

**ADAPTING
MODELING & SIMULATION
FOR NETWORK ENABLED
OPERATIONS**

JAMES MOFFAT

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The Command and Control Research Program (CCRP) has the mission of improving DoD's understanding of the national security implications of the Information Age. Focusing upon improving both the state of the art and the state of the practice of command and control, the CCRP helps DoD take full advantage of the opportunities afforded by emerging technologies. The CCRP pursues a broad program of research and analysis in information superiority, information operations, command and control theory, and associated operational concepts that enable us to leverage shared awareness to improve the effectiveness and efficiency of assigned missions. An important aspect of the CCRP program is its ability to serve as a bridge between the operational, technical, analytical, and educational communities. The CCRP provides leadership for the command and control research community by:

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- sponsoring a series of workshops and symposia;
- serving as a clearing house for command and control related research funding; and
- disseminating outreach initiatives that include the CCRP Publication Series.



This is a continuation in the series of publications produced by the Center for Advanced Concepts and Technology (ACT), which was created as a “skunk works” with funding provided by the CCRP under the auspices of the Assistant Secretary of Defense (NII). This program has demonstrated the importance of having a research program focused on the national security implications of the Information Age. It develops the theoretical foundations to provide DoD with information superiority and highlights the importance of active outreach and dissemination initiatives designed to acquaint senior military personnel and civilians with these emerging issues. The CCRP Publication Series is a key element of this effort.

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JAMES MOFFAT

This book is dedicated to my wife Jacqueline and my daughters Louise and Katherine, who continue to inspire me to greater things.

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FOREWORD

BY DR. DAVID S. ALBERTS

If there is a particular theme central to the body of literature produced by the CCRP Publication Series, it involves the challenges of complexity and the nature of an appropriate response to this complexity. This book continues our treatment of the subject of complexity and its implications for military organizations.

Network Enabled Capability, first introduced to a wide audience with the CCRP publication of *Network Centric Warfare* in 1999, is, as the author points out, the embodiment of the military's transition from the Industrial Age to the Information Age. The struggles to understand, accept, and develop a network enabled approach to military operations mirror similar developments in the adoption of the Internet that have given birth to a variety of new business and organizational models. The relatively rapid rise of online book stores and more recently eBooks came to many as a surprise. The traditional brick-and-mortar book

store is an endangered species that must adapt to these new realities or be relegated to a niche market. Hard copy books may soon follow.

The increasing complexity of military missions—from disaster relief through stabilization and peace support to warfighting—has, in the CCRP literature, been referred to as *Complex Endeavors*. In *Complex Endeavors* it is not only the environment that is complex; it is also “us,” no longer a single organization, but a heterogeneous collective.

Regrettably, this development, decades in the making, seems to continue to catch some by surprise. Many seem to think that business as usual is still an option. Many recognize that change is needed but do not understand how to change and do not accept the changes proposed by others. The rising calls for action are not advocating simply more expertise but a new kind of expertise; not more competencies but rather more agility.

Nowhere is this more true than in the critical area of Command and Control. The Napoleonic imperative must yield to new Information Age ideas based on the ability to adapt the command approach to rapidly changing operational circumstance—*C2 Agility*.

The essence of this book is to describe how the UK Ministry of Defence has risen to these challenges by investing in the development of new analytical tools, in particular closed form simulation modeling, in order to provide the evidence base for improved high level decision-making in government.

At the core of the approach is the development of a consistent representation of Command and Control across the suite of models. This development was itself significantly influenced by the interaction and exchange of ideas drawn from a number of NATO research task groups—and the development of these ideas is still continuing. These developments are brought together in illustrating how they impact the shaping of UK defense policy through informing high level decision-making by officials and government ministers. The efforts of NATO researchers and UK operations researchers and analysts must be emulated in other organizations, both military and civilian, throughout the world if we, collectively, are to meet the very real challenges of Complex Endeavors.

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CHAPTER 1

THE CHALLENGE

The Changing Defence Environment: World War II to the late 1980s

Let's start our journey towards information age warfare by first briefly reminding ourselves of the origins of the most direct operational analysis (OA)¹ support to decision-makers in the UK, namely the Second World War. OA support in those wartime days was almost wholly set in the present—the groups of wartime analysts were, naturally enough, concerned exclusively with operations, that is to say, with tactics and with the most effective use of existing resources at tactical, operational, and strategic levels. These researchers took largely for granted the continuous supply of data on the results of the day-to-day operations of front-line units and applied their methods to the urgent problems presented by operational developments, such as the opportunities afforded by new equipment or the challenges of meeting changes in enemy tactics or capabilities. The operational analysis groups also took as a given that there

1. Operational Analysis (OA) is the term used within the UK Ministry of Defence for the defence application of Operational Research (OR).

was only limited calculating power available to support them; methods were therefore relatively simple compared with those available as a result of today's computational capabilities.

The successful contribution of OA during hostilities naturally caused the then service ministries (the admiralty, the war office, and the air ministry) to see OA as an aid to the planning of the forces in peacetime. The problems presented in the early post-war years were indeed formidable: availability of nuclear weapons; the start of the Cold War; the increasing rate of technological advance of conventional weaponry; and the strong downward pressure on defence budgets as the nation recovered from war, only briefly reversed during the Korean War re-armament. Quite quickly, therefore, forward-looking studies to support the planning process for future acquisition became at least as important as direct support of operational commanders.

Moving forward to the Cold War, OA was increasingly used to consider potential future scenarios and conflicts—primarily, of course, in the hope that they would never come to pass. In the main, and certainly on land, such conflicts were seen as largely set-piece affairs in which major forces faced each other, in what we would now consider a symmetric fashion; for example, the significant NATO ground and air forces facing the Warsaw Pact in western Europe along the inner German border.

Throughout the Cold War, and indeed all the way to the current day, most OA requires us, at some point and in some way, to relate the outcome of a military operation to the resources deployed to undertake it and to the way in which those resources are used. In other words, we must be able to develop models of military operations that enable us to compare alternative

resource allocation options using appropriate military or politico-military measures of effectiveness. This is true whether we are considering the use of real resources in a real operation, as is the case when supporting operational commanders, or when examining more hypothetical situations to support future force planning and procurement. We can see a strong hint here of the need for modelling and analysis that reflects relevant operations and options for their conduct, a subject we'll return to in more detail a little later.

During the Cold War, OA was typically considering a fairly narrow set of operations, in particular those potentially arising from major conflict in western Europe. Such analysis was two-sided; NATO and the Warsaw Pact. Moreover, the military operation had primacy—should all-out military conflict have started, nonmilitary mechanisms such as diplomatic efforts at the United Nations would either have already failed or would have had little direct bearing on the conflict at hand, especially given a likely rapid escalation to nuclear exchange.

And then the Berlin Wall came down! And with it, came a whole series of changes to the nature and range of potential future operations; to the predictability—or, more pertinently, the lack of it—of such operations. This, together with a raft of other changes to the analytical support required by senior decision-makers, led to a series of challenges that analysis needed to address in order to remain relevant to such decision-makers. The following section addresses some of these key changes and challenges, explicitly labelling some of the latter so that we may return in due course to how the modelling developments addressed in later chapters help to meet them, and which of these require further research efforts. Some of these challenges

are outside the scope of this particular book. These are briefly touched on for completeness although they are being tackled elsewhere.

Beyond The Cold War

The Spectrum of Operations

OA now needs to consider a very wide spectrum of operations. One end of the spectrum can still be readily typified by major hostilities, although even here the manifestation of such hostilities is more likely to feature operations such as the two recent Gulf conflicts rather than more apocalyptic Cold War east versus west scenarios. The benign end of the spectrum features operations in support of the civil power and disaster relief operations in a non-conflict situation—UK examples might include military assistance during the recent fire fighters' strikes, during the foot-and-mouth epidemic or during international humanitarian aid operations such as after a hurricane, earthquake, or tsunami. Between these extremes sits a raft of other operational circumstances, the terminology for which is still evolving. This includes cases such as peacekeeping (PK), peace enforcement (PE), military aid to stability development (MASD), and power projection (PP). The first, PK, arises typically where a peace accord is in place to which all factions have agreed and thus the military force is operating with the consent of the various parties—the UK's continuing presence in Cyprus is an example. MASD, on the other hand, reflects a less benign situation where not all factions are in agreement—Afghanistan in 2008 is an exemplar. Additionally, since 2001, the likelihood of asymmetric operations has been increasing across the spectrum of operations; that is, the prosecution of activity outside the traditional field of battle whether via suicide

terrorism, cyber warfare or other means. Such actions can equally occur in the context of a major warfighting operation, a PE or as a homeland security issue. Finally, a PP is a military operation designed to influence, typically, a recalcitrant nation state by means of the use or threat of use of military force. This is typically done in such a manner as to preserve as much political freedom of manoeuvre as possible—by contrast with more direct military intervention operations—whilst deterring or coercing an opponent away from their preferred course of action.

Note also, that it is not just the potential range of such operations that is now very broad but also that the associated uncertainty is much greater. Who, in the early 1990s, could have predicted many of the changes in geopolitics, shifting alliances, regional (im)balances, and the like that have occurred over the past 15 or so years? Actually, it can be argued that the current uncertainty over potential futures is the norm and that the Cold War was the deviant from that norm—certainly a case can be made for this based on a longer look at history over the last 100 or so years. Unfortunately, the point is moot as, whatever the cause, the challenge remains concerning how to analyse such a multiplicity of potential future operations in a meaningful and timely fashion.

Challenge 1: How can analysis methods adequately represent a suitably wide range of operational types?

Another important feature of most of the types of operations discussed above is the multiplicity of actors involved. Long gone is the purely two-sided nature of Cold War conflict (*red* versus *blue*)—if it ever really existed, given factions within alliances,

refugees on the battlefield, likely “fifth column” and special forces operations, and so on. Current and future operations are almost certain to be many-sided. For example, a typical MASD or PE is likely to include several *flavours* of red, such as different factions that will cooperate to a greater or lesser extent with each other; indigenous *green* forces; a range of non-military elements, including non-governmental organisations (such as the Red Cross) and international agencies (such as United Nations bodies); and a variety of blue peacekeepers, possibly under UN auspices and almost certainly operating to particular national caveats, rules of engagement and so on.

Challenge 2: How can we appropriately represent the multisided nature of current and future conflict?

The Changing Technology and Concepts of Warfare

At the same time that the circumstances in which we deploy military capability have been changing, so too have the instruments with which we can exert that capability. On the whole, OA takes the changing technology of warfare in its stride. Over the years it has, for example, coped with the advent of jet aircraft, guided missiles, and nuclear submarines. Sometimes, more advanced technology may even be simpler to analyse, since there may be fewer complex tactical constraints to be modelled. It is, however, easier to reflect technology changes that are closer to *like-for-like*—such as replacing propeller-driven aircraft with jet aircraft, or air-breathing submarines with nuclear-powered ones—than to address truly radical technologies such as stealth or cyber warfare. This is, at least in part, because it is easier to

consider and therefore represent *doing things better* (improving what we know) rather than *doing better things* (striking out along a different path).

Challenge 3: How can we represent the genuinely different approaches enabled by evolving technology?

Information Age Warfare

One particular set of changes in technology poses particular problems for the analyst and is the subject of much of this book, namely developments that are putting the management of information at the heart of the way in which military operations will be conducted in future. The primary purpose of this information is, of course, to allow commanders, and indeed participants in operations at all levels, to make better and faster decisions. The key to this is the ability to collect, fuse, and disseminate accurate, timely, and relevant information with much greater rapidity (sometimes in a matter of only minutes, or even in real-time) to help provide a common understanding among commanders at all levels.

Challenge 4: How can we adequately represent information age warfare in our approaches?

Exponents of such network enabled capability (NEC) envisage that networked entities, with a high level of shared awareness and a common understanding of the overall intent of the operation, will be able to achieve missions in a self-synchronous way,

without the traditional hierarchical mechanisms for command² and control. Even if developments stop short of this point, the architecture of military operations will be profoundly influenced by such concepts.

Understanding the impact of information and human decision-making on military operations has always been a serious challenge to the analyst. Indeed, it was arguably the major piece of unfinished analytical business when the Cold War ended. As we now move towards modes of operation that are even more dependent on information management, the challenge becomes that much sharper.

Challenge 5: How can we represent the essential human decision-making elements that are critical to information age warfare?

The fog and friction of war have always been important determinants of the way in which it has been fought; significant reductions in either or both must have a major impact.

2. Here, and throughout the rest of this book, the terms *command*, *command and control*, and the acronym *C2* are, in general, used interchangeably, in an effort to reduce the number of acronyms, and increase the intelligibility of the English text, especially for those not experts in the subject. These terms refer to all of the processes associated with command and control, including the collection, assessment, and dissemination of information; decision-making; the promulgation of intent and orders to the force, etc.

Challenge 6: How can we capture the residual fog and friction of war, even when suitable information age capabilities are fielded?

Military Role in Operations

Another key point is that the role of the military in the complex operational environments described is, to a greater or lesser extent, subordinate to other governmental levers of power, in particular economic and diplomatic means. This means that any military operation needs to be set in a wider context, adding further complexity to the analytical process. For example, in consideration of homeland security situations arising from potential terrorist actions within the UK, primacy sits with the Home Office rather than the Ministry of Defence (MoD); the military role, if any, is a supporting one. Similarly, in PE, MASD or PK operations conducted abroad, the military role is but one element of an overall approach and must be aligned appropriately with non-military activity.

Challenge 7: How can our methods cope with such non-military factors?

Even where military forces are used in anger, their role these days is not solely to defeat or destroy all enemy forces. Traditional conflict models of the Cold War era relied almost wholly on attritional approaches. Such approaches recognised that, all other things being equal, it was a combination of a force's effectiveness and numbers that mattered in determining battle outcome—the “biggest with the best” would be able to win a military victory. Of course, not all other things were equal then and they certainly are not now; although the simplifications

inherent in such approaches have stood the analytical community in good stead over the years, provided they are applied intelligently by high-quality analysts aware of their strengths and limitations. To make progress, however, we need to identify and tackle some of the ways in which *all things are not equal*. One major element of this is to understand so-called non-kinetic effects, such as coercion and deterrence; and, more broadly, how military forces can be used to *influence* enemy thinking at either military or government level.

Challenge 8: How can we represent non-kinetic effects as well as attrition in our approaches?

Two Final Challenges

Two further areas of particular challenge are worth a brief mention for completeness. First, there is an increasing need to address not only the operation at hand, but also the implications of concurrent and sequential operations. For example, sequential operations can occur when a direct intervention precedes a PE, MASD, or PK. Unsurprisingly, the success or otherwise of the preceding operation and its manner of conduct will have a major impact on the course of its successor. Concurrency in operations is also important. Military assets cannot be in two places at the same time, and need time between operations to recuperate and train. Thus, the level and type of concurrent operations that are planned for have a significant impact on the overall force structure required and its cost.

Second, there is the impact of funding levels. Defence cannot—and nor should it—escape the general push for value-for-money from government spending. Any investment or

operational decision affecting the armed forces has financial implications. Thus we need to capture the cost as well as the effectiveness of potential military operations and options in order to support effective decision-making between options.

CHAPTER 2

MEETING THE CHALLENGE

Cybernetics and Command

I¹ want to start by discussing some ideas which have helped to shape the direction of my work. Cybernetics² is the science of control and communication in the animal (or human) and in the machine, as defined by Norbert Wiener [1]. It can thus provide some fundamental insights into the subject of human command and decision-making. A basic concept in cybernetics is *variety* (the number of different accessible states of a system, and thus a measure of potential system agility). In particular, *Ashby's Law of Requisite Variety*, discussed in [2], indicates that for a system to be in control, the variety of the controller must balance the variety of the system. For example a simple system only requires a simple controller. In the industrial age, our networks and communications gave rise to low variety (a simple controller), thus we had to partition the battlespace into sectors, and have specialised force units (a simple system), in order to

1. Throughout this book, the expression *I* denotes that the point or idea is the author's alone. The term *we* expresses the fact that the ideas or work presented were a team effort.

2. The word Cybernetics was first used by Ampere as the title of a sociological study. It is derived from the Greek work for steersman.

reduce the variety of the battlespace, in accord with Ashby’s Law. During the Cold War, the whole of western Europe was divided into sectors which were the responsibility of different NATO nations—low variety of the physical battlespace was matched to low variety of the command process. Command was also hierarchical, reflecting an efficient solution to a relatively stable external environment. To quote from [2];

One way of looking at this is to consider how management style and the environment interact in terms of a two by two matrix (figure 2.1);

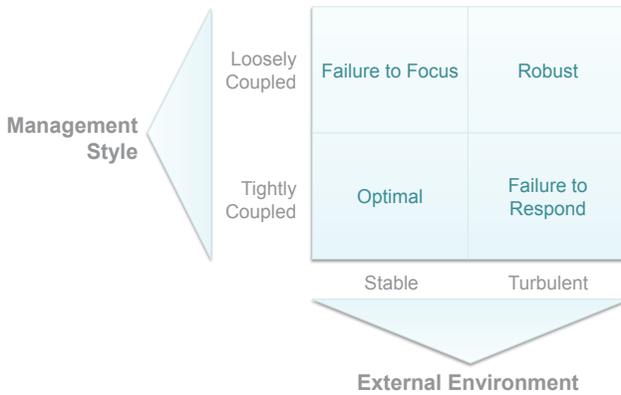


Figure 2.1: Management style and the external environment.

On one axis of the matrix, we have plotted “Management Style,” varying from “tightly coupled” to “loosely coupled.” By tightly coupled we mean management by detailed instruction, leading to a hierarchical management process. By loosely coupled, we mean the tolerance and encouragement of self-organising informal networks of key individuals who share trust and knowledge. On the other axis, we have plotted the external environment ranging from stable to very dynamically

varying and uncertain (“turbulent”). A tightly coupled management system succeeds when conditions are stable. In the defence context, the period of the Cold War was an example of awful stability—the threat stayed essentially constant for over forty years. As a consequence, detailed roles and specialist forces were engineered, operating inside well-defined sectors of operation, and managed by an unchanging hierarchy of command. Operational research of this “scenario” went into more and more detail of particular pieces of the puzzle. A loosely coupled management process succeeds when conditions are very uncertain and dynamic. Again relating to the defence context, multiple scenarios of the future now have to be considered, each with huge uncertainty associated with them. It is this uncertainty and a potentially very dynamic “battlespace” which is driving defence in the direction of “edge organisations” which have the agility to cope. Operational research of these situations puts the emphasis on the spread of likely futures, rather than on the detail of a specific “scenario.”

As we move into the information age, we thus foresee a turbulent and uncertain set of futures, and a battlespace with high variety. Thus we need to construct a representation of the human command and decision-making process which gives rise to high variety [2]. In my work I have captured this by creating two representations of command and decision-making denoted *deliberate planning* and *rapid planning*. Rapid planning, reacting to local and fast changing circumstances, creates variety, and corresponds in cybernetic terms to feedback control. This is then constrained by more strategic deliberate planning in order to produce the requisite variety of command. Deliberate planning corresponds to a broad, cognitively-based review of the options available. In cybernetic terms this is feed-forward control, since it involves the use of a model (i.e., a model within

our model) to predict the effects of a given system change. In developing these ideas into computer algorithms which can be implemented in simulation models [3] we have discussed how it is possible to exploit ideas from complex adaptive systems theory and artificial intelligence based agent approaches in order to develop algorithms corresponding to rapid and deliberate planning which avoid the use of lengthy rule sets, and instead use more generic mathematical representations. This approach has many advantages when it comes to actual model construction and use, as we will see later.

The Characteristics of Agility

An agile force can be characterised by the following six attributes [4]:

1. *Robustness*: the ability to maintain effectiveness across a range of tasks, situations, and conditions;
2. *Resilience*: the ability to recover from or adjust to misfortune, damage, or a destabilising perturbation in the environment;
3. *Responsiveness*: the ability to react to a change in the environment in a timely manner;
4. *Flexibility*: the ability to employ multiple ways to succeed and the capacity to move seamlessly between them;
5. *Innovation*: the ability to do new things and the ability to do old things in new ways; and

6. *Adaptation*: the ability to change work processes and the ability to change the organisation of the force.

These attributes are by no means orthogonal to each other—they are in fact interdependent. For example, resilience requires adaptable work processes and organisational structures as well as flexible and innovative decision-making. However, they are a useful way of unpacking the concept of agility into a number of force characteristics. Taking our cue from the discussion in [4], we can describe each of these attributes in more detail.

Robustness is a characteristic of command and control (C2)³ systems, operational concepts, and military forces across the full spectrum of the operational environment. It is particularly challenged by a threat environment which is complex in nature, and where robustness over time is also an issue. Key dimensions of the operational envelope are the mission type, the nature of the adversary, and the complexity, duration, and size of the operation. As the ability of the force to cover this space increases, so robustness also increases.

Resilience has two components: the ability to continue to function well under stress and shocks to the force, and the ability to recover. Greater resilience is thus characterised by being able to continue effectively under such shocks and stresses, and being able to be disrupted for less time. Aspects of the force which enable greater resilience include self-healing or redundant

3. As already noted in Chapter 1, the terms *command*, *command and control*, and the acronym *C2* are, in general, used interchangeably throughout this book, in an effort to reduce the number of acronyms, and increase the intelligibility of the English text, especially for those not experts in the subject. These terms refer to all of the processes associated with Command and Control, including the collection, assessment, and dissemination of information; decision-making; the promulgation of intent and orders to the force, etc.

networks with multiple paths. For example, random networks are less resilient than scale free networks, under random attacks on the network nodes [5]. Forces with more collaborative planning and knowledge-sharing processes will also be more resilient to attack on command nodes. Information enabled logistics, which can sense disruption to the operational force, and adjust accordingly, will also be a source of resilience.

Responsiveness includes the ability to control the tempo of proceedings, and to match it to the requirements of the situation. A more responsive force will recognise windows of opportunity more quickly, and act on them in a timely manner. A force with increased levels of shared awareness of the changing situation, and a shared understanding of the intent of the operation, will be able to be more responsive in this sense. A force which is more task organised may also be able to respond in a more timely manner to changing opportunities.

Flexibility of the command system allows the force to generate, consider, and undertake a variety of methods to accomplish its assigned missions. Flexibility in this sense is a characteristic of the command and planning system. However, force elements which can be used in a number of different ways, will allow a wider range of such plans to be contemplated. The deliberate consideration of alternative plans, and more collaborative ways of generating and updating plans, will both avoid focussing on too narrow a set of plan alternatives. Such flexibility of planning requires the ability to sense a change in the battlespace, which might offer new opportunities and challenges and the ability to easily adjust plans to take account of these changes. (We will see in later chapters how some of this plan flexibility has been built into our simulation models).

Innovation enables flexibility in the planning process through the development of novel options in the face of unfamiliar situations. For example, in the context of a complex and rapidly changing urban insurgency, with warfighting and peace support operations proceeding simultaneously and in close proximity (the “three block war”), each local unit needs to learn quickly and creatively what works and what does not. Innovation also includes the need to be able to learn over time (across missions or engagements) and across operations, in order to avoid predictability.

Adaptation includes the ability to alter the force organisation and work processes when necessary as the situation and/or environment change(s). It is inwardly focussed on one’s own force. Command can be characterised by three main factors: the distribution of information across the force, the degree to which the elements of the force can network both formally and informally, and the degree to which decision rights are delegated to subordinate force units. Together these three factors define a space which we call the *C2 approach space* (this will be covered in greater detail later in the book). The more adaptive the command of the force, the greater the amount of this C2 approach space which it can cover. More task organised ways of commanding the force can help to make the force more adaptive, by opening up more options across the C2 approach space.

