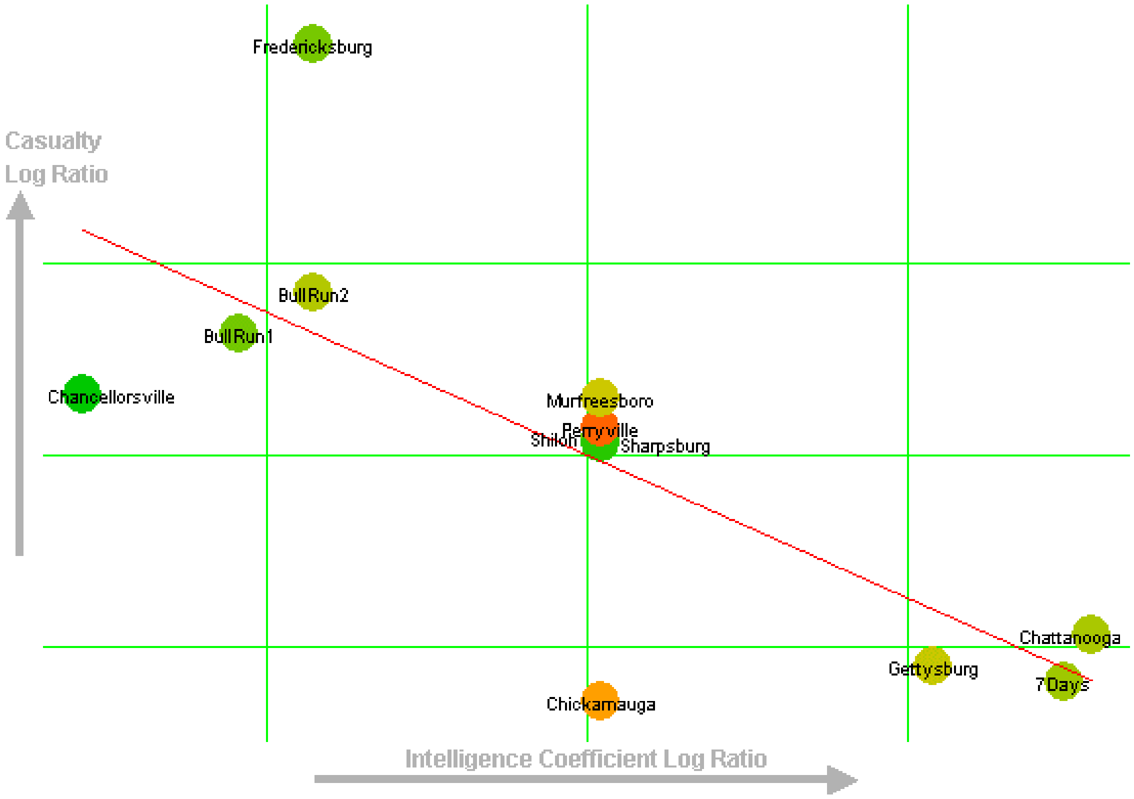

Figure 16: Casualty Log Ratio against Intelligence Coefficient Log Ratio

These results suggest that the intelligence coefficient is indeed useful in predicting performance of Land forces in the real world. However, this conclusion should be treated with caution. Our estimation process was extremely simplistic. It has also resulted in intelligence coefficients which correlate highly with other aspects of command competence, and it may be that these other aspects are more important in determining the outcome of the battle. Nevertheless, this tentative confirmation of the usefulness of intelligence coefficients does justify more detailed real-world studies.

7. Conclusions

In this study we have extended the FINC (Force, Intelligence, Networking and C2) methodology to a land-based scenario involving a hierarchical organisational structure combined with elements of Network Centre Warfare [13].

The FINC metrics were just as successful in predicting performance as in our previous “SCUD Hunt” scenario [19]. Indeed, in this study we could predict 95% of the variance in performance using just a single metric, the intelligence coefficient. This metric integrates information about architectural differences, quality of intelligence, and communication delays. The prediction of performance depends on the estimations that are part of by the FINC methodology, but not by too much.