An Example of a Possible Agile Force Structure

What does the force and command structure for an agile force look like? One possible solution is to consider the following force organisation, in figure 2.2, taken from [6]:

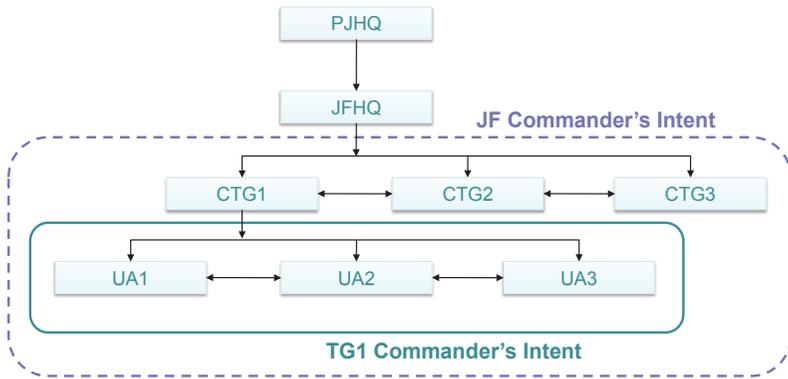


Figure 2.2: Possible force structure for an agile force.

In this potential agile force structure, PJHQ is the Permanent Joint Headquarters for UK force planning. On deployed operations, a Joint Force Command Headquarters (JFHQ) is created to command the deployed force. The intent of the Joint Task Force Commander is made transparent across the force (the large ellipse), and below him or her, the force is organised into comprehensive task groups (CTG) which can be a mix of air, land, and naval components. These in turn consist of task organised units of action (UA). CTGs can change and adapt their composition and bounds over time, through local, *horizontal* peer-to-peer interaction, in addition to the interaction *vertically* through the command hierarchy. Each set of UAs is also operating within the intent of the appropriate CTG; thus the structure is recursive. Within this intent, these units can also adapt their composition and bounds over time. This approach is consistent with the illustration of information age command and control shown in figure 6.2 of *The Agile Organization* [2] where high agility of the command process is matched to high

agility of the command environment. Here, rich peer-to-peer horizontal linkages complement the normal vertical flow of information and authority.

Working Towards an Agile Command and Force Structure

Firstly, I need to introduce the idea of a number of *domains* in which the force structure can be considered to operate. (These are discussed extensively in [7]). The lowest of these is the *physical domain*. This consists of the physical elements of the force and their physical interaction (such as the use of lethal force). At the next level we consider the creation and sharing of information across the elements of the force, and we call this the *information domain*. Moving up another level, we consider not only the generation and sharing of information, but the development and sharing of understanding and situational awareness. We call this the *cognitive domain*. Finally, we consider how larger communities of the force can share resources peer-to-peer in the *social domain*. In figure 2.3, we show a number of steps which allow progress to be made in working towards an agile command and force structure. These steps, which form different approaches to C2, are described in greater depth in the final report of the NATO RTO SAS-065 research task group which has developed the NATO NEC C2 Maturity Model [8].

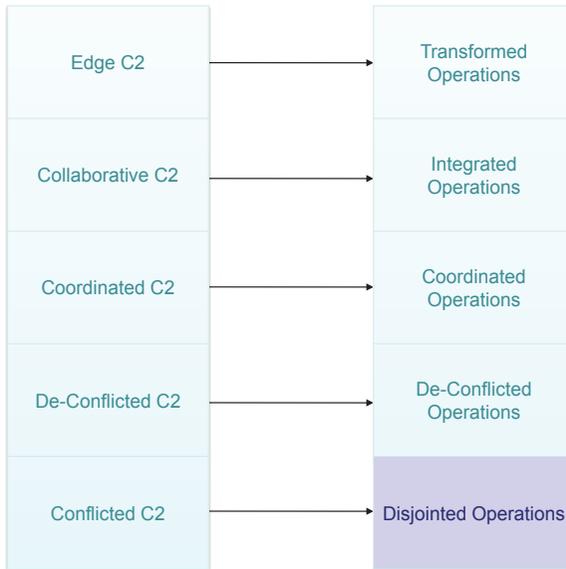


Figure 2.3: NATO NEC C2 approaches and NATO capability options.

The right hand side of figure 2.3 represents a set of increasing levels of force capability, as developed by NATO Allied Command Transformation (ACT). Each of the approaches to C2 on the left hand side of figure 2.3 is a potential option available to the commander. (In general we exclude conflicted C2 since this is an approach to be avoided). In broad terms, the more approaches to C2 that are available, the greater the level of C2 maturity. As the ability to have more options available increases, and the ability to easily transition between these approaches increases, C2 agility also increases.

Working up the left-hand side of figure 2.3, one or more characteristics of the approach to command change. This results in approaches to command that correspond to being located in different parts of the C2 approach space, shown in figure 2.4.

For example, one of the dimensions of the C2 approach space represents the nature of the interactions among participants. As we move from de-conflicted C2 through to edge C2, the frequency of interactions among the entities increases and their focus shifts from the information domain (from sparse to rich exchange of information) to the cognitive domain (from low to high degrees of shared awareness) and to the social domain (from low to high sharing of resources). These are key “tipping points” leading to qualitatively different C2 approaches. The net result is that entities have the ability to work more closely together [8].

These approaches to command thus occupy different regions of the C2 approach space. Neither responsiveness nor adaptivity are explicitly shown in figure 2.4. However, increasing C2 agility implies the ability to a) access a larger part of this space, and b) choose the appropriate part of this accessible space as circumstances dynamically shift.

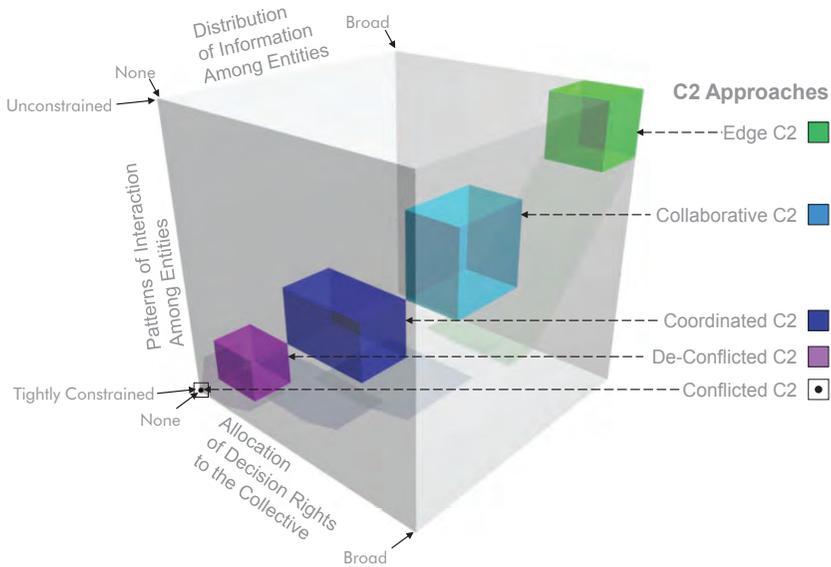


Figure 2.4: The C2 approach space.

In chapter 3, I describe two key examples used to validate the descriptions of these C2 approaches. The first is based on the US National Guard and active duty forces reaction to Hurricane Katrina, and the second is based on the consideration of current and future more agile force structures, using a synthetic environment to test these two structures and assess them. We thus consider the range of C2 approaches illustrated in figure 2.3 at both ends of the operational spectrum (humanitarian relief and warfighting). In reference [8], these two case studies have been integrated together with the extensive range of other case studies considered as part of the NATO RTO SAS-065 research task group effort. This integrated description then forms a validation of the C2 approaches consid-

ered in the maturity model, their description, and the ability to move from one C2 approach to another as circumstances dynamically change.

Agility and Complex Adaptive Systems

It turns out that many of the ideas we require can be found within the defining characteristics of a *complex adaptive system* (CAS), as described in reference [9], and based on the factors described below.

1. *Nonlinear Interaction.* Nonlinear interaction between two parts of a system (e.g., two actors within a multi-actor coalition environment) means that the outcome of the interaction is not a direct multiple of the input. Awareness and perception have a part to play. This manner of local interaction can give rise to surprising and non-intuitive emergent behaviour.
2. *Decentralised Control.* Natural systems, such as the evolution of an ecosystem, or the movement of a fluid front through a crystalline structure, are not controlled centrally. The emergent behaviour is generated through local interaction and co-evolution, where each element of the system changes its behaviour to take account of the environment created by the other elements of the system.
3. *Self-Organisation.* Natural systems can evolve over time to a special state of the system (called an *attractor* of the dynamics of the system since the system is attracted towards it as time proceeds), without the need for intervention or guidance from outside the system.

4. *Non-Equilibrium Order.* Order in this context refers to the emergent correlation created across large parts of the system, aligning the behaviours of these correlated elements. Such emergent order arises in *open* systems where energy and/or information are allowed to flow across the boundary of the system.

5. *Adaptation.* Such systems are constantly adapting—clusters or avalanches of local interaction are constantly being created and dissolved across the system. These give rise to the correlation effects discussed above, rather than being due to a top down imposition of rules or orders.

6. *Collectivist Dynamics.* The ability of elements to locally influence each other, and for these effects to ripple through the system, allows continual feedback between the evolving states of the elements of the system.

In chapter 2 of *Complexity Theory and Network Centric Warfare* [9], these were then applied to an information age force, as in table 2.1 (taken directly from [9]). This table illustrates the mapping between the CAS factors described above (labelled “CAS Concepts” in the table) and the characteristics of an information age force.

CAS Concept	Information Age Force
<i>Non-linear interaction</i>	Combat forces are composed of a large number of nonlinearly interacting parts.
<i>Decentralised control</i>	There is no master 'oracle' dictating the actions of each and every combatant.
<i>Self-organisation</i>	Local action, which often appears 'chaotic', induces long-range order.
<i>Non-equilibrium order</i>	Military conflicts, by their nature, proceed far from a static equilibrium. Local correlation of effects is key.
<i>Adaptation</i>	Combat forces must continually adapt and co-evolve in a changing environment.
<i>Collectivist dynamics</i>	There is a continual feedback between the behaviour of combatants and the command structure.

Table 2.1: Relation between complex adaptive systems and information age warfare (based on reference [9]).

Information Age Enterprise

We can also use a similar approach to the mapping in table 2.1, in considering an information age enterprise as an open, complex adaptive system, as discussed in *The Agile Organization* chapter 5 [2], and as shown in the following table 2.2.

Complexity Concept	Information Age Enterprise
<i>Non-linear interaction</i>	The Enterprise is composed of a large number of nonlinearly interacting parts.
<i>Decentralised control</i>	There is no centralised management dictating the actions of each and every entity.
<i>Self-organisation</i>	Local co-evolution induces long-range order.
<i>Non-equilibrium order</i>	Interactions within the Enterprise proceed far from static equilibrium. Local correlation of effects is key.
<i>Co-evolution</i>	Entities must continually co-evolve in a changing environment.
<i>Collectivist dynamics</i>	Cascades of local effects ripple through the Enterprise.

Table 2.2: The information age enterprise (based on table 5.1 of reference [2]).

These foundational ideas are used as part of achieving a deeper understanding of complex endeavours and network enabled capability in the discussion which now follows.

Complex Endeavours⁴

Complex endeavours [10] which could also be named *information age endeavours* consider a coalition force that is composed of a number of contributing elements, both military and civilian (inter-agency or whole of government) from the various NATO nations. Other contributing elements may include contributions from non-NATO countries and international organisations as well as non-governmental organisations (NGOs) and private voluntary organisations (PVOs). The heterogeneous make-up of the enterprise implies that no single element is “in charge” of the entire endeavour. The interactions among these contributing elements need to be considered in terms of the physical, information, cognitive, and social domains. Industrial age command and control was well matched to the predominant challenges of the industrial age. The low agility of the command process matched the characteristics of the mission environment; specifically the familiarity of the mission, the linearity of the battlespace, the predictability of actions and effects, and its relatively small rate of change. Hence industrial age approaches to command and control have proved to be successful in simple, linear (albeit highly complicated) environments where manoeuvre was limited, and the concepts of operation employed were based on massed forces to create attrition-based effects. “Industrial” approaches to command and control

4. In addition to the general acknowledgements at the beginning of the book, I would like to acknowledge explicitly the key contribution of David Alberts, Richard Hayes, and Reiner Huber to the development of the ideas expressed here.

begin to break down in more complex environments where the interactions that take place are less linear, more dynamic, and less predictable.

This is the nature of the 21st century missions that confront civil-military coalitions. These complex missions have to be addressed by increased *command agility* [2]. This requires a number of capabilities that include increased information sharing and increased shared awareness, both of which in turn require progressive enrichment of *peer-to-peer* interactions (e.g., horizontal exchanges and interactions with peer contributing force elements and other actors). These peer-to-peer interactions add to the well established vertical interactions present in the command hierarchies.

The term *complex endeavours* has thus been used [10] to refer to undertakings that have one or more of the following characteristics.

1. The number and diversity of the participants is such that:
 - a. there are multiple interdependent chains of command;
 - b. the objective functions (goals) of the participants conflict with one another or their components have significantly different weights; or
 - c. the participants' perceptions of the situation differ in important ways.

2. The effects space spans multiple interacting domains and there is:
 - a. a lack of understanding of networked cause-and-effect relationships; and
 - b. an inability to predict effects that are likely to arise from alternative courses of action.

The above characteristics embody many of the ideas from complex adaptive systems discussed earlier, as we now show.

- The number and diversity of participants result in a correspondingly large number of *degrees of freedom* that, in turn, can generate a large number of different ways in which participants could interact.
- The interactions that can and are likely to take place among participants (one of the three dimensions of the C2 approach space) are directly affected by the other dimensions of the approach to command that has been adopted (distribution of decision rights, distribution of information). These interactions are affected by the nature of the perspectives of the individual participants, the amount of information that is shared, their individual qualities of awareness, and the extent of their shared awareness. Given the large number of factors that influence the nature of each interaction, it is reasonable to assume that these interactions will not be linear (thus small differences in initial conditions may lead to large changes in outcome).

- The existence of multiple, interdependent chains of command means that there is no single person in command, hence no “master oracle” dictating the actions of each and every combatant.
- An agile command capability means that there is continual feedback between the behaviour of the combatants (the circumstances and context of the conflict) and the C2 approach adopted.

Networked cause-and-effect relationships are likely to result in cascades of effects that ripple through the physical and cognitive domains [7]. Our ability to predict these circumstances and the resulting effects is, at best, limited. However, we may be able to bound the range of values that could occur, or are likely to occur [11].

The NATO *Code of Best Practice for C2 Assessment* [12], while firmly rooted in decision theory and related analysis techniques, recognises the existence of analysis challenges that are not amenable to standard approaches or solutions. Complex endeavours present a series of major challenges that affect both the problem formulation and solution phases of traditional analysis, including:

- An incoherent objective function (i.e., there is no single set of dependent variables to be maximised or minimised); and
- Difficulty in predicting outcomes as a function of particular courses of action.

The nature of the participants makes it extremely difficult, in practice, to have a useful objective function that can be used to definitively measure overall achievement. A tractable objective function is one of the prerequisites for the application of traditional methods of problem solving. In complex endeavours, it is highly likely that the collection of individual entity objective functions cannot be reconciled. Thus there exists no outcome that would satisfy all parties. These endeavours therefore require negotiation to reach a suitable endeavour level objective function.

The nature of the effects space compounds the analytic problem since, in practical terms, it is not possible to associate specific outcomes with specific actions or sets of actions. There are a number of reasons for this. These include cascades of effects across multiple domains (political, economic, cognitive, social) that are very sensitive to initial conditions.

Without either the ability to find feasible regions of the effects space that represent solutions or the ability to map from courses of action (values of the controllable variables) to specific outcomes, the situation is not amenable to deductive analysis. Deductive analysis is used here to refer to the philosophic approach that involves breaking a problem into a number of parts in order to understand the whole. That is, the parts can be worked in parallel and when individually understood, amount to understanding the whole. The extent to which an endeavour is approachable solely by decomposition is perhaps the most important distinction between conflict situations that are amenable to de-conflicted C2 or coordinated C2, and those requiring higher levels of C2 approach (collaborative C2 or edge C2).

The Essence of Information Age versus Industrial Age Endeavours

The characteristics of complex adaptive systems thus identify key aspects and behaviours of information age entities (at the force or enterprise level) while the characteristics of information age/complex endeavours include both a characterisation of the nature of the collective enterprise and its operating environment. Can these two views of the defining features of industrial versus information age endeavours be incorporated into a single view expressed in a common vernacular? The discussion below is an attempt to extract the essence of both without using domain-specific jargon.

Both address the nature of command (leadership) of the collective (endeavour, force, enterprise, coalition). The C2 approach space has three dimensions: allocation of decision rights, dissemination of information, and the patterns of interaction among participants. Table 2.3 provides an aggregate comparison of the nature of information age versus industrial age endeavours along each of these three C2 approach dimensions based on the ideas discussed above.

	Industrial Age	Information Age
Decision Rights	<ul style="list-style-type: none"> • Centralised • Chain of Command • Single Objective Function 	<ul style="list-style-type: none"> • Decentralised (agile) • Multiple Chains of Command • Multiple Objective Functions
Dissemination of Information	<ul style="list-style-type: none"> • Follows chain of command • Prescribed by chain of command 	<ul style="list-style-type: none"> • On demand (agile) • Wide-spread
Interactions	<ul style="list-style-type: none"> • Prescribed by chain of command • Fixed • Relatively sparse 	<ul style="list-style-type: none"> • As required • On demand (agile) • Dynamic (agile)

Table 2.3: Industrial age and information age/complex endeavours.

The distinctions contained in table 2.3, map fairly closely to the traditional or *classic C2* and *edge organisation* corners of the C2 approach space shown in figure 2.4.

With respect to decision rights in the industrial age case, there could be multiple chains of command, but these are brought together in a top-down manner (e.g., through a synchronisation matrix) to form a single overall objective and plan. Since changes require a revised plan, this approach cannot adapt quickly and becomes fragile rather than agile. In the information age case, different participants are expected to have different goals. Furthermore, these goals will co-evolve within a coalition framework. If this process of goal co-evolution breaks down, then the coalition itself breaks or is re-defined.

The word *agile* has been added to at least one characteristic in each of the C2 approach dimensions for the *information age* column to indicate that these characteristics enable agile behaviours. Complex adaptive systems theory uses the word *adaptation*; the (components of the) forces or enterprises “continually adapt and co-evolve in a changing environment” (table 2.1). Adaptability is one of several dimensions, one that specifically addresses changes to self. The characteristics of a C2 approach enable more than just changes to self; they also enable changes in objective functions, assessments of the situation, tactics, etc. Thus, *agile* has been used here instead of *adaptive*.

The characteristics of a complex adaptive system discussed earlier also include the concept of feedback between the behaviours of participants and the adopted C2 approach. This is the essence of agile command, where the circumstances and context of the conflict are continually fed back to enable the appropriate choice of C2 approach. Feedback (using

information about the situation to influence the C2 approach and course of action) is more widely available in the information age case than the industrial age case. The implication is that the feedback mechanisms in the industrial age case are fewer in number and more highly constrained than those that are found or possible in the information age case.

Network Enabled Capability (NEC)

NATO and member nation transformation (*Network Enabled Capability* or NEC) is rooted in the theory of network-centric warfare/operations [13]. The basic tenets of this theory involve the enabling of shared awareness (by information sharing and collaboration) and the leveraging of shared awareness (by self-synchronisation⁵). Self-synchronisation occurs in both the cognitive and social domains, affecting the decisions that are made and the actions that are taken (including interactions among entities). Shared awareness and self-synchronisation are associated with higher levels of command maturity and are defining characteristics of information age entities and endeavours.⁶

A key consideration in complex adaptive systems involves the nature of the interactions among entities and between entities and the environment. These interactions involve both entities and effects. They can be either direct or indirect. A

5. *Self-synchronisation* is a condition where “force elements intuitively synchronise their actions without (centralised) control” [17].

6. The term self-organisation is not used here because it has a specialised meaning in which it is used in conjunction with objects without any cognitive capability or free will.

direct interaction⁷ requires that the entities or effects have no intervening entity or effect interposed (they are like adjacent links of a chain). An indirect interaction involves one or more intermediaries, as in a cascade of effects or a chain of command. Thus, in the physical domain the entities need to be in close proximity to one another and these interactions are usually one-on-one. In the information, cognitive, and social domains, physical proximity is not relevant and there can be a one-to-many relationship. Consider those who are directly affected by a media report. They may be widely distributed geographically and may number in the thousands if not the millions.

In industrial age endeavours, interactions between and among entities are to a large degree prescribed by job descriptions, process design, and culture while in the effects space, effects do not create significant cascades. Interactions among entities in information age/complex endeavours largely lack the institutional or cultural constraints found in industrial age endeavours, resulting in an incomparably richer set of direct, peer-to-peer interactions that take place. Effects are also connected, creating cascades among a number of domains. There are a number of reasons for the richer set of interactions in information age endeavours. First is, of course, the lack of constraints. Second are the networks that make it possible to have a direct connection with many more entities. But beyond this, there is the greatly increased probability that an action or effect will be noticed globally and create an indirect interaction with one or more entities that would not have previously been aware of it.

7. A direct interaction is called a local interaction in the language of complex adaptive systems. This may be due to the fact that a significant part of this work involves the study of emergent behaviours of natural systems and the interactions being studied are in the physical domain.

If we think of these interactions as parts and consider the behaviour that emerges in industrial age cases, the behaviour of the whole can be deduced or understood from the sum of individual behaviours (the largely independent behaviours of the parts). This is not true for the information age case where one may easily understand individual behaviours (local decision options associated with agents, for example) but not be able to understand or predict overall behaviour. The same argument holds true for interactions in effect space.

The balance between deliberate planning and the more emergent rapid planning changes as we progress to more mature levels of command. These maturity levels can also be thought of as milestones on the *transformation journey* to higher levels of network enabled capability, shown in figure 2.5, progressing through a number of *epochs* of NEC: initial NEC, transitional NEC, and mature NEC. In UK doctrine these are described in [14]. The highest maturity level for the employed force includes the option of edge C2, corresponding to the epoch of mature NEC, with natural or self-synchronisation of force elements represented by emergent rapid planning at the unit level, constrained by broader shared awareness and shared intent rather than by deliberate planning.

Capturing the span of these ideas in our operational analysis and systems engineering models has been, and continues to be, the focus of my work, because the development of a network enabled capability is one of the UK Ministry of Defence's top priorities.

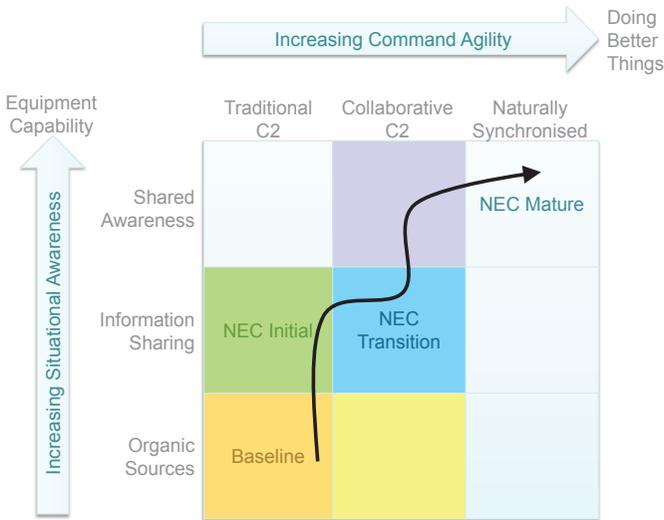


Figure 2.5: The journey towards higher levels of network enabled capability (NEC).

Building the Simulation Model Set

Now I want to show how all of these ideas have come together to form the basis of a number of linked closed form, constructive simulation models, which underpin the Defence Science and Technology Laboratory's (Dstl) ability to offer advice on balance of investment across the equipment budget (including sensors and command systems), future force structures, and the implications of high level defence policy [15].

Deliberate planning represents decision-making based on a rational choice among alternatives. (As we have already noted, in cybernetic terms it is a feed-forward process). In such rational choice decision-making the emphasis is on the explicit generation, and subsequent evaluation, of alternative courses of action. In military terms it corresponds to the generation

of a plan which involves the allocation of multiple forces both in space and time, in order to prosecute an intent and objectives. This is complemented by the rapid planning process (in cybernetic terms a feedback process), based on the psychological construct of naturalistic decision-making. In military terms, the emphasis is on making sense of the immediate situation, in a rapidly changing environment, and applying the decision-maker's expert experience of similar situations stored in long term memory (and built up through training and experience) to proceed directly to a workable solution. The situation is described by a number of cues, which define a *decision space*. The stored situations in long term memory correspond to fuzzy regions in this decision space.

The mathematical algorithms which implement these two approaches of deliberate and rapid planning are described in detail in [3]. In summary, the approach I have adopted is to strike out on a new path and exploit novel ideas from complexity mathematics in order to create a representation of the command process which is sufficient, yet still transparent. This avoids the use of extensive sets of special expert system rules (the previous available approach to such issues). Examples of the simulation models either developed or under development are:

- The COMAND campaign level maritime, air, and land model is a command and control centred model which is based on the rapid and deliberate planning processes. This model is the key component of Dstl operational analysis studies looking at joint balance of capability (including C2) across the defence budget.

- The DIAMOND model represents non-warfighting scenarios at a joint level (including the effects of non-military entities such as refugees or aid agencies) and exploits the agent architecture developed as part of my research. This model is now in use in operational analysis studies related to peace support operations and has been given to a number of other countries, including the USA.
- The CLARION campaign level land/air model is due to incorporate the rapid planning process. CLARION is the main model within Dstl for analysis of land/air force structure trade-offs across the equipment budget.
- The SIMBAT model (providing underpinning analysis at the tactical level) is a pure instantiation of the rapid planning process. It typically represents a number of companies under battlegroup command and is used to support lower level studies as well as high level analysis.
- The SIMBRIG model at brigade level spans the gap between SIMBAT and CLARION. It has been developed using elements of the rapid planning process to drive the manoeuvre units.
- The SIMMAIR maritime/air model is currently under development as a system level model to bridge the gap between tactical naval models and the COMAND model. It will be driven by the rapid planning process.
- The WISE formation level wargame comprises a number of military players at up to divisional and brigade level, underpinned by a simulation engine. This

engine is driven by the rapid planning process. We are developing a closed form simulation version of WISE, incorporating aspects of the deliberate planning process (and some exploratory results from this effort will be discussed later). The gaming structure is now supporting a range of operational analysis studies such as the consideration of future UK army operational level force structures.

All of these models (with the exception of WISE) are closed form, constructive⁸ simulations. Figure 2.6 indicates how they fit together to form a hierarchy for application to analysis across the spectrum of requirements. In chapter 4 I have summarised recent work which supports this approach to command and human decision-making at the agent level, with a focus on the application of these ideas to the models which we have now developed in Dstl. In chapters 5 and 7, I will describe in more detail how these agents interact within the COMAND, CLARION, DIAMOND, and WISE models.

8. A synthetic environment consists of real and simulated people interacting with simulated environments. A closed form, constructive simulation consists of simulated people (i.e., computer algorithms) interacting with simulated environments, with no human intervention during the model run.

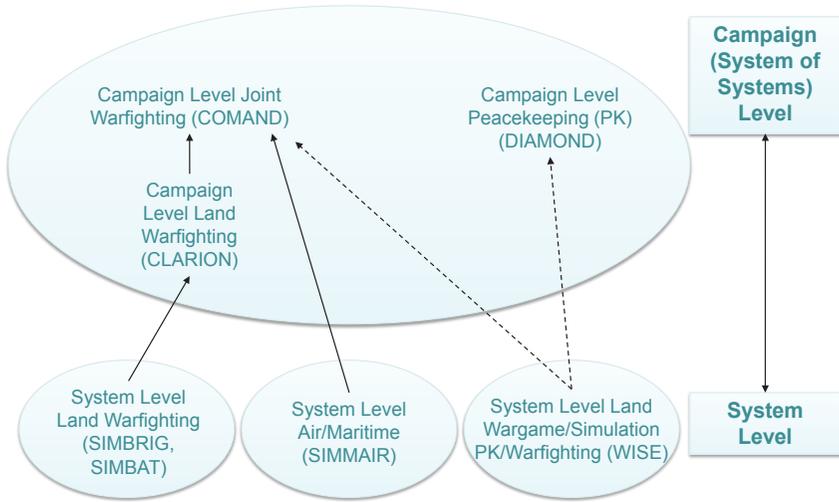


Figure 2.6: How these models fit together as a systems hierarchy.

Validation of Deliberate and Rapid Planning Through Comparison with Historical Events

Now I want to give some examples of how these apparently rather abstract models do actually reflect key aspects of command and decision-making by commanders in the field. Indeed, as part of transitioning such models to the study programme, they have to undergo a rigorous validation process. This includes both detailed scrutiny of the model assumptions and behaviour by military officers, and (where possible) comparison of the model behaviour with historical conflicts of relevance. For example, as part of the process of commissioning the COMAND model, a detailed comparison was made between COMAND and the Falklands conflict of 1982. The outputs we examined were the casualties suffered. Since these are essentially a product of the number of engagements, and the effectiveness per engagement, if we calibrate the comparison back

to the effectiveness levels per engagement historically achieved, then this is a fair test of whether we are correctly modelling the number of engagements (an essential outcome of the command and decision-making process).

Since COMAND is a stochastic model this comparison was between the single actual outcome of the 1982 conflict, and the *fan* of results from 160 replications of the COMAND model [16]. Three main types of agent decision-making were represented in this comparison: a) In terms of the (*deliberate*) campaign plan for each side's maritime assets, this consisted of a string of missions. At various points, triggers were built into the plan, allowing it to branch to a new string of missions dependent on the situation at the trigger point, leading to the representation of flexibility in planning (as discussed in terms of agility earlier in this chapter). b) In terms of *rapid planning*, maritime missions could be adapted to reflect local circumstance. For example a UK ship in transit to a patrol area could mount an attack of opportunity if its sensors detected such a threat and the attack was likely to succeed. c) Air missions were developed and prosecuted as a function of the sensor information on targets. For example all Argentinean air missions attacking the UK task force were created by the model (i.e., were generated by the model, not by scripting) in response to sensor information (mainly from maritime patrol aircraft [MPA] and sensors based on the Falkland Islands). We were thus able to explicitly represent both UK and adversary decision-making in the model.

Entity/group missions are the building blocks of the scenario and are the key to COMAND's representation of human intelligence as represented by the decisions made by the various commanders and the emergent effect of these decisions.

Broadly it was possible to represent all types of missions; for example: the retreat of the Argentinean navy to port, following the loss of one of their ships; and the regrouping of the various UK ships into a single amphibious landing force and its subsequent passage to San Carlos.

In terms of overall campaign outcome, we performed a number of comparisons of casualties (actual versus predicted by the model). The effectiveness per engagement was scaled back to 1982 levels in the model based on the historical records and log books in order to reflect the actual probability of a successful engagement given a set of circumstances. Thus (as discussed earlier) this comparison was a true test of the validity of our representation of the command and decision-making processes. Many detailed comparisons were carried out. Just one of these is shown here, in figure 2.7, comparing the actual historical record of the number of UK ships sunk or operationally rendered incapable, versus that predicted by the model. The result is convincingly close. The decision-making process represented in the model must therefore be close to that which was used in practice in the historical campaign. This is of course just a single point estimate. Our models undergo a continuing process of refinement and scrutiny by both expert analysts and in-house military advisors.

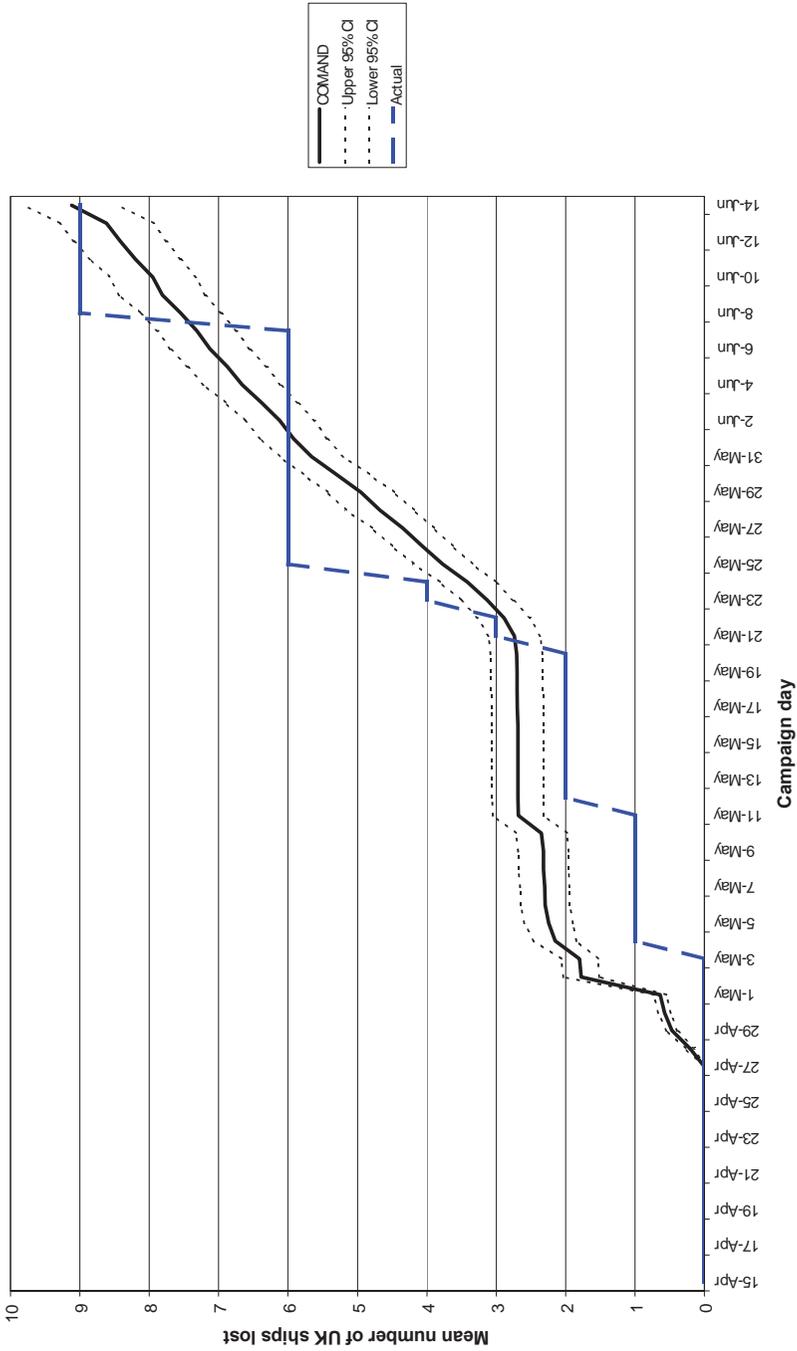


Figure 2.7: Comparison of the Falklands conflict with the COMAND simulation.

COMAND is a cross-environment model at the campaign level. As a contrasting example, SIMBAT is a tactical model of army combat at the battlegroup level. We were also able to show that with the inclusion of rapid planning, such tactical models begin to show the correct time and casualty dynamic associated with such tactical level warfighting. Previously, models at this level typically indicated a time of battle which was two or three times too short, due to lack of proper representation of the command process. The introduction of rapid planning at both the platoon and company level within the simulation, coupled with the representation of a number of other human factor effects, allows more of the fog and friction of real conflict to be captured.

Consider now the battle of Goose Green, fought as part of the Falklands war between UK 2 PARA Battlegroup and a mixed force of Argentinean conscripts during 28/29th May 1982 [16]. The infantry battle started at midnight and finished at 20:00 the following evening. The Argentinean forces involved were approximately equal in number to the British. The British force was highly trained and motivated; however, they were fatigued from six days with little shelter on the slopes of Sussex mountain, and by an 18Km march to the battlefield with little sleep. They were also shocked by an air attack on their ammunition point prior to the march. The British troops were opposed by Argentinean conscripts with barely four months training and little motivation; however, they were fresh for battle, although shocked from low-level tactical British overflights and surprised by the British move to attack. We discuss below how these human factors, together with the C2 process, were modelled and how the results compared to the reality.

We represented the concept of overall *force strength* in the SIMBAT model, as being composed of overall effectiveness. This was then factored by a number of constraining effects, namely, unit participation (i.e., the percentage of the force prepared to contribute to the battle), the effect of being shocked, the effect of being surprised, whether the troops were close combat trained, and their resilience to fatigue. The detailed quantitative assumptions are discussed in [16]. This allowed us to define quantitatively, three categories of force; Strong, Medium, and Weak, for both the British and Argentinean forces, which took account of all of these human factors effects. Decision-making by platoon and company level commanders was simulated using the rapid planning process. This allowed their perceptions to be explicitly modelled, as well as their choices of local course of action based on those perceptions. The SIMBAT model was then run for each of the 3x3 combinations of force on each side (looking at a fan of 30 simulation runs in each case, since the model is stochastic). Again, as for the COMAND model, considering casualties (actual versus predicted by the model) is a good way of testing whether the decision-making approach (i.e., rapid planning) represented in the model accords with what happened in practice. Modelling Strong to Medium British forces versus Weak Argentinean forces gave total casualty results (and hence a decision-making process) close to the historical record, as described in detail in [16].

In the historical battle, there were a number of key objectives achieved by the British forces, and the times at which they were achieved were recorded. Thus it was possible to compare the model prediction of times to these objectives (averaged over 30 runs of the model), with this historical record, as shown in table 2.4.

Key Objective	Historical Record	Strong British v Weak Argentine	Medium British v Weak Argentine
Burntside house and hill secure	04:00	02:30	03:00
A Company at Coronation Point and B and D Companies through Northern Positions	06:30	04:30	04:30
A Company held at Darwin Ridge, B and D Companies held at Middle Hill	07:30	06:00	06:15
A Company take Darwin Ridge, B and D Companies take Boca House	10:30	10:45	11:15
Companies at their finish positions	17:00	18:30	19:15
Proportion total battle time deviates from actual historical record.	N/A	8%	13%

Table 2.4: Comparison of SIMBAT model times to achieve key objectives with the historical record.

The close correlation between the model results and the historical record again demonstrates that the rapid planning process representation of decision-making in SIMBAT must be close to the real decision-making process employed in the historical battle. In chapter 6 I will discuss the whole process of validation of such models, and some more detailed results comparing simulation with reality.

The simulation models which we have built, incorporating these concepts of decision-making at their core, represent a significant monetary and intellectual investment by the UK MoD. As described in detail earlier, the rapid planning process and

aspects of the deliberate planning process have been implemented in a number of these models. They are thus sufficient to take us along the journey from our current capabilities to the transitional epoch of NEC [14] as shown in figure 2.5.

However, our understanding of agile command and the mature stage of NEC, envisaged as towards the end of the NEC journey, are still not sufficient for the full development of tools and methods by which they can be modelled. A key aspect is the *adaptivity* of *task organised force units*. I am thus continuing to work on enhancing both our conceptual understanding, and the model set, to represent these ideas. For example, the term and concept of *Agile Task Organised Groupings* (ATOGs), which I developed, now form part of UK high level doctrine, as discussed in the UK High Level Operational Conceptual Commentary [17].

Capturing these ideas requires a proper representation, in the constructive simulation environment, of how edge organisations [4] share situational awareness (including command intent) and constrain the emergent behaviour of a number of interacting entities in order to produce the *natural* or *self-synchronisation* indicated in figure 2.5. It also requires the ability, with agile command, to shape and adapt the command approach to the changing circumstances in a timely manner. These emerging ideas are discussed more fully in chapter 7, focussing on the WISE model development.

Finally, in this book, I have attempted to give an insight into the intellectual ideas and modelling developments lying behind the simulation models we use. These models are used as the basis for many of the operational analysis studies we carry out and the trusted advice we give to decision-makers in Government.

Chapter 8 illustrates the great impact this modelling approach has had, in terms of helping to address the UK Ministry of Defence's most important problems.

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CHAPTER 3

INCREASING THE MATURITY OF COMMAND TO DEAL WITH COMPLEX, INFORMATION AGE ENVIRONMENTS

In chapter 2 I introduced the idea of a number of different C2 approaches, which are able to match an increasingly complex and dynamic operational context, as shown again in figure 3.1.

The situation considered is one in which there are two or more coalition force elements (entities) present and one or more of the following conditions exists: the entities have overlapping intents and/or assets; the entities are operating in the same area at the same time; and the actions taken by an entity can come into conflict with those taken by another entity. The ability and willingness to share risk are also important considerations. The temporal dynamics of the situation and the timeliness requirements associated with a response can vary widely. Clearly, recognising the appropriateness of a particular C2 approach and putting it in place in a timely way (which we refer to as C2 agility) involves a consideration of responsiveness.

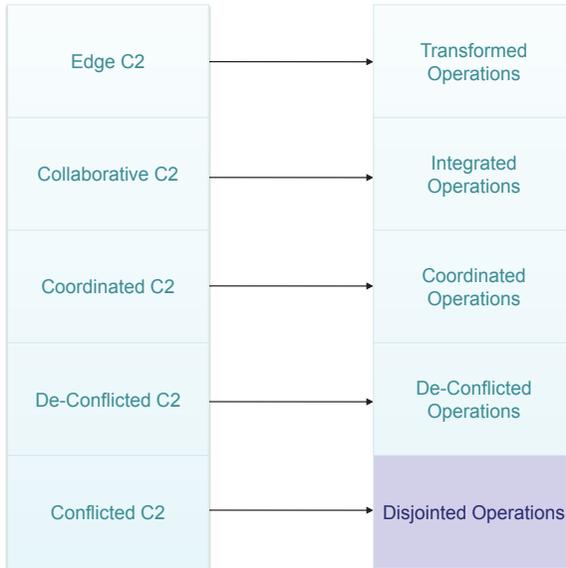


Figure 3.1: NATO NEC C2 approaches and NATO capability options.

The five C2 approaches depicted in figure 3.1 are scalable, in that they can be applied to groups of individuals and organisations of any size. In the discussion below we are applying these concepts to a coalition force as a whole, not to the manner in which contributing entities approach command but how the *collective* approaches command.

Objectives of Command

Given this complex coalition environment, the objective of each of these approaches to the command of such a civil-military coalition differs significantly. Note that each entity is expected to have its own approach to command, one that may

or may not be compatible with the approach adopted by (or defaulted into by) the coalition. The objectives associated with each of the C2 approaches are as follows:

- a. **Conflicted C2:** To exercise command by the individual participants only over their own forces or organisations, ignoring any adverse cross-impacts which this might cause.
- b. **De-Conflicted C2:** To avoid adverse cross-impacts between the participants by partitioning the problem space and the solution space.
- c. **Coordinated C2:** To increase overall effectiveness by 1) seeking mutual support for intent, 2) developing relationships and links between entity plans and actions to reinforce or enhance effects, 3) allowing some initial pooling of non-organic resources,¹ and 4) increasing sharing in the information domain to increase the quality of information.
- d. **Collaborative C2:** To develop significant synergies by 1) negotiating and establishing shared intent and a shared plan, 2) establishing or reconfiguring roles, 3) coupling actions, 4) allowing rich sharing of non-organic resources, 5) allowing some pooling of organic² resources, and 6) increasing interactions in the cognitive domain to increase shared awareness.

1. Non-organic resources refers to resources not “owned” by participants. These include access to bridges and roads, and sharing of higher level ISTAR and logistics.

2. Organic resources are those “owned” by a participant. They may include vehicles, weapons, or local supplies.

- e. Edge C2: To provide the enterprise with additional C2 approach options that include the ability to self-synchronise when appropriate.

Implications at the Collective or Coalition Level

We now discuss some of the implications for the collective and for the contributing entities associated with operating at these different levels of command.

Conflicted Command

It should be kept in mind that for the conflicted C2 approach, no command is being exercised at the endeavour or collective level. Each entity is pursuing its individual intent and taking independent action. Entities are operating in the area of operations without communicating with, sharing information with, or engaging in any command-related interaction. This means that there is no way to avoid some negative cross-impact between force elements. Some actions will, in all likelihood, lead to adverse interactions, actions that interfere negatively with others. The net result is that the option space for mission accomplishment is less than the sum of the option spaces of the individual entities. The sum is less than the sum of the parts and to the degree it is less there is an opportunity cost. There may be some urgent situations where this approach is initially unavoidable. For example, in the very early stages of disaster relief it may be appropriate to operate in this way in order to immediately save lives. However, it has been shown that to succeed, command needs to evolve rapidly from this initial

conflicted state. An example of this happening is given by the events following the landfall of hurricane Katrina, discussed in detail later on in this chapter.

De-Conflicted Command

Entities that wish to de-conflict must be willing, at a minimum, to accept a constraint on their plans or actions. In return they hope to avoid or remove any adverse cross-impacts. Limited peer-to-peer interaction in the information domain (discussing and agreeing on boundaries for example) must be sufficient to dynamically resolve potential cross-impacts. Total effectiveness approaches “the sum of the parts” in the limit. The main emphasis is still on vertical interaction along stovepiped chains of command within each entity. This approach to command allows partners of different levels of maturity to work together, coexisting in the same operational space (an example being the coalition command adopted for the first Gulf war). The nature of the constraints imposed will vary, but may include the creation of boundaries (exclusive areas assigned to a given entity) along time, space, function, and/or echelon lines. This serves to constrain each entity’s option space. Planning is required to establish the initial conditions (the decompositions or boundaries). This may be a lengthy process. Should these boundaries need to be changed, re-planning is generally cumbersome and slow. The boundaries become fault lines and are themselves targets; vulnerabilities to be protected. This approach to command is most appropriate when the situation and the response are stable and decomposable in terms of objectives, space, time, and function. Hence the situations that can be effectively handled by de-confliction are *complicated*, but are not *complex* in the sense described in chapter 2.

Coordinated Command

The de-conflicted C2 approach did not require any linking of plans or actions. Coordinated command involves seeking opportunities to generate synergy by linking the plans and actions of one entity with those of another. In this manner actions may reinforce each other in the action or effects spaces or they may, in effect, combine resources to achieve a necessary threshold for effective action or significant effects. Total effectiveness is more than the sum of individual actions, and the option space expands for participating entities. However, planning time may increase as a function of the number and nature of the links between plans. This level of command begins to make it possible to form *task organised* forces with contributions from different entities to simplify interactions across the air, land, and maritime domains, and other non-military actors. Coordinated command is appropriate for decomposable problems in terms of objectives, space, time, and function.