A survey of 12 real-world examples from the US Civil War provided tentative confirmation that the intelligence coefficient is also useful in predicting real-world performance.

This study has therefore further validated the FINC methodology, and helped to justify future work which we plan to conduct. This future work will use the FINC methodology to assess joint and coalition architectures.

Further work is still required on the FINC methodology, particularly on the process of estimating delay factors for headquarters and links, on assigning quality scores to intelligence assets, and on the use of “misunderstanding factors” for cross-cultural links. We intend to explore these in a future simulation experiment which will investigate joint and coalition issues. We also plan to further validate the FINC methodology with real-world examples.

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Appendix A: Table 12

Table 12: Experimental Results for 1,000 Runs

C4ISR Arch.	**Comms delay**	**Search/manoeuvre time**		
		Quadrant-based search plan	**Terrain-based search plan**	**Intelligence-based search plan**
CH	1	56.5	60.0	40.8
CH	2	62.6	64.9	47.8
CH	3	67.2	69.7	51.9
CH	4	71.0	72.9	57.4
CH	6	81.2	83.4	67.5
CH	8	91.9	93.5	78.8
CH	10	100.5	101.8	89.7
SH	1	47.4	49.5	39.0
SH	2	53.7	58.0	45.4
SH	3	58.4	60.1	51.1
SH	4	62.8	65.5	54.6
SH	6	73.2	75.0	65.2
SH	8	83.3	85.2	74.7
SH	10	92.4	93.3	84.4
SN	1	35.4	35.8	28.1 (best)
SN	2	42.1	42.8	36.4
SN	3	47.1	48.2	42.0
SN	4	52.6	54.1	46.7
SN	6	63.7	64.4	57.0
SN	8	73.3	73.2	67.6
SN	10	81.8	82.8	75.8
CN	1	37.1	37.0	32.6
CN	2	44.0	44.3	39.3
CN	3	48.9	49.3	43.1
CN	4	53.9	54.3	47.6
CN	6	65.3	65.7	57.7
CN	8	74.1	74.5	67.1
CN	10	82.7	82.6	75.2

Add 39.8 to search / manoeuvre times to obtain the total time taken.

Appendix B: Civil War FINC Assessment

The estimation process in Section 6 is simpler than that described in Section 4, and simply estimates the intelligence coefficient to be an estimated average intelligence quality factor divided by an average delay factor (since the area of operations is the same for both sides).

The average intelligence quality is estimated by summing a score of 0 or 1 for the following intelligence-related factors (where a factor only applies partially, a score of 0.5 is used):

- Minimum value of 1
- Intelligence on the size of the opposing force
- Intelligence on the location of the opposing force
- Intelligence on the plans of the opposing force
- Intelligence on the fall of shot
- Intelligence on the terrain
- Effective use of cavalry for intelligence-gathering

The average delay is estimated by summing a score of 0 or 1 for the following factors which degrade the efficiency of communication (where a factor only applies partially, a score of 0.5 is used):

- Minimum value of 1
- General disorganisation of forces
- Separation of forces, without effective use of telegraph communication
- Orders lost or misplaced
- Excessive reliance on verbal (rather than written) orders
- A senior General out of touch with his subordinates
- Conflicts among senior officers

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19. ABSTRACT

In this paper we re-examine the FINC (Force, Intelligence, Networking and C2) methodology for analysing C4ISR architectures, studying its applicability to hierarchical organisational structures in the Land environment. For this study we utilise a search-and-manoeuvre experimental scenario, implemented using an agent-based simulation written in Java. The FINC methodology allows the calculation of three metrics or coefficients for every C4ISR architecture: the information flow coefficient, the coordination coefficient, and the intelligence coefficient. Our experiment shows that the FINC intelligence coefficient alone was able to predict 95% of the variance in performance. Consequently, the intelligence coefficient can be used to compare C4ISR architectures, and predict with moderate accuracy which one will give the best performance. A brief study of some US Civil War battles confirms the usefulness of the intelligence coefficient.