Collaborative Command

Collaborative command involves the sharing of resources in addition to a requirement for more information sharing and interactions among the entities. It envisions going beyond specific and explicit links among plans to the collaborative development of a *shared single plan* that establishes symbiotic relationships across the participants. Total effectiveness is significantly more than the sum of individual actions due to the synergies that are created, and the option space is significantly expanded. Entities plan in parallel basing their individual plans on the shared plan. This requires rich and near continuous interaction in order to dynamically update the shared plan and the individual plans. Because of this parallelism in planning,

planning times can be reduced. Collaborative command may also involve the use of *positive control*³ to allow richer peer-to-peer interworking. To a far greater extent than is present in lower levels of command, entities become interdependent. This is made possible as a result of the trust that is developed as a product of developing the necessary shared understanding required to create the single plan. As a consequence, risk is also shared. This level of command allows the full implementation of *task organised* forces across the coalition. It is appropriate for problems that are not fully decomposable in terms of objectives, space, time, and function, and thus for which an holistic approach is desirable.

Edge Command

Reaching the edge level of command is predicated upon achieving a high degree of shared understanding of a common (collective) intent. It requires a rich and continuous set of interactions between participants, involving widespread information exchanges to allow the build up of shared understanding, and the ability to self-synchronise. An example is the command approach adopted by a tight-knit team of special forces combatants who share high levels of trust and mutual understanding. Edge command is most appropriate for situations characterised by rapid change, uncertainty, and complexity.

3. Positive control allows the superior commander (military or civilian) to be informed of such interchange, and to intervene only when he/she can see that such an interchange would not match with higher level, more strategic requirements.

Transition Requirements

The ability to achieve a given level of command, that is to move from any given level to the next higher level, requires the addition of one or more key capabilities that in turn require improvement in the *infostructure* (the supporting information networks) and changes in command concepts and processes. We now identify some of these transition requirements.

From Conflicted to De-Conflicted Command

- Force entities need to identify potential planning conflicts and resolve these conflicts by establishing constraints and/or boundaries;
- In order to accomplish this, limited communications involving limited individuals and limited information exchanges are required.

From De-Conflicted to Coordinated Command

- Force entities need to develop limited shared intent, and links between individual plans and actions;
- In order to accomplish this, a coordination process needs to be established, supported by sufficient communications and information-related capabilities involving appropriate individuals and necessary information exchanges.

From Coordinated to Collaborative Command

- Force entities need to develop shared intent, shared understanding and trust, together with the development and continuous updating of a single shared plan. This requires additionally the rapid adaptive development of entity plans that synchronise with the overall plan;
- In order to accomplish this, a set of collaborative processes needs to be established supported by a sufficiently robust and extensive distributed collaborative environment available to all appropriate individuals and organisations.

From Collaborative to Edge Command

- Force entities need to develop rich shared intent, awareness, understanding and trust;
- In order to accomplish this, *power to the edge* principles [1] and associated doctrine must be adopted, supported by a robust, secure, ubiquitous, and interoperable infrastructure that extends to all participating entities.

Illustrating the Command Maturity Model: Hurricane Katrina

Having described these approaches to command in some detail, I want to turn in this section to the humanitarian relief aspects of hurricane Katrina, which struck New Orleans and surrounding areas on the 29th August 2005. This provides an illustration of these ideas in practice, and an empirical test of the validity of our descriptions and levels of command. Our

discussion draws from a set of three authoritative reports on the events surrounding hurricane Katrina, which are available in the public domain [2, 3, 4].

The US national response plan, resulting from Department of Homeland Security Presidential Directive No. 5 in 2004, recognises that planning for, preparing for, and responding to natural and other disasters are primarily responsibilities of the individual states. This reflects the US constitutional perspective, and results in a *pull* response assumption, with local authorities having the lead at the start, escalating to state level and then to federal level, if necessary and if requested.

The Stafford Act reiterates the philosophy that, in a disaster, local resources should be used first, then state and finally federal resources. The Stafford Act also outlines the process by which state governors can request assistance from the federal government when the event becomes one of “national significance.” The US President then has to decide whether this merits designation as an *emergency* (releasing limited resources to the states), a *major disaster* (releasing much greater resource to the states), or a *catastrophe*. The first two of these result in a pull response where the states request and draw down from federal resources as the event unfolds. The third category of catastrophe had not been fully implemented at the time of Katrina. If called for by the President, it would have resulted in a proactive *push* of resources to the region, states, and local levels, irrespective of the states’ requests. (Note: The USA is divided into regions consisting of several individual states. Below the state level there are also local authorities).

Under the national response plan, a comprehensive framework of response to major incidents is set up. At the federal level, the Homeland Security Operations Center, the FEMA (Federal Emergency Management Agency) National Response Center, and the Interagency Incident Management Group jointly coordinate the response across government departments. The Federal Coordinating Officer (FCO), a representative of the Secretary for Homeland Security, is authorised to lead a Joint Field Office (JFO). This is a temporary federal facility established locally at the time of a disaster to coordinate the local, state, and federal response. It consists of senior representatives from all of the agencies and responders involved, and develops objectives, strategies, plans, and priorities. The membership of this office is envisaged as growing and adapting over time as the incident escalates or diminishes.

Figure 3.2 shows how these various agencies interact, and indicates the place of the US Department of Defense (DoD) Joint Task Force (JTF) Katrina within this context. The icons in the figure indicate key committees or agencies.

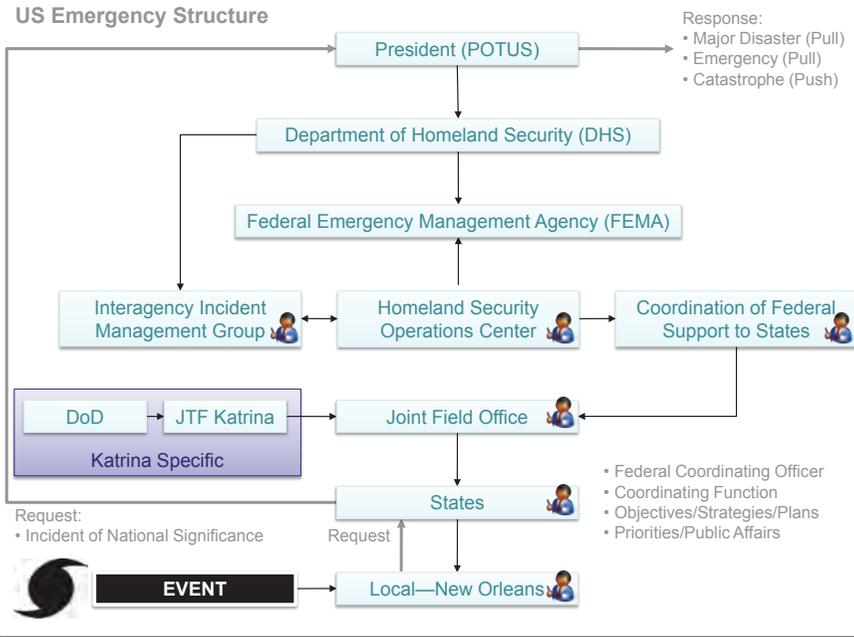


Figure 3.2: US emergency structure: How the various agencies should interact, and the place of Joint Task Force Katrina in this context.

The Timeline and Response to Hurricane Katrina

I want to draw out here some key features of the events surrounding landfall of the hurricane. One day after landfall, on 30th August 2005 the Joint Task Force (JTF) Katrina was established. States forwarded their requests for assistance to federal civilian officials, and these requests then moved through a series of military channels. Inherent in this process was the need for time to assess the capabilities required by each request and to design an appropriate military response.

There was, at this early stage of events, an incorrect situational awareness and understanding at the DoD level. Civilian and military decision-makers throughout the government apparently judged that the projected flow of National Guard units would be sufficient. Only on the 30th of August did the Deputy Secretary of Defense give the commander in charge a “blank cheque” for any DoD resources, and on 31st August a high level military officer still “did not believe that federal ground forces were needed.”

Federal military forces lacked situational awareness of which National Guard units were in the area and how they were operating. The command of the National Guard units and the federal level could not exchange information due to incompatible communication systems. No unified command system was put in place during the search and rescue, evacuation, and supply delivery missions. The effect was that of having multiple rescue teams operating in the same area while other areas were left uncovered. This is an example of *conflicted command*, and occurred over the first week after landfall, from 29th August to approximately 4th September. At the initial stage then, *conflicted command* was in place. Only after some days were National Guard and active-duty units deliberately deployed into different geographic areas where they carried out various relief and rescue missions using separate command structures, increasing the command approach to *de-conflicted command*.

Following this, by about the end of the first week post-landfall of the hurricane, a complex and multifaceted command structure began to emerge, given that *coordinated command* arrangements had to be made among states, between civilians, and military organisations at both state and federal levels, and among multiple military organisations and staffs. At this more

mature stage, plans and actions began to be linked together, including the following organisational links which were in place by 4th September:

- NORTHCOM commanded most active-duty forces through JTF Katrina. JTF Katrina in turn commanded the majority of its active-duty forces through separate task forces: a joint logistic task force and one for each service (Air Force, Navy, and Marine Corps).
- A planning group from the US 5th Army under JTF Katrina assisted FEMA in identifying what DoD assistance was needed. It also helped the PFO (Principal Federal Officer) with the task of coordinating active-duty and National Guard forces.

Migration of the C2 Approach over Time

As we have seen, during the initial response phase National Guard and active-duty forces operated independently of one another within the same operational area, under *conflicted command*. Over time, within the first post-landfall week, they began to move up the scale, using liaison arrangements, and reached *de-conflicted command*. With the creation of JTF Katrina, these liaison arrangements became more formalised; however, there was friction in this process. For example, 24 hours were needed to agree within the federal government and by federal officials and the governor of Louisiana, on a structure of separate active-duty and National Guard task forces. The final agreement was not reached until 5 days later (i.e., six days after landfall of the hurricane).

More generally, there were some examples of *coordinated command*. Firstly the evacuation of the general populations (i.e., without medical or special needs) went relatively well in all three states (Louisiana—the most affected—Mississippi, and Alabama). Once activated, the Emergency Management Assistance Compact enabled an unprecedented level of aid assistance to reach the disaster area in a timely and effective manner. A law enforcement coordination centre was established in New Orleans on 6th September. It provided a unified command consisting of New Orleans police, Louisiana state police, National Guard, and all federal law enforcement personnel. This is an example of fairly rapid transition from *conflicted command* through *de-conflicted* to *coordinated command*, showing high C2 agility, and had an immediate positive impact.

The only reported example of *edge command* observed was a single isolated case. This was the response of an individual pharmacist to the crisis in medical supplies in New Orleans. He raided the flooded pharmacies and repositioned these supplies in local downtown hotels. His rich understanding of the situation led to a local response consistent with the overall intent—saving lives.

At the other end of the spectrum of possible contingencies, we have also considered these command levels in the context of a future coalition warfighting environment, and I now want to take you through that.

Synthetic Environment Modelling of Agile Task Organised Groupings

Following a workshop on future command led by the UK Vice Chief of the Defence Staff, which I helped to support, we performed a number of wargames, using the WISE synthetic environment (SE),⁴ and this has illuminated aspects of the benefits, risks, and resource implications of command concepts which emerged from the workshop discussions. WISE (the Wargame Infrastructure and Simulation Environment) will be discussed in detail in chapters 5 and 7. For now, we want to concentrate on the results of these games, as further illumination of the meaning behind the different levels of command.

For the purposes of this gaming, a *baseline* and *treatment* experimental structure was defined, as follows. The baseline structure comprised *current command* but with extant investment in new information, sensors, and command systems. The treatment structure included new command constructs, in particular (i) a limited degree of non-componency⁵ (noting that the scenario was in this case dominated by the land component) and (ii) non-geographic, task organised groups endeavouring to adopt behaviours such as agility and horizontal trading of tasks and assets.

4. A synthetic environment consists of real and simulated people interacting with simulated environments. A closed form constructive simulation consists of simulated people (i.e., computer algorithms) interacting with simulated environments, with no human intervention during the model run.

5. Replacing land, maritime, and air components with more joint and task oriented headquarters.

Broadly, the results of the synthetic environment experimentation using WISE in this context relate the baseline to *coordinated command*. The treatment case corresponds mainly to *collaborative command*, with some practices and behaviours corresponding to *edge command*.

An experiment of this kind, by its nature, focuses on two or more “sides” conducting a campaign and trying to achieve their particular desired outcomes, allowing all sides to react dynamically to the evolving situation. As such, it particularly concentrates the players’ and analysts’ attention on defining outcomes and hence measures of effectiveness (MOE) that can be judged qualitatively and supported or refuted by quantitative data. It can thus expose substance in new constructs—do they actually deliver what they promise and how? Moreover, as new ideas have to be put into effect by military players, new ideas have to be substantive and realisable, and the opponent can try to counter them.

As part of the experimental plan, much effort went into a discussion of the benefits and risks of the proposed new command constructs before the WISE gaming. This was needed in order to design the game itself and to help players and analysts recognise and implement the associated behaviours. Hypotheses developed prior to the experiment are summarised as follows:

- The new command constructs will deliver a greater ability to be robust in the face of uncertainty and cope with unexpected events.
- The new command constructs will adopt agile task-organised groupings that are not limited by geographic boundaries, as units would be under current command.

- There will be horizontal trading of tasks and of scarce resources between agile task organised groupings.
- The wargaming will examine qualitatively and if possible quantitatively both achievement of outcomes (including battle outcome) and the behaviours of the players, who are representing command constructs broadly aligned to brigade level.
- The wargaming will seek to illuminate the implications of realising new command constructs and associated behaviours across other lines of development, such as collective and individual training, as well as equipment.

It became clear in these early discussions that “soft” issues would be a key feature of the study. In particular the new command construct envisaged new player command behaviours that required shared understanding; trading of tasks, risks, and resources; and hence trust between players. Players, all experienced military officers, also considered whether such behaviours were already practised to some extent in current command. These discussions examined the nature of command, as modelled, compared to reality. Our modelling constructs perhaps take command wiring diagrams too literally—they are a convenient abstraction of reality in themselves. For example, industrial age hierarchical command suggests a stovepiped structure dominated by the chain of command and “the commander” whereas actual practices suggest much more horizontal interaction conducted by subordinates, staffs, and wider entities. In other words, headquarters interactions are richer than we might construe from a command diagram. In addition, as an active player in a multi-sided closed game, the opposing

red coalition was bent on defeating *blue* (our own forces) by all and any means, and creating unexpected events was one means by which the red coalition could do this.

The game also provided an opportunity for the experienced military subject matter experts to reflect on wider issues such as resources required to achieve some command levels including, for example, collective military training, wider training with other government departments, and with coalition partners.

Conduct of the Experiment

The experiment was carried out using a *closed game* approach, in which each side could only have access to information about the other side generated from its intelligence and sensor assets. The blue command cells consisted of three brigade headquarters under divisional command in the baseline, and three agile task organised grouping headquarters with minimal higher level command in the treatment case. Each of these WISE headquarters cells was staffed by an expert WISE user supported by an external military expert, which is in itself an abstraction of a real headquarters where there would be both the commander and his staff. In addition to data extraction from the wargame itself (e.g., casualties, or sensor detections), considerable effort was made to gather insights from the players using plenaries and one-on-one structured interviews.

The scenario used for the wargaming was a focused intervention in support of another state by a coalition. The opponent, red, had some sophisticated land capabilities but was primarily exploiting asymmetric options (such as improvised explosive devices [IEDs]) in the context of complex terrain and civilians. Our own forces, blue, represented a three nation coalition

but with the emphasis on UK command and force elements. The full complex of actors was not explicitly gamed: civilians and insurgents were included, but others such as humanitarian relief organisations and private military companies (contractors) were not.

The blue forces had a wide range of resources including “tradeable” assets such as sensors, air support, indirect fire artillery, and some logistics, but the dominant elements in the order of battle were conventional land assets such as armour, armoured reconnaissance, mechanised and light infantry, and associated combat support and combat service support.

Insights

During the course of the gaming it became apparent that the scenario was not as challenging as originally anticipated. In particular, there did not appear to be a scarcity of assets, and hence there was no competition for them to stress the players. (Of course, only by doing the experiment do we find these things out). In addition, the opposing red groups were working towards simple goals and could operate largely autonomously, hence they were unlikely to be stretched by blue tempo or concurrent attacks. These serve as moderating factors on the insights offered by the players.

For the current command case (the baseline) the following were considered to be the principal advantages and issues:

- Players could concentrate on their own areas; they did not need to know what the other brigades were doing as there was less dependency upon them for individual success. This was perceived to be a less stressful command environment.
- There was positive control from the divisional commander with a view to (potential) longer-term issues.
- Communication requirements (between brigades and to/from divisional level) were reduced due to procedural control (although it should be noted that only a subset of the operational command structure was examined).
- There was reduced interest in higher level operational requirements (the counter to the first perceived advantage) at the brigade level.
- This baseline case was more risk-averse in comparison to the treatment case due to the longer-term view being held at divisional level, with assets kept in reserve to deal with possible future contingencies.
- The opposing red force perceived that our own forces appeared to be operating with reduced tempo.

For the future command case (the treatment) the following were considered to be the principal advantages and issues:

- There was greater unity of effort, as demonstrated by the altruism shown by the players, offering and seeking help amongst agile task organised grouping peers (encouraging a sense of teamwork).
- Shared awareness of the operational requirements increased as the players tried to understand the issues facing the other agile task organised groupings.
- More pro-active, collaborative planning was encouraged as the players looked for opportunities to achieve outcomes unconstrained by boundaries or assets.
- It was perceived that agile task organised groupings might be inclined to follow the path of least resistance, since with more flexibility in the task, these more ad hoc groups might be incentivised to reduce their own exposure to failure.
- In the post-game analysis it was emphasised that new collaborative ways of working place greater demands on joint and combined training, require planning tools to support this collaboration (not just a shared awareness of the situation but of intent also) and lead to increased horizontal communications requirements between agile task organised groupings. Effective, robust, and frequent joint and combined training are essential in order to engender trust and mutual understanding.
- An issue raised by the gaming was: who takes ownerships of *tasks in the gaps* (e.g., provision and security of logistic resupply, as agile task organised groupings may not have the capability to provide this for themselves)?

Furthermore, agile task organised groupings might break or blur the leadership inherent in command and the bond between commanders and subordinates; the idea of a “band of brothers.”

A major issue that was not fully addressed but was at least exposed by the gaming was that of the ownership of assets and the risk inherent in their use and potential loss. It was observed that in the future command case, the players were tending to hold nothing in reserve, instead being reliant upon each other to provide that contingency to cover the unexpected. This might have been players taking unrealistic risks in a game in order to win. There may be a deeper issue in that under this new command “trading scheme” there might be a diminution of the moral bond between a commander and his men and a lack of overall ownership of assets. This could lead to the question over who is concerned with the attrition of the UK force capabilities and what are the implications of this on the longer term (beyond the immediate operation) viability of the defence forces.

Overall, it was felt that the treatment case, the new NEC construct based on agile task organised grouping, encouraged a cultural shift towards less constrained, more innovative planning and action, greater co-operation, and pro-activity.

Placing this experiment in a larger context, we can consider synthetic environments (SE) as being used in two broad ways for analysis, as shown in figure 3.3, namely problem structuring and problem solution. These are two of the key steps recommended in the *NATO Code of Best Practice for C2 Assessment* [5] within the overall approach to problems centred on command (the heart of network enabled capability, and command in the

information age). At the problem structuring stage, SE can be used to explore the consequences of agile task organised grouping, prior to capturing these effects within constructive simulations. At the problem solution stage, an initial hypothesis set up within a constructive simulation (e.g., the relationship between headquarters resources and headquarters planning time) can be calibrated using an SE, and then input into the constructive simulation. This is known as the *model-test-model approach*.

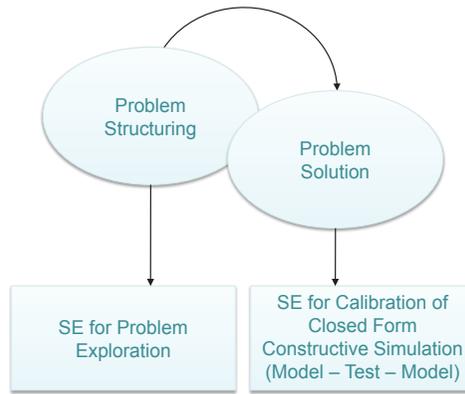


Figure 3.3: The interaction of synthetic environments and closed form constructive simulation.

As illustrated by my earlier discussion at the problem exploration stage, evidence from such synthetic environment experimentation can contribute uniquely to better understanding of network enabled capability issues and, in particular, soft aspects, non-equipment aspects, and aspects of how opposing red forces might seek to counter or exploit new command concepts. These can then be used to develop focused hypotheses for more detailed quantification in constructive simulations.

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CHAPTER 4

THE CONTEXT AND VALIDATION OF INDIVIDUAL AGENT BEHAVIOUR

From a complexity, or complex adaptive systems perspective [1], validation of a modelling approach takes place at two different levels. The interactions between the agents create emergent behaviours which are validated at the *collective level*. At the *individual agent level*, we are concerned with the algorithms which drive each agent's local behaviour. In this chapter I focus on the individual agent level. In chapter 6 I will consider the validation of emergent behaviour at the collective level.

I have already introduced, in chapter 2, the idea of deliberate planning (or in cybernetic terms, feed-forward control), which corresponds to a top-down, or collective C2, while rapid planning corresponds to the C2 exercised at the individual agent level (in cybernetic terms, feedback control). In chapters 2 and 3 I also introduced the idea of different approaches to command. As we move up these approaches to command, the balance between deliberate planning and rapid planning changes. At the lower level, corresponding to de-conflicted command, the balance is very much towards deliberate planning. Moving

up the scale towards edge command, we wish to focus on the representation of a force driven by a broad overall intent with the ability to self-synchronise. To do this, we first have to consider how to define and represent both intent and shared situational awareness.

Shared Situational Awareness

There are a number of ways of looking at shared situational awareness (SSA). Formally, in the academic literature [2], situational awareness is defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.” These three aspects are often referred to as Endsley levels 1, 2, and 3. Our aim should be to capture each of these three levels of situational awareness. In military terms, [3, pp. 120-121] SSA is defined in terms of understanding a situation which spans both own and other actors’ physical, information, and cognitive domains, and has the following components:

- missions and constraints on missions (e.g., rules of engagement);
- capabilities and intentions of relevant forces;
- key attributes of the environment including terrain, weather, social, political, and economic elements;
- time and space relationships; and
- opportunities and risks available to the forces.

This corresponds to Endsley level 3.

Additionally, in [4, p. 102], sensemaking is discussed in terms of generating options, predicting adversary actions and reactions, and understanding the effect of particular courses of action: “Sensemaking is much more than sharing information and identifying patterns. It goes beyond what is happening and what may happen to what can be done about it.” In [5, pp. 122-123] the perceptions of the stakeholders in the conflict are discussed in terms of:

- values and trusts – the enduring values and trusts of the people involved;
- commitment to objectives – how committed people are to real achievements;
- current situational assessment – the perceptions people have of what is going on; and
- predictive situational assessment – how things are likely to evolve from here.

Reference [6] defines SSA in terms of a consensus team view whereby “aspects of the individuals’ mental models will have a degree of commonality, which will enable the team to act in a cohesive and consistent way.”

Finally, in the NATO command and control reference model [7], *sensemaking* is defined in terms of the following composite variables:

- mental models;
- quality of awareness;
- quality of shared awareness;
- quality of plan;
- quality of understanding;
- quality of shared understanding;
- culture; and
- team characteristics.

These all give a sense of what is meant by SSA, and what it contains.

Levels of Shared Situational Awareness and Command Agility

From the preceding discussion, we assume that the aim of SSA is to provide a consensus understanding and interpretation of the situation, the intentions of other actors in the battlespace and their potential courses of action. Figure 4.1 reminds us of the relationship between SSA and levels of command agility.

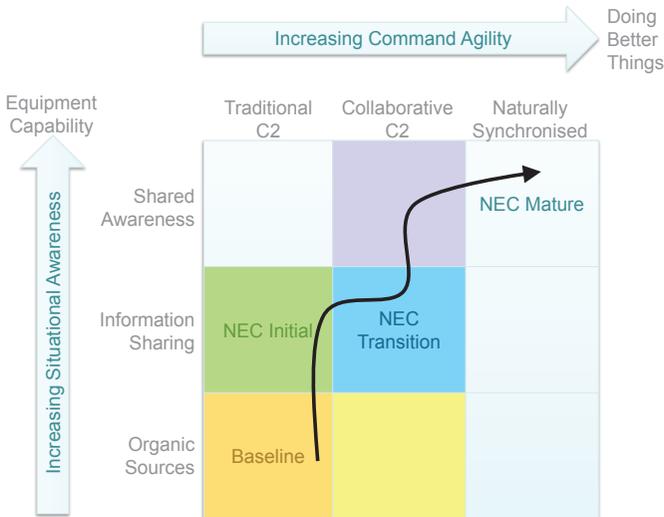


Figure 4.1: The relation between command agility and levels of shared situational awareness.

High level UK doctrine [8] emphasises agility as the goal to which the UK armed forces are heading over the next 20 years or so. Agility, as I introduced it in chapter 2, comprises the following features: robustness, resilience, responsiveness, flexibility, innovation, and adaptation. It is at the heart of attempts to move from *doing things better* to *doing better things*. This journey is based on the development of network enabled capability (NEC), moving through a number of *epochs* as shown in figure 4.1—*NEC initial*, *NEC transition*, and *NEC mature* [9].

The Command Process

Before proceeding further, let us consider the nature of the command process itself. British defence doctrine describes the philosophy of command in the following terms:

A sound philosophy of command has four enduring tenets. It requires timely decision-making, a clear understanding of the superior commander's intention, an ability on the part of subordinates to meet the superior's remit, and the commander's determination to see the plan through to a successful conclusion.

The exercise of command includes the process by which a commander makes decisions and impresses their will on, and transmits their intentions to, their subordinates. It entails authority, responsibility, and accountability. Authority involves the right and freedom to enforce obedience if necessary. Whilst a commander can devolve specific authority to subordinates to decide and to act within their own areas of delegated responsibility, he or she retains overall responsibility for their command. Responsibility is thus fundamental to command. Accountability involves a liability and obligation to answer to a superior for the proper use of delegated responsibility, authority, and resources; it includes the duty to act. Thus (s)he who delegates responsibility should grant sufficient authority to a subordinate to enable them to carry out their task; the subordinate, meanwhile, remains accountable to their superior for its execution.

In chapters 2 and 3, I introduced the idea (drawn from the work of the NATO RTO SAS-065 task group) that different approaches to command, ranging from conflicted command, through de-conflicted, coordinated and collaborative, to edge command, can be represented as different regions in the C2 approach space. These regions thus correspond to different approaches to command. The inter-related dimensions defining this C2 approach space (as shown again in figure 4.2) are the distribution of information, the allocation of decision rights, and the patterns of interaction among the entities. Different values of these dimensions thus correspond to a different

approach to command, and the ability to *change* the approach to command corresponds to changing one or more of these key dimensions significantly.

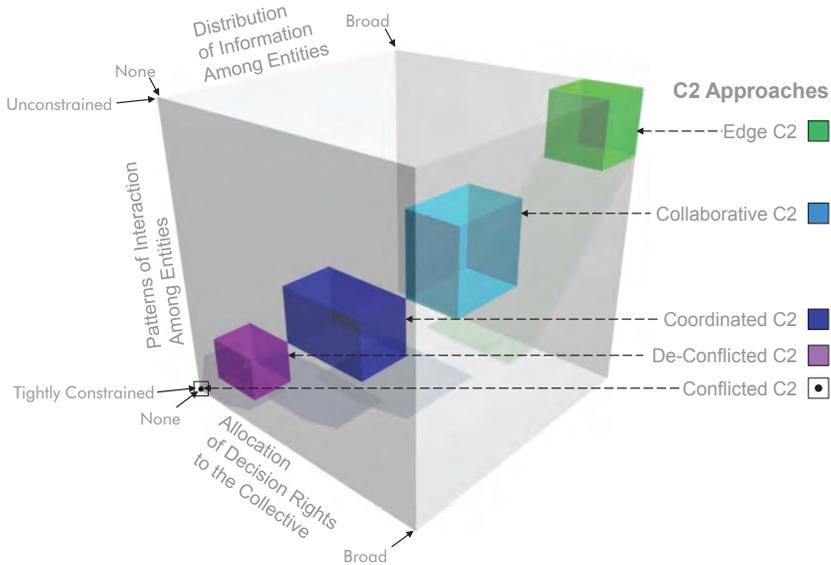


Figure 4.2: The C2 approach space.

Situation Awareness and Planning

From our earlier discussion, it is clear that shared situational awareness includes the understanding of command intent. This relates to the ability to share not just information, but (to the extent possible) some degree of sharing of understanding and mental models. Leaving aside for the moment the edge command case, which we will return to later, we assume that the command intent of the superior commander is represented by his current deliberate plan [10]. This intent, together with the perceived layout of forces and objectives (on both sides)

derived as part of the plan, forms a common relevant operational picture (CROP),¹ as shown in figure 4.3, taken from reference [10]. This is promulgated (to a greater or lesser extent) to the commander's subordinate units of action. Windows onto the CROP are thus available to commanders at the tactical level.

The deliberate planning algorithms naturally produce force elements which head towards de-conflicted objectives, as indicated in figure 4.3, where we see geographically separated force elements and objectives which do not have adverse cross-impacts. This separation on the ground can then be captured within the CROP and we can use this as part of our baseline representation at the de-conflicted command level.

1. Relevance here means relevance at the operational level.

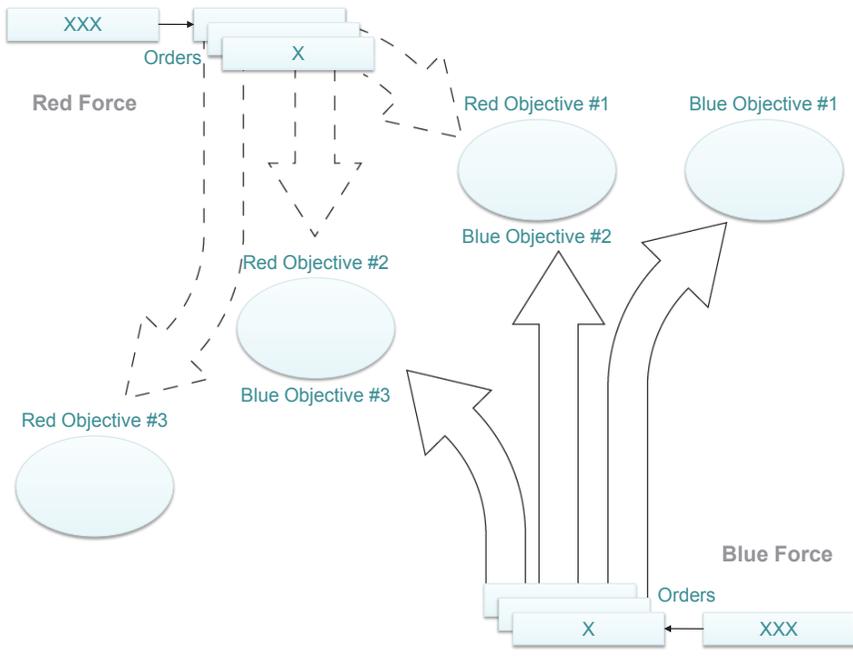


Figure 4.3: The outcome of the deliberate planning process: the common relevant operational picture (CROP).

The process of planning, including sharing of the CROP, more local peer to peer information, and the development of local plans, is summarised at figure 4.4. The sharing of the CROP could be by word of mouth, radio, physical maps, or (more likely) sharing of narrative descriptions and video material via electronic links including websites and email. Note that each unit of action (UA) now has not only its own rapid planner (RP) but also a perception of a portion² of the CROP. Sharing of this CROP across the units of action corresponds to the sharing of intent, sharing understanding about force capabilities

2. This portion could vary from nothing to the full CROP, dependent on the amount of shared situational awareness which exists.

and intentions, key attributes of the environment, and time and space relationships. Sharing information about cues across the rapid planners of the UAs corresponds to horizontal (peer-to-peer) sharing of information (as also described in [11]). These cues are updated on the basis of information in the CROP, information from sensors feeding directly to the units of action, and information shared horizontally between the units. The sharing of the CROP and the sharing of information among the rapid planners of the UAs together constitute our initial definition of shared situational awareness. With full SSA, each unit is assumed to have a complete understanding of the CROP. In addition, each unit will share the same set of cue values. Perception and cultural assumptions also have a part to play, of course, in terms of the interpretation of such shared information, and the choice of a course of action. In modelling terms we represent SSA firstly in terms of the sharing of information, and then overlay these additional cognitively based perception and cultural factors. Such ideas are not easy to take in at first encounter. Rather than give an abstract discussion here, an illustration of how we do this within a complex multi-actor peace support operation model (the DIAMOND model) is discussed in chapter 5.

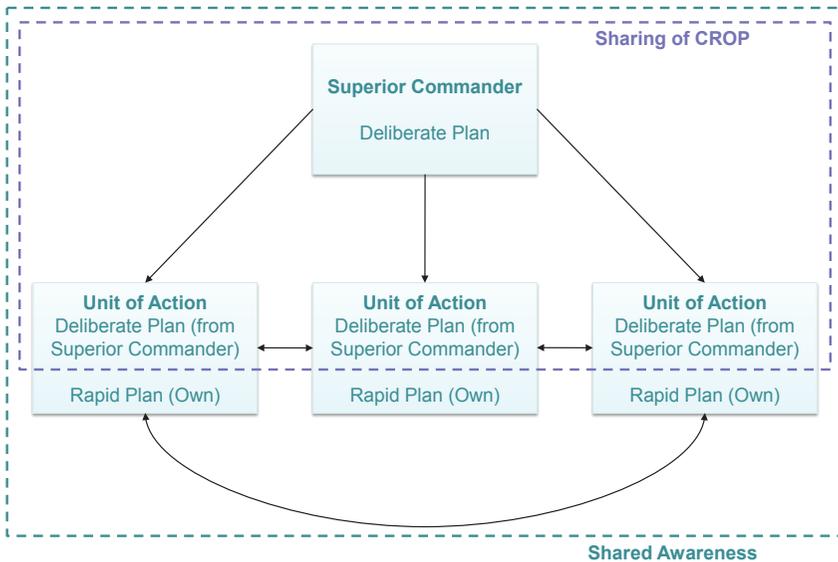


Figure 4.4: Shared situational awareness including shared intent and sharing of the CROP.

Modelling Different Command Approaches

De-Conflicted Command

In this case, the superior commander defines the objectives, boundaries (such as mobility corridors), and level of information exchange, to ensure that separate objectives do not interfere with one another in time and space. One example is the layered structure of NATO forces on the central front facing the Warsaw Pact during the Cold War. Another is the structure of quasi-independent terrorist cells.

The de-conflicted command approach can be modelled by ensuring that each task-organised force (i.e., each unit of action) allocated by the deliberate planner has a separate objective

and that they do not interfere with each other. Over time, the *plan repair* process [10] allows for adjustments of capability across these units of action as the plan unfolds. An example is shown in figure 4.5 where we have implemented the deliberate planning algorithms in the Dstl Wargame Infrastructure and Simulation Environment (WISE) simulation framework introduced in chapter 2 as part of the hierarchy of Dstl simulation models. Here we can see blue force units moving towards their objectives, taking account of developing sensor information, and hence, unfolding awareness of enemy force locations.

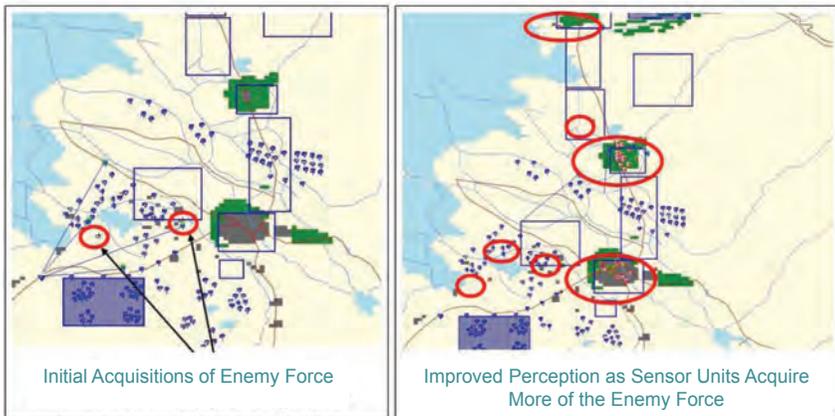


Figure 4.5: Blue forces moving towards their objectives and the unfolding awareness of enemy force locations.

For this approach to command there is only a small amount of *horizontal* peer-to-peer interaction in the information domain, thus the shared awareness structure is as shown in figure 4.6, with the main emphasis being on the *vertical* command structure rather than horizontal peer-to-peer interaction, and hence, the understanding and carrying out of the superior commander's intent and more detailed orders. In the C2 approach space

(figure 4.2), this level of command occupies a small locus of points near to the origin. Thus there is tight control of decision rights, a low level of peer-to-peer interaction, and access to information is also tightly controlled.

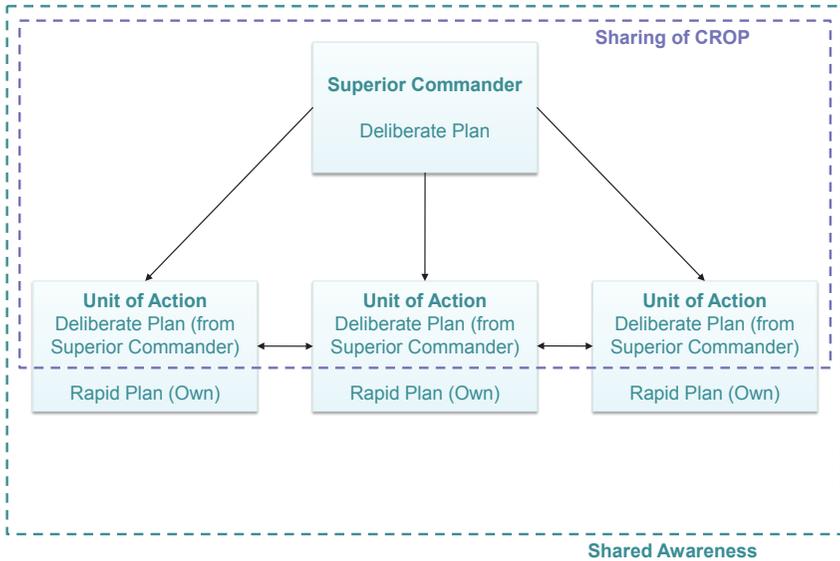


Figure 4.6: De-Conflicted command where the emphasis is on vertical interactions, with little horizontal interaction.

Other Approaches to Command

By changing the balance between the deliberate planner and the rapid planners of figure 4.6 and allowing more peer-to-peer interaction between the rapid planners, we can represent the delegation of decision rights, the increased sharing of information, and the increase in the patterns of interaction corresponding to other approaches to command—until we reach the point where edge command and self-synchronisation come into play; then we need to do something different.

Edge Command

Edge command allows the possibility of self-synchronisation. This includes the ability of smaller cohesive modules of force to transfer to other units in a fully dynamic way, as required. These task-organised units can also opt to act together as formed units if they wish. There is minimal intervention by the superior commander, thus control in this case is emergent [4]. Decision rights are fully delegated and there is a rich and full informal and formal network of interactions between the force elements. The superior commander in this case reverts to a *parenting and ownership* role in relation to key assets which need to be held at high level, but also reserves the right to intervene again when required.

As I discussed in chapter 2, a possible solution is to consider the following change depicted in force organisation, in figure 4.7:

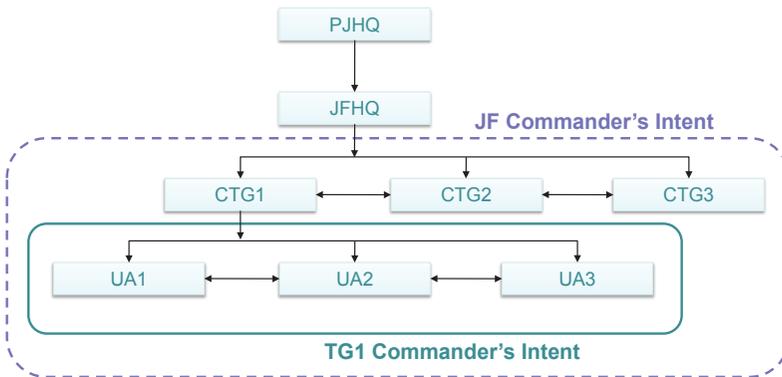


Figure 4.7: Possible force structure for an agile self-synchronising force.

The intent of the Joint Task Force Commander is made transparent across the force (the large ellipse), and below him or her, the force is organised into comprehensive task groups (CTG) which can be a mix of air, land, and naval components. These in turn consist of task organised units of action (UA). CTGs can change and adapt their composition and bounds over time, through local, horizontal peer-to-peer interaction, in addition to the interaction vertically through the command hierarchy. Each set of units is also within the intent of the appropriate CTG, thus the structure is recursive. Within this intent, these units can also adapt their composition and bounds over time. As also noted in chapter 2, this approach is consistent with the picture of information age command discussed in [5] where high agility of the command process is matched to high agility of the command environment.

In terms of the C2 approach space, edge command allows the collection of units to operate within the largest volume of command options and reaches into the furthest corner—the edge organisation [4].

As an illustration of setting the conditions of command to match the prevailing circumstances, consider making a smooth command transition from warfighting to peace support operations. Consider also making a smooth command transition from an initially homogeneous force with high trust and high levels of collective training to a heterogeneous coalition environment later on. These involve two separate capabilities—first, recognising the changing state of the mission space (requiring high shared situational awareness of the changing intent), and secondly, the ability to adapt the command approach accordingly. This requires high flexibility of the command process (changing the allocation of decision rights for example) and the ability to

easily and rapidly reconfigure the underpinning infostructure (changing the distribution of information, creating new information *hubs*³ for access by all, or linking existing information hubs for example). In order to do this in an enduring way, the infostructure and the command structure will require many of the aspects of agility I have already discussed in chapter 2, such as robustness and resilience. An edge command structure for example, will be more likely to endure across a number of dynamically changing mission situations and hence be more robust.

The shift of emphasis we are discussing, in moving from the classic C2 corner of figure 4.2 to the edge organisation corner is summarised in figure 4.8. This indicates how the deliberate planning element of the process is now bypassed to a large extent and replaced by an assessment of broad intent for the force, based on perceived indicators of collective behaviour of possible threat groupings, together with a shared situational awareness of this potentially rapidly shifting collective behaviour. These perceptions then feed directly to the force elements and their local rapid planning, together with some means of self-synchronising these local plans with other peer units. Again these ideas are rich and rather than discuss them further in the abstract I will give a detailed illustration of how they can be implemented in modelling terms in the WISE model in chapter 7.

3. A hub in network theory terms is a node (e.g., a website) which is richly connected to other nodes of the network.

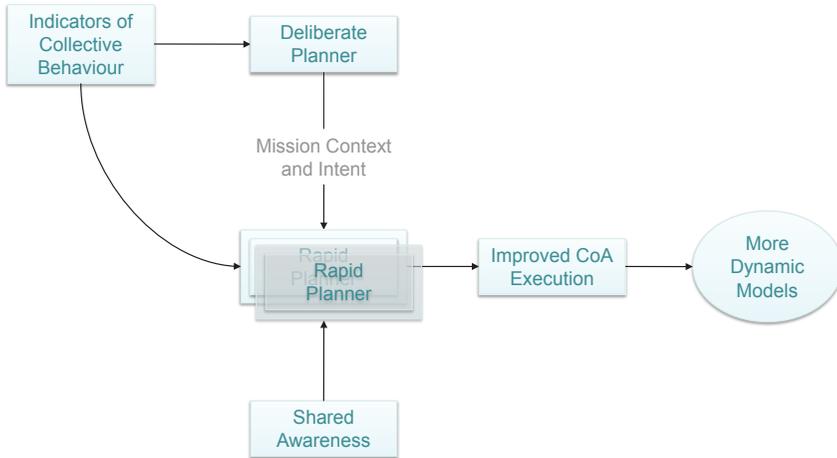


Figure 4.8: Modelling an edge organisation.

Validation of Individual Agent Behaviour

Having now introduced the context of the approach we are adopting, I now want to turn to some of the underpinning research. This also helps to demonstrate that our approach is anchored in real human effects. In a previous book [10] I discussed the context and validation of the basic approach to rapid planning. Here I want to discuss some more recent follow-on validation efforts.

The results of the first set of experiments helps us to explain why decisions at the tactical level differ qualitatively, dependent on the decision-makers' experiences and preferences. Utility theory attempts to quantify such preferences, and demonstrate how they change (in a nonlinear way) as circumstances change. These utility curves have then been used to enhance the mathematical algorithms of the rapid planning process [12].

More precisely we wish to understand:

- a. how the objective inputs (based on incoming information) and the subjective inputs (based on an individual's training, experience and personality) combine in the decision-making process; and
- b. how considerations of utility influence this process; in particular, when there are conflicting local and global values within the decision-making structure.

Theoretical Perspective

The missions described in our experimental situation are simplified to just two levels of attributes. The first set of attributes measures the local outcome of the mission in terms of relatively immediate, close-to-home considerations (such as loss of tactical assets). The second set of attributes measures longer-term and more global concerns related to more strategic considerations (for example, integrity of the NATO campaign). Our analysis describes how this tension between local and global concerns can formally be modelled. The choice of course of action depends on the interpretation of mission orders (i.e., weighing of priorities in terms of utilities) and the subjective situation assessment (i.e., weighing of evidence derived from subjective informational attributes). The commander may be unable simultaneously to reconcile, even partially, the objectives associated with the attributes pertaining to the high-level mission objectives and their own local appreciation of immediate potential threat. When this happens (s)he may be forced to choose an action that focuses on local, shorter-term success, marginalising the longer-term implications of their action. Alternatively, (s)he may place more weight on global concerns.

This tension between objectives is the basis for the derivation of the subjective utility and depends on subjective descriptors of the conflict situation, interpretation of the mission orders, and general appreciation of the context. The relative importance each commander places on local and global objectives is central to a conceptual understanding of *value* in decision-making. It seems that such qualitative relationships are enduring in this context and that they provide a useful framework for modelling.

In practice, most Bayesian decision analyses usually begin by assuming that the decision-maker's utility function, U , has an associated set of value-independent *situation* attributes [13]. In our application, these attributes are associated with situation features that are immediately local to the decision-maker and those that have a longer-term, more global impact. For a decision, d , a decision-maker's utility function thus has to capture the trade-off between the different goals by assigning weights, $\alpha(\lambda_1) = \{\alpha_1(\lambda_1), \alpha_2(\lambda_1)\}$, to reflect the importance of achieving the desired values of the attributes, whose achievement is evaluated by the utilities. (λ_1 is a set of shape parameters describing this utility function).

Projected future values of the attributes are represented by a probability distribution function $p_j(\theta_j | d, \lambda_2)$ which reflects the decision-maker's current (subjective) probability of the outcome θ_j relative to the goal attribute x_j , given decision d , where λ_2 is a set of shape parameters for this probability distribution.

The decision-maker should thus choose d to maximise the utility function $U(d, \lambda_1)$, averaging over his beliefs about different outcomes θ_j and their utilities. The decision-maker also implicitly sets weights $\alpha(\lambda_1)$ reflecting, for instance, their

priorities and ambitions. In military settings a decision-maker will be held accountable for their chosen course of action d . It is therefore reasonable to expect that the specific nature of the mission objectives and the previously absorbed general training and personal history will be reflected in the commander's setting of $\alpha(\lambda_1)$.

The Single Decision Game

A single decision game was thus designed to measure the predisposition of commanders, in a situation in which they should be experts, by requiring them to make a rapid determination of a course of action. Participants were presented with an operational picture and situation brief. Following an initial ten minutes to appraise the situation, an intelligence report was briefed which might (or might not) demand action. The participants were then asked to choose and write down a course of action without being given further time for analysis. The intelligence update was designed to give them some room for choosing different courses of action so that their predispositions were allowed to surface as variations in choice.

After the course of action was selected, participants were invited to record their situation appraisal and assessments along with the key indicators considered relevant to their course of action choice. It was accepted that this data might reflect post-hoc rationalisation to some extent. To account for any changes in situation assessment due to the process of having to analyse and express it, the participants were also offered the opportunity to record any other courses of action that they might have considered.

The experimental game results provide a context within which to explore and test our nonlinear utility theory; in particular, the ways in which individuals' predispositions affect the weights given to the situational attributes. It appears that the extent to which each attribute is (or is not) considered in the pattern-matching process of rapid planning strongly determines the choice of course of action. The experimental game was based on decisions at battlegroup and company levels set in two different conflict scenarios: war-fighting and peace-support. More details of the gaming approach and scenarios used are in reference [12].

Based on the results of these games, the rapid planning process representation has been extended to include weightings on the cues which span the decision space, and utility curves similar to those of Prospect Theory⁴ [14] which represent the utility of a cue value given a particular course of action. Thus for a given cue j , we define a weight α_j , with $0 \leq \alpha_j \leq 1$ and $\sum_i \alpha_j = 1$. For

each cue j , with outcome values θ_j , and each course of action d , we also define a nonlinear utility curve $U(\theta_j | d)$. The cue value θ_j at any given point in time will have an uncertainty associated with it, and thus a probability distribution of values $p(\theta_j)$. We combine these together to obtain the overall utility $U_j(d) = \int U(\theta_j | d) p(\theta_j) d\theta_j$. We then sum this over all cues to

obtain the overall utility of the course of action d as follows:

$$U(d) = \sum_j \alpha_j U_j(d)$$

4. The Nobel Prize for Economics was recently awarded to the originators of Prospect Theory.

In the extended form of the rapid planning process, this is used to choose between a course of action which is consistent with higher level orders, and one which is locally more appropriate (through comparing their relative utilities). This choice was found to correlate with the *commander characteristic* from the 60PF personality profile which was applied to each participant as part of the experimental process. Implementation in the UK Qinetiq HiLOCA model shows encouraging results, being able to capture some key characteristics of more mature levels of network enabled capability [15].

Second Set of Experimental Games

The second set of experimental games which we analysed were originally developed as part of a study of tactical command decision-making in the context of NBC (nuclear, biological, and chemical) battlefield threats.

After an initial year of exploratory work it became clear that the key problem was one of relating the information available to commanders to the decisions they then made [16]. This problem was not one that could be solved purely through a theoretical treatment, thus an experimental method was devised to investigate, and if possible quantify, the relationship between information received and courses of action selected.

The method chosen was the use of a series of card-based decision games. The decision games used a simple map and situation briefing, with additional information being presented on a series of cards, organised into a number of serials. This gaming structure is similar in principle to the one we have used in previous decision games in the naval and land contexts [17, 18]. The innovative aspect of the gaming described here was the way

in which the information was presented to the players, which allowed a high degree of experimental control over the amount and type of information presented to them as the experiment progressed. As also previously developed in [18], the method generated large quantities of data, with each information update (presentation of a card) being a data point. Previously, we used entropy reduction as a measure of the benefit of this information. Now, for the experiments described here, the volume of data allows the use of multivariate probit regression models to analyse the results. These statistical models show a high degree of ability to predict the observed behaviour, as we will see.

Given that we can develop a statistical model of such decision-making, and we have also previously developed the rapid planning process to describe such decision-making, this leads to the question: To what extent are these statistical models, developed to represent the behaviour observed in these decision games, compatible with the rapid planning process? Further, can we use these statistical models to help validate and improve the rapid planning process?

Card-Based Decision Games

Two main decision games are considered in detail here. The first of these is essentially a single decision game in which an NBC commander chooses (or not) to raise an alarm based on accumulating incoming information. The second looks at multiple decisions taken by a wider set of tactical commanders over the course of an advance towards an objective. We call the first the *single decision game* and the second the *multiple decision game*.

The Single Decision Game

The first study dealt with the problem of responding to biological detector alarms. These do not give an unambiguous indication of an attack. For example, they can respond to aspects of the environment that are not necessarily due to an enemy biological attack. Because of this, the current doctrine is to insert a human into the loop to decide whether or not a particular set of circumstances, including both detector alarms and other indicators, constitute sufficient evidence to issue a wide-area alert. This study explored what information was needed to trigger the issuing of the wide-area alert.

As already discussed, the experiment was conducted in a similar format to previous single decision games such as those described in [17, 18]. For example, players operated in pairs, with the pairs being permitted to discuss any proposed course of action and being required to come to a joint decision. The players were presented with an introduction to the game context, containing a minimum amount of contextual information, together with a map of the area of operations and a short verbal briefing on the situation.

The innovative aspect of this gaming approach was the presentation of the incoming information as a sequence of cards. Each card gave a single, simple piece of information. The cards were presented in order, one at a time, with the next card being presented when the players requested it, forming a *serial*. Once a card had been presented, it was retained by the players. Each serial thus represents a particular unfolding scenario with accumulating information. These scenarios are not scripted, as

the cards are essentially randomly shuffled, capturing the effect of a dynamic and unpredictable set of events occurring as the scenario unfolds.

The introductory contextual material asked the decision-makers to decide, after each card, whether or not to take either or both of two courses of action:

- a. issuing a precautionary alert to troops in theatre, leading to the donning of individual protective equipment (IPE); and/or
- b. declaring a probable attack—including recommending the taking of medical countermeasures and reporting up the chain of command as a probable biological attack.

The key to the experiment was the use of the information cards. The information element of the cards was contained in a short sentence. Again, as in [17], the information was defined in a number of categories. Six categories of information were used, and these were represented on the card by a simple picture (i.e., one picture for each card category). The number of categories was an important decision—too many categories and the analysis would have insufficient data to produce results; too few and different types of information would end up being placed together in the same category, blurring the different effects.

As already discussed, the information cards were assigned to the serial at random in order to create a series of events in a given scenario. These were deliberately randomised in order to avoid scripting of scenarios and an artificial narrowing of the potential decision options at any given time. To do this, a small

spreadsheet was used to generate each of the serials used. The spreadsheet was a simple random number generator and was used to determine;

- a. how many specific and generic alarms there would be and at what locations; and
- b. how many of each of the other types of cards would be present.

Eight serials were developed in total, with all pairs of players being exposed to all serials. The allocation of the order of serials to individual pairs was decided using an 8 x 8 Latin Square design, which ensured that each pair not only saw the serials in a different order, but also saw each serial preceded by each of the other serials, to compensate for learning effects.

The subjects consisted of seven pairs of military NBC specialists. Two pairs were drawn from Dstl internal military staff, one from the NBC staff at RAF Strike Command, two from the Defence NBC Centre at Winterbourne Gunner and two from the Joint NBC Regiment. All had a thorough NBC background and, in the case of the pair from Strike Command and the two from the NBC regiment, recent relevant operational experience. All of the remaining trials were conducted as pairs, although in two cases one member of a pair had to leave part way through the trial.

Approach to the Analysis

We wanted to analyse the strength of the link between the information presented to the players, and their response in terms of making a decision (such as issuing an alert), or waiting for more

information. Each pair of players was presented with a number of cards, one after the other. Thus at any given time, they will have seen a certain number of cards in each of a number of information categories. If x_i is the number of cards seen of information category i , a simple measure of the information presented is some linear combination of these x_i , weighted to reflect the relative importance the pair of players either implicitly or explicitly put on information of a certain category, giving an expression of the form $\sum \beta_i x_i$ where the β_i are these weightings. There will also be a constant value α corresponding to the situation at the start of each experiment where no information has yet been presented to the players. The outcomes in the experiments are the decisions by the pairs of players as to when they decide to *change their state* (by for example issuing an alert, thus going from the *no alert issued* state to the *precautionary alert issued* state).

In probit analysis [19] of these kinds of situations, the emphasis is on the *probability* (across all pairs of players taking part) of the pair deciding to change their state given a particular amount of information, and this may or may not give a good fit to the data, depending on how good a model it is of what the decision-makers are actually doing.

Game Results

The use of probit analysis in fact proved very successful in analysing the response data. The statistical model used was as follows.

There are three possible action states:

- $j = 0$ (no alert issued);

- $j = 1$ (precautionary alert issued);
- $j = 2$ (report of probable attack issued).

A probit analysis of the players' decisions is made based on the six information categories (x_1, x_2, \dots, x_6) . These represent the numbers of cards of each information category exposed to a pair of players in a given experimental serial. Thus we define (for such a pair of players)

$$\gamma_j = P(< \text{state } j)$$

and assume this is related to the information by

$$\gamma_j = \Phi\left(\alpha_{j-1} + \sum_{i=1}^6 \beta_i x_i\right) \text{ for } j=1,2$$

where Φ is the cumulative distribution of the standard normal distribution $N(0,1)$. The model thus far is shown in figure 4.9.

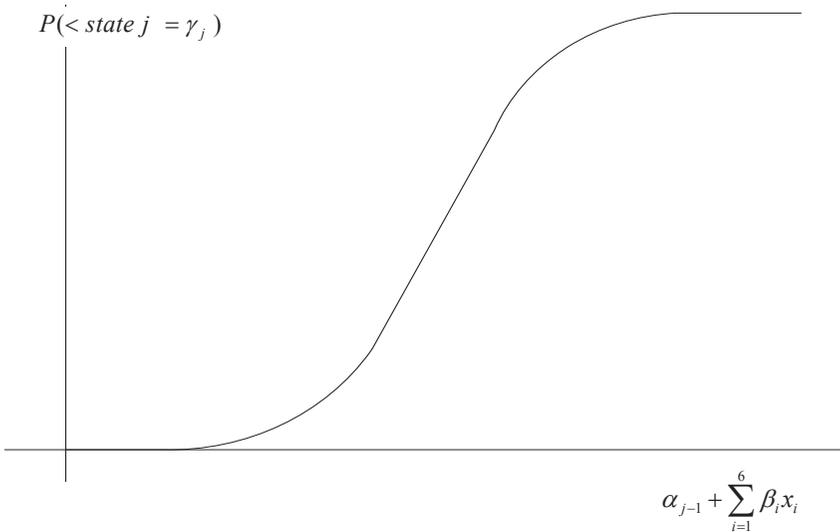


Figure 4.9: Initial statistical model for the single decision game.

In figure 4.9, the probability of action (y -axis) is shown as an increasing function Φ (the cumulative density function of the standard normal distribution), the x -axis being the sum of a constant value (α_{j-1}) for the particular type of decision, and a weighted sum $\sum_{i=1}^6 \beta_i x_i$ of the individual pieces of information exposed to the players.

This allows for two intercepts (α_0 and α_1), one for each of the two types of response, and weights (β_1, \dots, β_6), calculated from multivariate probit analysis, for each of the six information categories. These weights represent the relative importance to the players of each information category. This is the simplest model giving a good fit to the data, although more complex models, breaking down these information categories further, were also investigated.

We need to augment our statistical model slightly in the following way:

Firstly define

$$y_j = \alpha_j + \sum_{i=1}^6 \beta_i x_i$$

Then define the probability of being at least in a certain action state as

$$\Pr(Y \geq j \mid x_1, x_2, \dots, x_6) = 1 - \Phi(y_{j-1})$$

Using this as our statistical model, the probit analysis indicates that the weights β_i are all negative, so that as the number of cards of a given type increases we are moving towards the

origin of the x -axis, and thus *climbing up the probability slope of the probit transform* (i.e., the probability $1 - \Phi(y_{j-1})$ is increasing), as shown in figure 4.10.

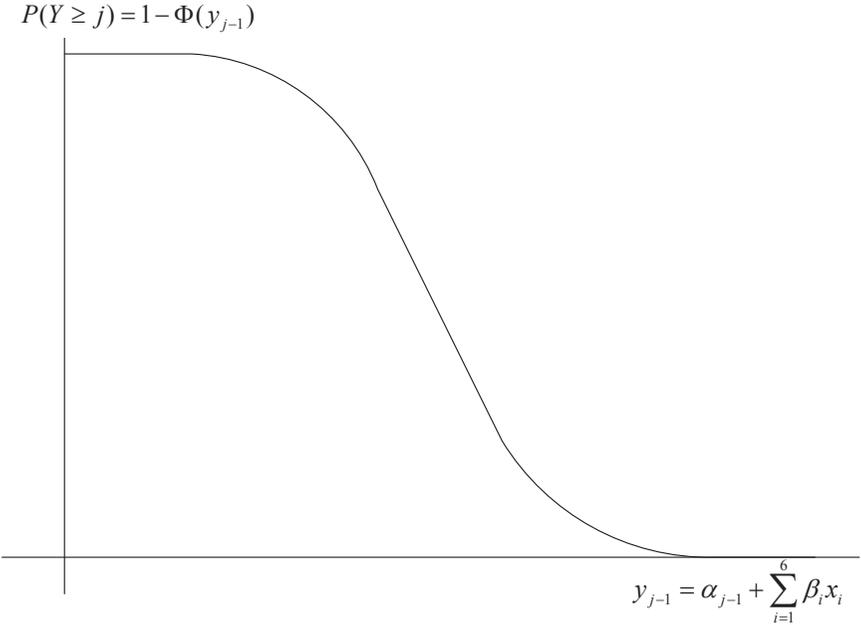


Figure 4.10: The probability of being in at least state j .

In summary, the x -axis of figure 4.10 gives us the total value of the intercept (α) and the individual weights (β) for the covariates. This is the total information presented to the pair of players. This is then used to calculate the probability of the players choosing to be in the action state j or greater (y -axis of figure 4.10). From this we can then calculate the following *decision probabilities* as a function of the information presented

$$P(Y \geq 2) = P(\text{Probable Attack}) = 1 - \Phi\left(\alpha_1 + \sum_{i=1}^6 \beta_i x_i\right)$$

$$P(Y \geq 1) - P(Y \geq 2) = P(\text{Precautionary Alert}) = \Phi\left(\alpha_1 + \sum_{i=1}^6 \beta_i x_i\right) - \Phi\left(\alpha_0 + \sum_{i=1}^6 \beta_i x_i\right)$$

$$P(Y < 1) = P(\text{No Action}) = \Phi\left(\alpha_0 + \sum_{i=1}^6 \beta_i x_i\right)$$

As an indication of the predictive power of this decision model, applying it to one of the scenarios (serial 2) gives results as shown in figure 4.11, showing the probability of a precautionary alert.

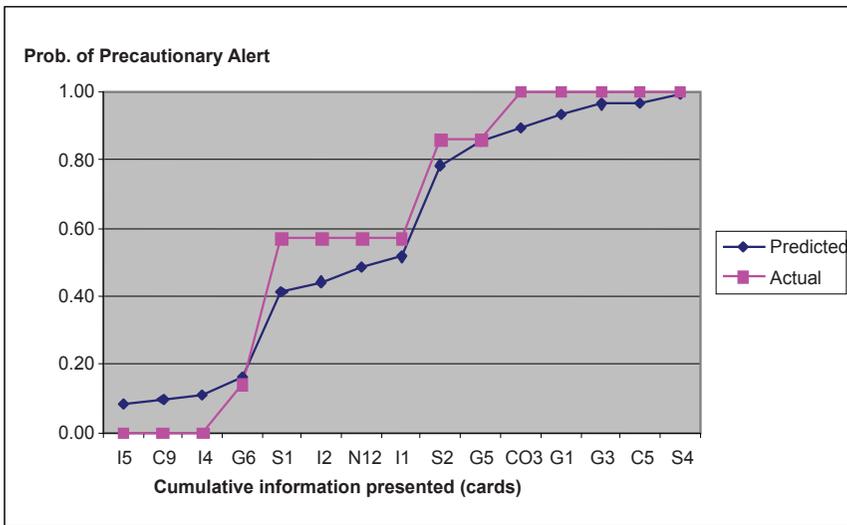


Figure 4.11: Probability of declaring precautionary alert: serial 2.

Each label on the x -axis of figure 4.11 represents an individual card of information. The y -axis shows the total probability of being in the precautionary alert state (either predicted by the probit model, or assessed from the game results across all pairs of players). Clearly, the prediction gives a good fit to the observed data, not only tracking the general rate of increase

of probability of issuing an alert, but also following closely the degree of upward movement for each of the individual steps as each of the information cards is exposed to the players.

Overall, this statistical model of the decision process, where the covariates correspond to the six information categories, can account for 60% of the variability in P(probable attack warning issued) and 80% of the variability in P(precautionary alert or higher issued). This obviously gives confidence that the model is representing a significant element of the factors involved in the decision.

There are a number of limitations, however, the key one being that the problem addressed was one of a monotonic increase in the information presented to the players as time progressed, and that there was essentially just one decision being taken (the issuing of an alert of some form). It is possible that any fit to the normal distribution, based for example on the *total* number of cards presented to the players, would give a reasonably good fit to the data. There is also a comparatively limited data set in terms of the number of pairs, and a quite wide variation in behaviour across the pairs.

One of the advantages of the method is that it allows separation of the two major aspects of variability, the pair-pair variability, and the serial-serial variability, giving quantitative estimates of each. The pair-pair variability represents the human variability between one command team and another (a surrogate measure of the effect of commander personality on the outcome), whilst the serial-serial variability measures the degree to which the individual cards comprising the serial tell a consistent and

believable story. This has been called the *semantic variability* and represents the kind of variability that would be expected from occasion to occasion.

The Multiple Decision Game

The second set of games looked at a different problem appropriate to a wider set of tactical commanders. This was the problem of *risk-taking*. The current approach of UK forces is that, where NBC protective measures are concerned, the local commander has the freedom to modify the protective *dress state*, taking higher levels of risk in terms of a possible NBC attack in exchange for benefits in terms of freedom of action to achieve their objective and reduced degradation (including reduced fatigue or increased speed of movement).

This problem was significantly more complex than that addressed in the single decision gaming, since it involved non-monotonic decision-making; troops could move up and down dress states as the serial progressed, making the problem of modelling significantly more difficult than general fitting to a cumulative normal distribution.

Approach to Analysis

The general method followed was similar to that in the single decision gaming, though with a number of important differences. A number of routes towards tactical objectives were identified, labelled from *A* to *H* (with each objective having just one route associated with it). The routes were selected to give a variety of lengths, with all routes being in a general northerly

or north-westerly direction within a relevant scenario context. In each game, the player's intent was to move along a single route towards their objective.

The introductory contextual material asked the players to decide, at the beginning of the serial and after each card, the following:

- a. the dress state to be adopted—one of:
 - i. DS1 (equipment carried but not worn);
 - ii. DS2 (suit worn);
 - iii. DSR (use of the respirator); and
- b. whether or not to continue advancing on the route.

As before, the heart of the experiment was the information presented on the cards, which were similar in format to those for the first trial; however, for these risk-taking experiments, the number of card types was increased to eight, with the specific inclusion of a *time has passed* card that was intended to investigate how quickly players returned to normal after an incident. All versions of this card simply gave the information that a certain time had passed. This avoided any possible alternative interpretation of the information.

Players were given only a general idea of the total amount of time available—they had no information on the number of cards in a serial or the total number of serials to be completed, only that it was reasonable to assume that a day would be sufficient to complete the available serials. Because the rate of

advance during each serial was restricted by the NBC dress state, yet no additional time was available, pressure was put on those trying to complete the routes, enforcing the need to balance risk to personnel against risk to the mission.

Two types of map were provided, a high-level map showing the theatre of operations, which was retained by the players throughout the exercise, and a number of smaller maps showing the route to be taken for each serial. Both types of map were deliberately abstract in order to minimise the amount of uncontrolled information given to the players, whilst remaining sufficiently realistic to ensure that the players retained a sense of context and treated the situation seriously. Players were required to measure distances on the maps for themselves.

The player pairs (18 in total) were allocated to the serials using a Graeco-Latin Square design, which permuted routes with serials. Pairs were allocated lines in the Graeco-Latin Square at random without replacement. Once all lines had been allocated, all lines were replaced and the procedure repeated. Serials were generated in a similar manner to the first set of experiments, again in order to avoid narrowing of the potential choices by the players through overt scripting of the scenario as it unfolded.

In this wider command environment, players did not require specialist NBC expertise. To produce a sample set representative of UK ground forces, with a wide variety of levels of NBC knowledge, training, and background, one pair was drawn from Dstl military personnel; this pair was used in a validation and method development pilot experiment. The remainder included pairs from the Joint NBC Regiment, Royal Marines, Royal Armoured Corps, Royal Artillery, Royal

Engineers, Infantry, Royal Logistic Corps, Royal Electrical and Mechanical Engineers, and Royal Air Force Regiment. A large proportion of players had recent operational experience in Northern Ireland, Iraq, or the Former Yugoslavia. Players ranged in rank from Sergeant to Lieutenant Colonel, although care was taken to ensure that each pair contained at least one officer.

Game Results

The second set of games generated much more data than the first, with almost 1800 data points being produced. This allowed for some more sophisticated treatment of the data. Early investigation seemed problematic however, with attempts to fit a model similar to that from the previous single decision game failing to produce consistent results. The key was to appreciate that, not entirely surprisingly, having moved to a non-monotonic problem, a cumulative model was not appropriate.

We then developed a model of behaviour that took account of both the previous dress state and the information category (i.e., the type) of the last card presented. A very important difference between this model and that in the previous study is that it did not consider any cumulative effects, with the *memory* of the situation being entirely incorporated in the effect due to the previous dress state.

Our statistical model of the process is also based on a probit analysis, as follows:

Firstly we define the different dress states as

- $j = 0$ corresponds to DS1;

- $j = 1$ corresponds to DS2; and
- $j = 2$ corresponds to DSR.

We then define the probability of being in at least dress state j

$$P(Y \geq j) = 1 - \Phi(y_{j-1})$$

where

$$y_{j-1} = \alpha_{j-1} + \beta_{prevDS}(prevDS) + \beta_{typeoflastcard}(lastcardtype)$$

The variables of interest are thus the previous dress state (*prevDS*) and the information category of the last card played (*lastcardtype*).

We now can calculate, as in the single decision game model, the following *decision probabilities*;

$$P(Y \geq 2) = P(DSR) = 1 - \Phi(\alpha_1 + \sum \beta_i x_i)$$

$$P(Y \geq 1) - P(Y \geq 2) = P(DS2) = \Phi(\alpha_1 + \sum \beta_i x_i) - \Phi(\alpha_0 + \sum \beta_i x_i)$$

$$P(Y < 1) = P(DS1) = \Phi(\alpha_0 + \sum \beta_i x_i)$$

In this case, the variables x_i are categorical variables (the last dress state or the type of the last card played). Probit analysis makes no assumptions about the underlying distribution of such variables, and thus handles categorical variables easily. An important point is that much of the cumulative information on a rising level of alarm is being represented in the statistical model by the allowance for the previous dress state, which makes a significant difference to the probability of response.

This model effectively has no memory of the past cards shown to it, other than through the previous dress state, which will be the cumulative result of the previous cards presented. Representing this effect requires a more sophisticated model of human behaviour than was used for the previous study. To compare the predictions of the model with the sequences of responses in the individual serials requires a continually updating set of estimates of the probabilities of being in the various dress states.

In order to capture the effect of the previous dress state on the behaviour of the players, the observed behaviour was compared with a simple Markov chain, with three states, corresponding to the three dress states, and transition probabilities calculated from the statistical analysis. The model is illustrated in figure 4.12.

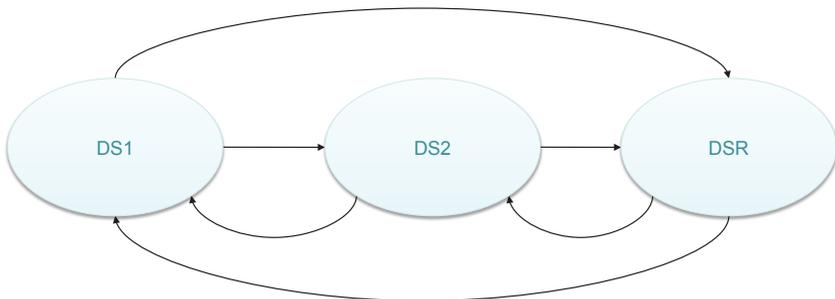


Figure 4.12: The Markov model for transition between the dress states.

The transition probabilities illustrated in figure 4.12 are calculated in the following way:

$$P(DS1_{k+1}) = P(DS1_k).P(DS1_{k+1} | DS1_k) + P(DS2_k).P(DS1_{k+1} | DS2_k) + P(DSR_k).P(DS1_{k+1} | DSR_k)$$

$$P(DS2_{k+1}) = P(DS1_k).P(DS2_{k+1} | DS1_k) + P(DS2_k).P(DS2_{k+1} | DS2_k) + P(DSR_k).P(DS2_{k+1} | DSR_k)$$

$$P(DSR_{k+1}) = P(DS1_k).P(DSR_{k+1} | DS1_k) + P(DS2_k).P(DSR_{k+1} | DS2_k) + P(DSR_k).P(DSR_{k+1} | DSR_k)$$

The conditional probabilities involved are calculated from our earlier decision probabilities, given that we also know the information category of the last card presented to the players.

The model is thus fully described in the equations above, which show the probabilities of being in a given dress state after presentation of the k -th card. The Markov element of the model updates the probabilities of being in the three individual dress states.

To estimate the performance of the model, the Markov model is initialised for timestep $k = 1$ with the initial model proportions set equal to the initial proportions derived from the complete set of games. The probabilities are then updated as each card is presented.

Figure 4.13 shows the results of estimating the probability of being in DSR using the Markov model described above, with the transition probabilities for the model being calculated as we have described. These are compared with the game results across the population of players.

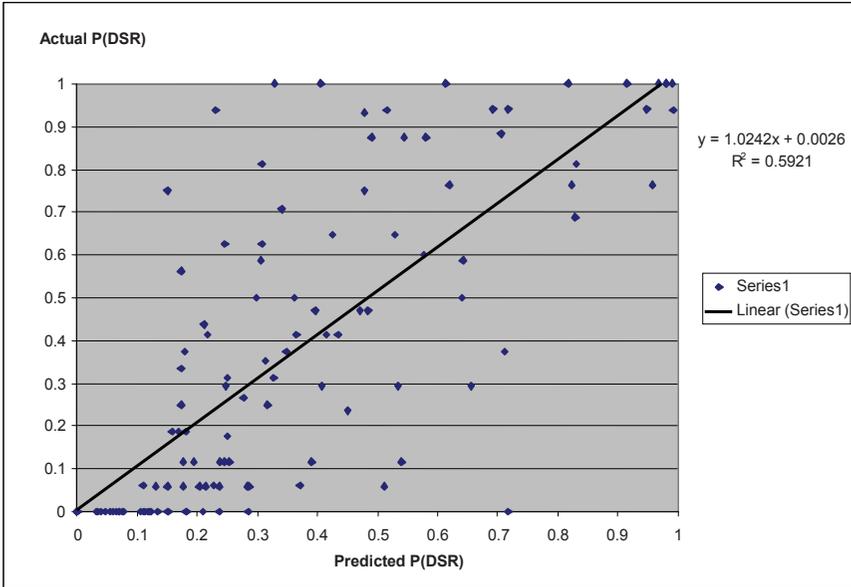


Figure 4.13: Performance of the Markov model for the multiple decision games.

The performance of the model is encouraging, particularly since this is not a direct comparison of the statistical model against its data set, but required the added assumption of a Markov process. The Markov model provides a consistency test, showing how the conditional probabilities calculated from the statistical model perform when iterated through the sequence of cards from the actual serials. If there were significant differences between cards of the same information category we would expect to see scatter, and the more significant the differences the more scatter there would be. The model shown above has quite a lot of scatter in the top left hand quadrant, with higher actual probabilities than predicted probabilities. This tends to indicate that the categories of cards conceal further

hidden detail. Having said that, the model still explains 59% of the variability in $P(\text{DSR})$ and somewhat more of the variability in $P(\text{DS1})$.

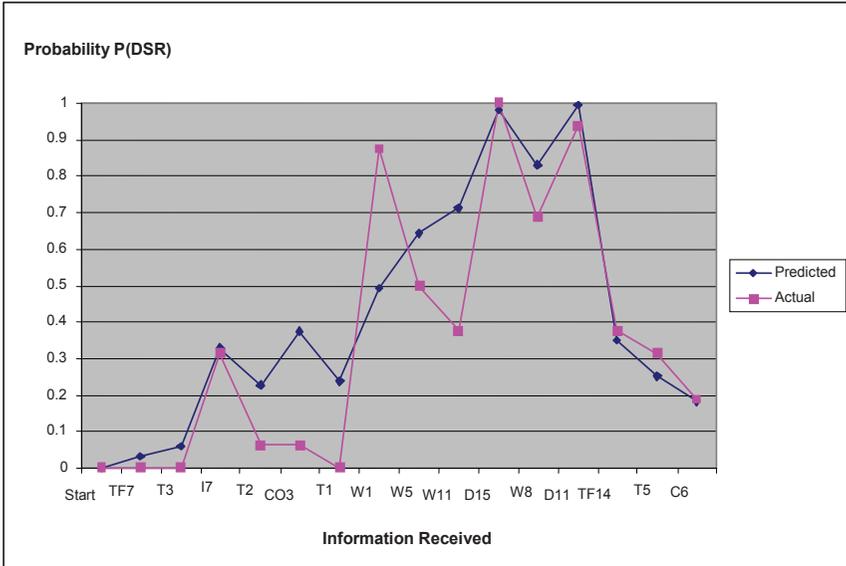


Figure 4.14: Performance of the Markov model against serial 1 for dress state DSR.

The performance of our Markov model over an individual serial can be seen in figure 4.14, which shows the predicted and actual probabilities for serial 1. Again the x -axis here shows the actual information cards played over the serial. The y -axis shows the probability of being in dress state DSR, based on the actual game results (all players for this serial) compared with the Markov model predictions. This shows a good match for the data, not only predicting the general rise in the proportion of the population in DSR but also showing the timing and the extent of the fall in this proportion towards the end of the serial.

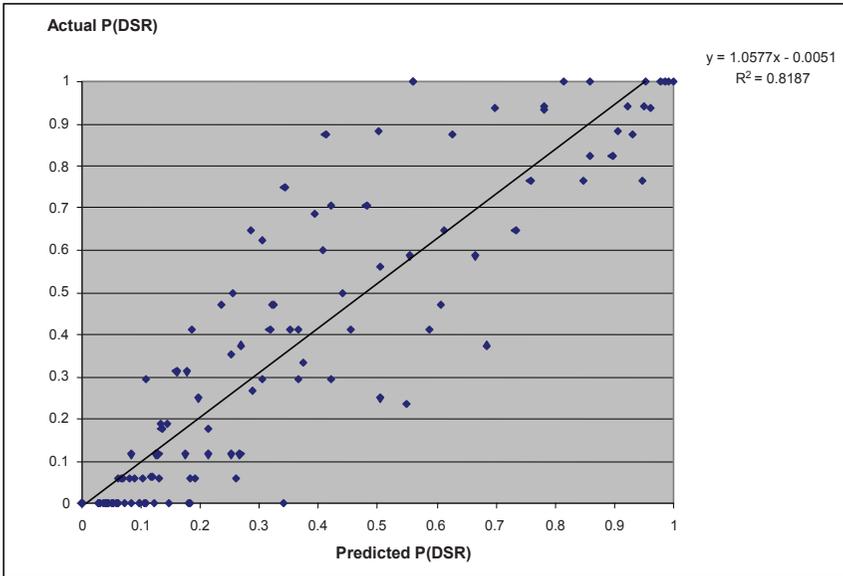


Figure 4.15: Performance of the Markov model with more refined information categories.

This performance can be improved by recognising that some of the information categories can be further divided. The more refined Markov model is shown in figure 4.15. Comparing the proportion of players in the state DSR from the games, with the proportion predicted from the Markov model, we see that the model now accounts for 82% of the variability in the data.

Additional Validation of the Markov Model

An additional validation check on our models of behaviour can be made by comparing the model generated from a part of the data with the behaviour of the remaining portion of the data. We used the more refined division of information categories to do this. The first attempt to split the serials was based upon the

first four serials, but produced a model that did not converge. The second attempt used the last four serials. This model was then applied to the first four serials to test whether the model could predict behaviour that was not part of the dataset used to generate it.

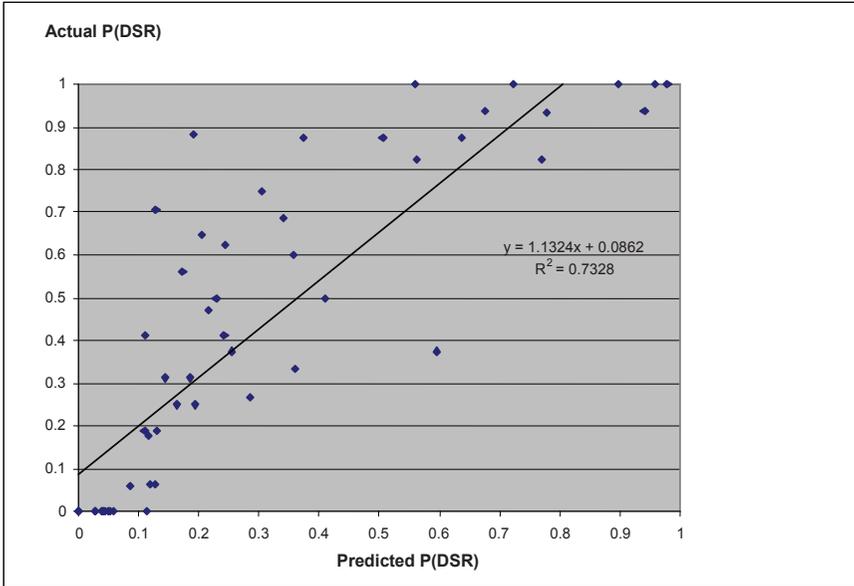


Figure 4.16: Result of validation test: serials 1-4 using model calculated from serials 5-8.

The results are shown in figure 4.16, which shows the fit for the first four serials. The model still explains 73% of the variability, down from 82% with the fully fitted model (figure 4.15). Changes in significant regression parameters are by less than 10%. Clearly, the effect of the cards of a given information category is remarkably consistent, though the level of the intercept and the values for the nonsignificant cards vary somewhat. There is also a consistent bias in the results, shown by the line

in figure 4.16 not passing through the origin. Normally the tests using regression lines against the whole data set naturally pass through or close to the origin. Here, the intercept is a little high, probably due to the effect of the serial-serial variation.

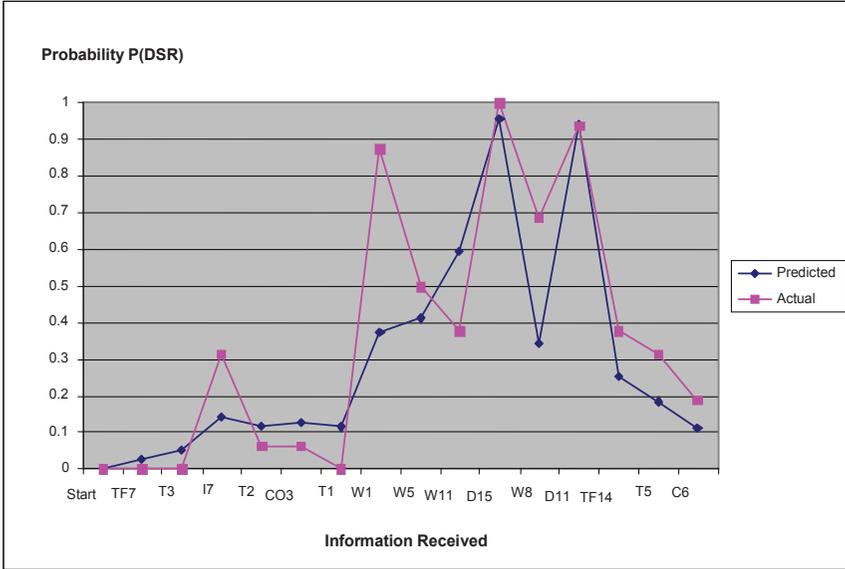


Figure 4.17: The refined form of the Markov model fitted to serials 5-8, applied to serial 1.

Figure 4.17 shows the effect on an individual serial (serial 1), for comparison with figure 4.14. The values in figure 4.14 are based on the whole data set, while those in figure 4.17 only use the data in serials 5 to 8. The fit remains good and this indicates that the information categories and weightings of the cards are not just statistical conveniences, but actually represent some property of the card that has a degree of stability between individual instances. What this value or property might be will be discussed next.

Relevance to Decision Modelling

An important outcome of the statistical analysis is the clear linkage between the information presented to the players, and the decisions they took. Moreover, these decision games appear to allow the statistical modelling of decision-making, albeit within the context of the games, to a surprisingly large degree. This raises the question of what lessons this may hold for the modelling of command decision-making in more general contexts. In particular this section will address the question of whether or not the kind of decision-making behaviour described here, as well as the statistical models used to describe it, are compatible with the models of decision-making which are incorporated in the extended form of the rapid planning process.

Nature of Decision-Making

The single most important lesson to be drawn from the results of the games would seem to be that models of decision-making can be simple, even if the decisions themselves and the inputs to them are subjectively very complex.

The simplicity of the cards and the very stark nature of the decision to be taken should not be taken as indicating that the decision-making process itself was simple. The players would often spend long periods discussing the pros and cons of a particular course of action and trying to deduce from the information provided the nature of the true situation. The fact that there was no preferred solution was not apparent to the players, who devoted considerable effort and ingenuity to the decision-making process. Because each card had different descriptive information, many subjective factors above and beyond the type of the card were considered in making the decisions.

Experts and nonexperts alike seemed to be able to take quite long periods discussing what action to take; the experts could think of more possibilities whilst the nonexperts were less certain as to what to do and took longer to think through the problem. Despite this, the decision-making behaviour resolved to a comparatively simple model. This is very reassuring from the point of view of decision modelling—in principle, decision modelling might be highly complex. From the evidence here, it would seem that simpler models have much of the *requisite variety* to represent human decision-making behaviour to an acceptable level of approximation.

If the models are simple, then it is probably also important that they are probabilistic. The games do not produce a rule-based model of decision-making; different players did not display any great consistency in their behaviour, even where formal and explicit decision rules exist in the doctrine—such as the *immediate action drill*. The use of a probit model for decision-making explicitly recognises that human decision-making is probabilistic and that out of any population there will be somebody who does not “do the obvious thing” no matter how convincing the evidence that a particular decision may be the correct one. (This human characteristic was also exhibited in the games described at [17]). Individual pieces of evidence, no matter how seemingly unambiguous, in fact have a semantic and psychological context, and this will influence behaviour in ways that may be beyond the scope of any decision model. The evidence here, however, is that such effects do not dominate the decision process.

The particular commander of a particular unit may have a tendency to be at one end of the decision spectrum or the other, and the games were able to show how such individual

tendencies were distributed; but, the exact subjective detail of the situation and the circumstances may put the remaining 20-40% of variability unexplained by these models beyond the grasp of prediction, particularly at the level of modelling detail consistent with the constructive simulation models of conflict we discuss in chapters 5, 6, and 7. Because of this, decision models should be statistical and probabilistic in nature. The critical question is not what a commander will do in a situation but what they are *likely* to do.

In the games, certain rules of thumb became apparent from the players' behaviour, but these rules were not followed in all circumstances; they were fuzzy rules, subject to override based on local conditions, personal preference and different perceptions of the situation. Had the behaviour been more strongly rule-oriented, the initial attempts to analyse the data using analysis of variance (ANOVA) based approaches would have proved more productive. This is because an ANOVA-based approach is in many ways a statistical analogue of a rule-based approach, considering the effect of different combinations of circumstances on the likelihood of behaviour. The use of ANOVA in the modelling was restricted to ruling out complex interaction effects and only when the statistical modelling moved to the probit analysis did it achieve significant levels of confidence. This experience is similar to that observed when using probit analysis to link the selection of pilots for fast-jet training to their probability of success in flight training [20].

Models of Decision-Making

Aside from these two fundamental questions as to the nature of a sufficient and appropriate model of decision-making, the experimental games can shed some light on the representation

of expert decision-making both in terms of its psychological underpinning and in terms of its mathematical form. This applies particularly to military commanders working under fast moving and stressful circumstances (typically at the tactical level of command), which I introduced in chapter 2 as rapid planning.

The algorithms representing rapid planning are based upon the recognition primed decision-making (RPDM) model of Klein [21, 22], which views decision-making under pressure as being a process closer to that of recognition than to that of a rational analysis of alternatives. The decision-maker, under this view, has a number of potential courses of action, each of which will be appropriate in one or another type of situation. When making the decision, the decision-maker compares his current situation, or more properly his perception of that situation, with his library of possible, archetypical, situations and selects the one which seems the closest match to his current problem. The advantage of this method is that it can be very fast and can combine both conscious and unconscious perception.

This psychological model of decision-making is entirely compatible with the decision games. In many ways, the problem placed in front of the players was one of making a pattern out of the information with which they were provided. The stability of the effects of cards and the effectiveness of the simple statistical models used implies that the decision-making was at least 60-80% in accordance with the RPDM model.

If the psychological model seems appropriate to the kind of results obtained from the games, then the next question is whether or not the specific mathematical form of the rapid planner is compatible with the kind of behaviour observed.

The rapid planner works by comparing a number of different decision options to an estimate of the current situation, consisting not only of an estimate of the value of different parameters of the situation, but also an associated set of estimated uncertainties. The model compares the probabilities that the true situation is that which is associated with each of the decision options and chooses amongst them.

In terms of a decision process, we can thus illustrate this as shown in figure 4.18 for the single decision games, where the value 0.5 is illustrative, and where there are only two information types.

We define two regions in figure 4.18. The first (Region A) corresponds to the set of values $\{x_1, x_2\}$ (i.e., the number of cards of each of the two information types which have already been shown to the commander), and for which the probability $1 - \Phi(\alpha_0 + \beta_1 x_1 + \beta_2 x_2)$ is ≥ 0.5 . This corresponds to the region of the decision space within which the commander would choose the course of action: *issue precautionary alert or higher*. The second region (Region B) is the subset of Region A corresponding to the set of values $\{x_1, x_2\}$ for which the probability $1 - \Phi(\alpha_1 + \beta_1 x_1 + \beta_2 x_2)$ is ≥ 0.5 . This corresponds to the region within which the commander would choose the course of action: *issue probable attack warning*.

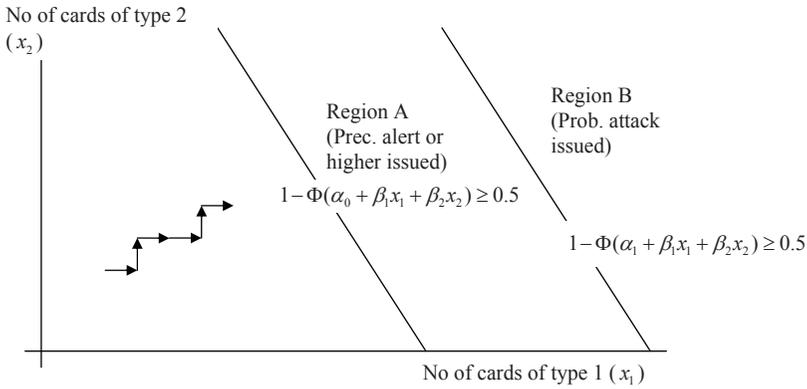


Figure 4.18: How the changing values of the cues (the numbers of cards of each information type) affect the decision taken.

The cues of the decision process are thus the different information categories in this case, and they are weighted by the constants β_i . The regions corresponding to the different decisions are represented probabilistically, corresponding to fuzzy membership functions (as in the rapid planning process itself [10]).

Analysis of the multiple decision games (which allowed movement between the three states DS1, DS2, and DSR) shows that the commanders' decisions can be captured in a similar way, and in fact form a simple Markov process, which is also to be expected from rapid planning considerations [10].

In each case, then, the statistical model which explains the commanders' decision-making process is the rapid planning process (to an acceptable level of approximation), and is thus a relatively simple probabilistic model, rather than one based on complex, embedded and deterministic decision rules.

Measuring Information

The interpretation of the dimensions of the decision space is an interesting question. In the usual formulation of the rapid planner, the axes of the decision space are real world variables about whose value the decision-maker is uncertain. Here, there is no obvious equivalent to that process. Rather than estimating a value, players are proceeding directly to their decisions.

Treating the numbers of cards of different information categories as the axes of the decision space leaves open the question of what the cards are representing. In particular, the relative values of the information categories (i.e., the regression weights) are remarkably stable when the analysis is varied slightly or if only partial data sets are selected. This seems to indicate that the weights given to the different information categories are representative of some kind of quantity, rather than merely being a statistical convenience. The validation exercise also seems to indicate that the weights assigned to the cards have some real meaning.

There is further evidence from these experiments that there is a Bayesian element to the decision-making process—the initial intercepts (α_0 and α_1) look remarkably like Bayesian prior beliefs—the belief that an action is appropriate, even if no information has yet been received.

Bayes' Theorem tells us that we can update probabilities given a prior $P(A)$:

$$P(A | B) = P(A) \frac{P(B | A)}{P(B)}$$

This can be translated into an additive form using logarithms thus

$$\log P(A | B) = \log P(A) + \log \frac{P(B | A)}{P(B)}$$

There is an alternative formulation of the statistical model that allows this kind of Bayesian updating [23]. The linear logistic model is based upon the *logistic transform*, defined as

$$\theta = P(Y = 1 | x) = \exp(\alpha + \beta x) / (1 + \exp(\alpha + \beta x))$$

where θ is the probability of an event given a determining variable x , and $1 - \theta$ is the probability of the event not taking place. This allows a linear regression similar to the probit model, but instead of using the cumulative normal Φ we use the log of the *odds ratio*:

$$P(\theta = 1) = \frac{e^{\alpha + \beta x}}{1 + e^{\alpha + \beta x}}$$

$$\begin{aligned} P(\theta = 0) &= 1 - P(\theta = 1) = 1 - \frac{e^{\alpha + \beta x}}{1 + e^{\alpha + \beta x}} \\ &= \frac{1}{1 + e^{\alpha + \beta x}} \end{aligned}$$

$$\text{Hence odds ratio} = \left\{ \frac{P(\theta = 1)}{P(\theta = 0)} \right\} = e^{\alpha + \beta x}$$

$$\text{and } \log(\text{odds ratio}) = \alpha + \beta x$$

This gives us regression outputs in terms of the odds ratio, and means that a change in either the input variable x , or a change in the weighting β can be interpreted in terms of a shift in the odds ratio. More generally, x is vector of variables, with a corresponding vector of weights β , so that $\beta x = \sum_i \beta_i x_i$.

The logistic transform $L(y) = \frac{e^y}{1+e^y}$ is also very close numerically to the cumulative normal distribution $\Phi(y)$, once a scaling factor has been applied. Table 4.1 is taken from reference [23] and shows the agreement out to the 99.9% point on the normal distribution. Here the scaling factor has been chosen so that the curves agree at the 80% point.

y	Logistic $L(y)$	Normal $\Phi(y)$
0	0.500	0.500
0.5	0.622	0.619
1.0	0.731	0.728
1.5	0.818	0.818
2.0	0.881	0.887
2.5	0.924	0.935
3.0	0.953	0.965
3.5	0.971	0.983
4.0	0.982	0.992
4.5	0.989	0.997
5.0	0.993	0.999

Table 4.1: Logistic transform and cumulative normal distributions compared.

The agreement is clearly close until we reach the 95% point on the two distributions, where the curves start to diverge and become increasingly sensitive to the choice of distribution. An alternative formulation of our decision model is thus possible in terms of likelihood ratios and odds ratios.

We consider $O(A | B)$, the odds ratio of A given evidence B , and $\Delta(B | A)$, the likelihood ratio of B given hypothesis A , defined as follows:

$$O(A | B) = \frac{P(A | B)}{P(-A | B)}$$

$$\Delta(B | A) = \frac{P(B | A)}{P(B | -A)}$$

From Bayes' Theorem we have

$$\frac{P(A | B)}{P(-A | B)} = \frac{P(B | A)}{P(B | -A)} \frac{P(A)}{P(-A)}$$

and hence

$$O(A | B) = \Delta(B | A) O(A)$$

Note that this odds ratio formulation is independent of $P(B)$.

This formulation would, by taking logs, give us a quantity of the kind that we are looking for:

$$\log O(A | B) = \log \Delta(B | A) + \log O(A).$$

It is also independent of the number of alternative hypotheses B , which is important when dealing with complex, multiple decision-making.

Thus, if we can describe the data using a logistic model L rather than a probit model Φ , we can potentially produce a model equivalent to our probit model, with the value of a piece of new information being expressed as a likelihood ratio which updates the odds ratio.

The logistic model for the multiple decision games is similar to the model used before for the probit analysis and can be similarly stated, as follows:

$$P(Y \geq j) = 1 - L(y_{j-1})$$

where

$$y_{j-1} = \alpha_{j-1} + \beta_{prevDS}(prevDS) + \beta_{typeoflastcard}(lastcardtype)$$

with $x = \{x_1, x_2\}$ where $x_1 = prevDS$ (the previous dress state)

and $x_2 = lastcardtype$ (the type of the last card played).

Thus, as with the probit model, we can define the following *decision probabilities*:

$$P(DSR) = 1 - L(\alpha_1 + \sum \beta_i x_i)$$

$$P(DS2) = L(\alpha_1 + \sum \beta_i x_i) - L(\alpha_0 + \sum \beta_i x_i)$$

$$P(DS1) = L(\alpha_0 + \sum \beta_i x_i)$$

Here, L is the logistic transform $L(y) = \frac{e^y}{1 + e^y}$.

Figure 4.19 shows the result of applying a logistic model to the results of the second set of games (with multiple decisions). This should be compared with figure 4.13. In statistical terms, it uses an ordinal logistic regression with a logistic transform link rather than a probit (cumulative normal) link. The model is the simplest of the information category models, with none of the categories being divided further. The amount of the variance explained by the two models is identical (0.59). Note that in principle there is no reason why the model would not improve with additional refinement of the information categories.

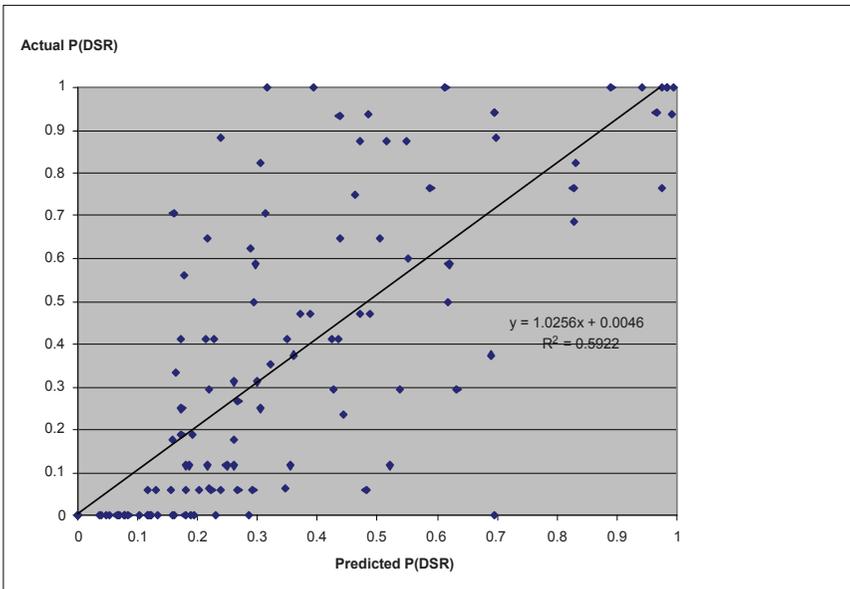


Figure 4.19: Markov model for the multiple decision games using a logistic statistical model fit.

Clearly the agreement between the two models is very good, as could be anticipated—the differences between the two models are mainly significant at the outer ends of the probability distribution, when we are dealing with rare events.

By using a logistic transformation, we have not lost accuracy in estimating likely future behaviour, but now have a potentially more intuitive interpretation of the weightings of the information categories in terms of how they change the odds ratio for a decision.

In Summary

- From the statistical analysis of the two types of game (single decision and multiple decision) it is clear that information is a more significant driver of the commanders' decision-making process than the variation across players (which could be taken as a surrogate measure of commander personality).
- This decision-making can best be described by models which are probabilistic in nature rather than models which are deterministic and rule-based.
- The statistical models which provide a best fit to the command decision-making investigated here are entirely compatible with the rapid planning process, and provide further support for rapid planning.

- It is possible to use such card-based decision games to assess the weightings which the commanders place on the different categories of information they use in their decision-making, as incorporated into the extended form of the rapid planning model.
- A statistical model based on the logistic transform rather than the probit transform can provide additional insight into the value of these weightings in terms of how they change the odds ratio related to a decision.

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CHAPTER 5

MODELLING FOR THE INFORMATION AGE: THE CORE SIMULATION MODEL SET

I have already introduced, in chapter 2, a key idea concerning our approach to developing simulation models for operational analysis, namely the idea of a hierarchy of models. Defence problem domains tend to be either at the larger capability, or *system of systems* level, or at the contributing *systems* level. Examples of these are the complete complex of elements of a land/air force (system of systems level) or an individual army company (system level). Where we pitch these terms depends on our level of resolution (one person's system could be another person's system of systems at a finer level of resolution). However, in terms of the defence acquisition process, this is a useful way of thinking about the problem space.

At the system of systems level, we are considering trade-offs between major elements of defence capability across the defence budget or comparing significantly different ways of filling a capability gap. Once a particular way forward has been

decided at the capability level, different more resolved system level solutions can be compared against each other. An example at the system of systems level is trading off investment in anti-armour systems (for example longer range indirect systems or shorter range front line systems). This was the essence of the “Anti-Armour Study” which has significantly affected the UK army’s resulting force structure. As an example of a capability gap assessment, consider the procurement of the airborne standoff radar (ASTOR) system, with an advanced long range radar for detecting ground targets. Initial studies considered the trade-off between providing more information to the force, or at an equal level of investment, providing more “teeth arms” (e.g., more tank companies). Only when that question had been resolved in favour of additional information, did the analysis move down to the systems level, in considering various ways of delivering the information.

At the system of systems level, we typically place these future technologies and ways of working (our evolving doctrine and ways of employing our forces) into a range of future conflict scenarios so as to measure their relative contribution to the effectiveness of the force. In this way, for a constant level of investment, we can weigh in the balance a number of possibly quite disparate defence capabilities. At the systems level, our measures of effectiveness will tend to be more focussed (in the case of ASTOR we would be assessing the ability to deliver the required information in a timely way for example).

Broadly then, modelling at the system of systems level sets the capability context within which modelling at the systems level is carried out. We thus require models to support these two levels, with the systems level models supporting the modelling at

the system of systems level. Figure 5.1 (introduced in chapter 2) shows the core simulation model set which we have developed to carry out this analysis.

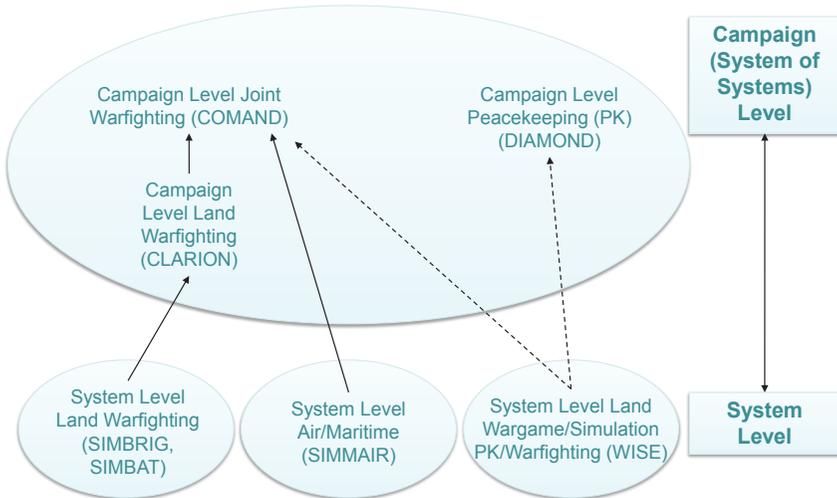


Figure 5.1: The core simulation model tool set.

These models are under constant development and some are more mature than others. However, they all share two key attributes:

- Their organising principle is the representation of command—a human centred activity key to capturing the effects of the information age, information networking, and network enabled capability.

- Their representation of command is *mission-based*. This means that the set of decision options for a commander is the choice of a plan (which is in essence a string of missions) or the choice of an individual mission chosen from a small discrete set (much more of this later).

Both of these have a fundamental effect on widening the range of studies which we can conduct. Operational analysis played a significant part in the Cold War between NATO and the Warsaw Pact. The simulation models we developed in the UK, to provide advice in this context, were organised around the principle of attrition of enemy forces where the goal was to draw down the invading force and give some space for the political process to operate.

After the fall of the Berlin wall in 1989, we transitioned from this industrial age of grinding attrition warfare to the information age, where information, understanding, decision-making, and non-attrition effects are all of great importance. Our simulation model set clearly has had to respond to this phase change in political circumstances, so that we can continue to provide advice that is both relevant and timely. As a result, over the past 10 years, we have constructed and continue to iteratively develop the core set of simulation models shown in figure 5.1, together with other supporting models.

This represents a significant monetary and intellectual investment by the UK Ministry of Defence, supported, as it is, by one of the largest operational research groups in Europe, within Dstl. The approach taken has been coherent across the piece, being command focussed, and with a *mission-based approach* to command [1, 2].

As also introduced in chapter 2, the mission-based approach to command is based on the ideas of deliberate planning and rapid planning. Deliberate planning considers the whole campaign context and corresponds to the allocation of groups of forces to various operational areas. This high level planning is complemented by lower level planning at the individual unit level, which we call rapid planning.

Rapid Planning

Research both in the USA and UK, some of which I discussed in chapter 4, indicates that rapid planning is carried out using a form of pattern matching referred to as recognition primed decision making (RPDM) [2]. In order to capture the essence of the RPDM approach, the rapid planning process thus uses pattern matching, where the patterns are directly linked to possible courses of action. This is achieved by exploiting the mathematical properties of the dynamic linear model [2]. Clearly, in developing such models, we also have to be aware of how to handle situations which are unfamiliar (hence there is no pattern to match) or where an opponent is deliberately putting forward a false pattern in order to deceive. Thus rapid planning in isolation is not enough.

Corresponding to the spirit of mission command, it is assumed that there is a small set of alternative missions defined. These missions are applicable to any level of command, so that the process is recursive (or *fractal*). Thus the rapid planning problem is the same at every command level; namely whether to move from one of these missions to another, at any given point in time. The perceived pattern of events is thus tied to

one of these small number of alternative missions. In chapter 4, I discussed in detail some of the evidence supporting this psychological model in the context of military command.

Deliberate Planning

Complementing rapid planning, we consider also the course of action, or in other words a campaign plan, available to the high level commander, which is assumed to correspond to a set of operational areas linked to key military objectives. These represent broad areas of activity. For each choice of an allocation of force to these operational areas, a *fitness function* is defined which measures the value of this allocation in military terms (such as the ability to break through and achieve campaign success). A commander may misallocate forces if his perception of the battlespace is poor, leading to a poor plan. Genetic algorithms are used to breed a number of plans, and select out those with good levels of fitness from which a plan is chosen. The algorithms required to implement these levels of planning are described in detail in [2], together with the psychological context of the human behaviours relevant to such decision-making.

I now want to illustrate the development of our core model set shown in figure 5.1 by discussing in depth those at the system of systems level. The three simulation models which are used to support analysis at this level are CLARION, COMAND, and DIAMOND. They are all closed form constructive simulation models.¹ Historically the first of these to be built was CLARION, which entered initial use following, as we do for all

1. A synthetic environment consists of real and simulated people interacting with simulated environments. A closed form, constructive simulation consists of simulated people (i.e., computer algorithms) interacting with simulated environments, with no human intervention during the model run.

models, an extensive series of validation tests [3]. In chapter 6, I will discuss in detail how some of these validation activities are carried out.

CLARION

CLARION sits at the system of systems level, and is the main model used within Dstl for analysis of land/air force structure trade-offs across the equipment budget. The core of CLARION—which puts it into the information age class of models, is its representation of command decision-making, and how this decision-making is affected by the networking of information across commanders. At the level of campaign planning, this affects which plan (consisting of a string of missions) to pursue. At the individual mission level it affects the perception of the local commander and how/whether they should continue with that mission.

In terms of the mission-based approach to command, the CLARION mission types are Secure, Defend, Fix, Search, MoveTo, Support, and Reserve. Not all of the mission types are valid for all commanders. Examples of the valid mission types for each commander are shown in table 5.1.

Commander Type	Valid Mission Types
Land Commander	Secure, Defend, Fix, Reserve
Deep Fire Commander	Secure, Fix, Reserve
Rear Security Commander	Defend, Reserve
Helicopter Commander	Defend, Secure, Fix, Reserve
Close Combat	Secure, Mobile_Defend, Static_Defend, Fix, MoveTo, Reserve
Reconnaissance	Search, MoveTo, Reserve
Artillery Units	Support, MoveTo, Secure, Reserve

Table 5.1: Examples of valid mission types for various commanders represented in the CLARION model.

We can see from table 5.1 how we can use these missions recursively—they apply at multiple command levels within the model. At the tactical level, a close combat commander has to decide which mission he or she should choose, drawn from the small set shown in table 5.1. Higher level plans are represented by strings of such missions, in essence. The commander has to choose between alternative *plans* at this higher level.

Figure 5.2 shows the top level command hierarchy which can be represented in CLARION.

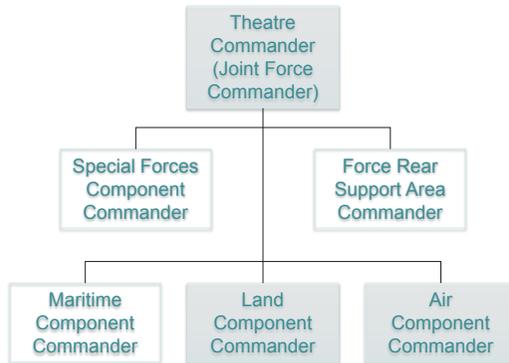


Figure 5.2: Top level command hierarchy represented in CLARION.

Lower down the command hierarchy, figure 5.3 shows the sort of command structure which can be represented for the land commander.

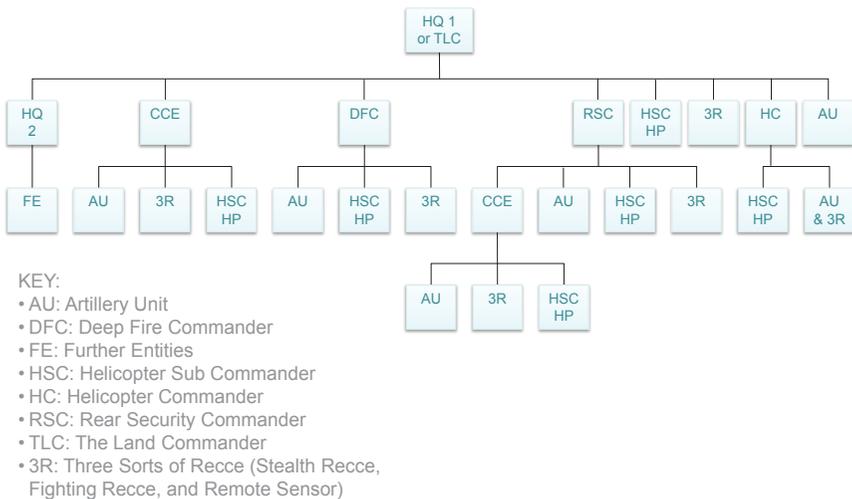


Figure 5.3: An example of the command structure in CLARION below the land commander.

At the higher level, an overall campaign plan corresponds to sets of consecutive missions. If we had only one string of consecutive missions for our campaign plan, this would be what we term *fully scripted* behaviour. Clearly, this does not capture the benefits of information gathering (from sensors), the sharing of information via information networks, or the ability to adapt the overall plan to a change in circumstances, all of which correspond to different command approaches. Thus we represent the higher level command decision-making process (the overall campaign plan) as a choice between alternative plans. Each plan then requires a set of criteria to define when it should be chosen. This could be in terms of information about a significant event in the conflict (such as the enemy securing a key piece of terrain and successfully implementing *their* plan) or could be defined by the success or failure of our own current plan, or may be defined by a specific time in the simulation.

Each such plan consists of a set of missions. These can have branches, as shown in figure 5.4, with the decision at the branch point dependant on the outcome of the mission at that branch point, or possibly due to some other time dependent event within the simulation. Plans themselves can also be chained together, as we have described, the successful end of one plan triggering the start of another, or the failure of a plan triggering another.

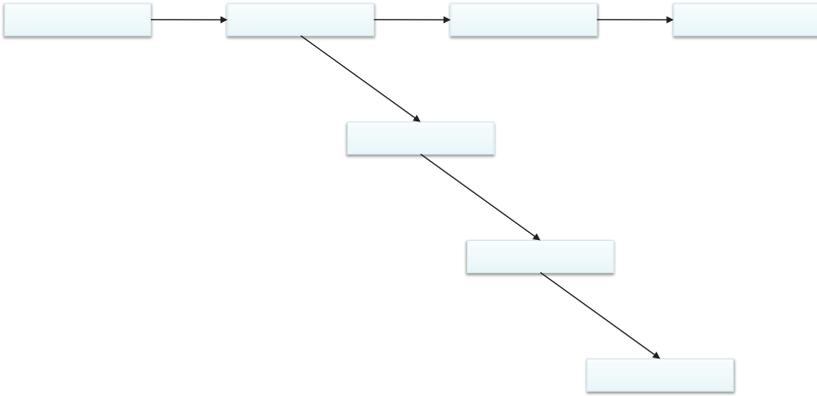


Figure 5.4: An example of a set of missions with a branch point, constituting a plan.

The particular path which results from this set of alternative plans and missions thus adapts as the simulation unfolds, depending on the success or failure of these plans and missions and the occurrence of other events in the simulation. This all becomes quite complex to set up and test, although it does begin to capture the ability of the friendly blue or opposing red side in the campaign to adapt dynamically to changes in information shared, sensor information delivered and other events occurring as the simulation unfolds.

As a further development of this approach, we are moving towards a more loosely coupled algorithmic implementation of planning, exploiting again the ideas of deliberate and rapid planning. As we have already described, deliberate planning allocates a group of force units to an operational area. Rapid planning allows a unit to choose a particular mission, and allows this mission choice to adapt and change over time. Between these two, we are currently developing a mission planning algorithm (as indicated in figure 5.5) which will co-ordinate the

missions of the individual units within an operational area. The model itself will then be able to, in essence, create these plan branches and missions dynamically as the simulation unfolds. This will be a significant step towards capturing the effect of self-synchronisation of these units in our simulation models.



Figure 5.5: Dynamic plan generation in CLARION (under development at the time of writing).

In any given piece of analysis, a choice has to be made between constraining these decision-making choices in the model in order to show clear linkage between cause and effect, (more effective weapons leading to an improved battle outcome for example) and allowing these choices free and full scope to adapt dynamically with evolving circumstances as the simulation proceeds (when, for example, more effective weapons on one side, might lead to an adaptation of their plan by the other side which negates this advantage, thus *not* leading to improved battle outcome). This is the essence of the transition

from *complicated models* rooted in the industrial age, to *complex models* looking towards the information age and the complex endeavours of the future, as I discussed initially in chapter 2. Our current model set is thus a waymark on the journey from the industrial age and *complicated models*, towards the *complex and adaptive* models required for the information age and 21st Century future contingences, such as the complex endeavours described in chapter 2 and reference [4].

COMAND

The COMAND model is the key component of Dstl studies looking at joint balance of capability across all environments (air, land, and maritime, and including command aspects) across the defence budget, and at the campaign, or system of systems level.

The COMAND model also uses the mission-based approach as its core representation of command, decision-making, and the influence of information networking. Of course, the list of missions in COMAND is different from the list for CLARION, and includes a range of air and maritime missions. Figure 5.6 shows a typical command structure which can be represented in COMAND.

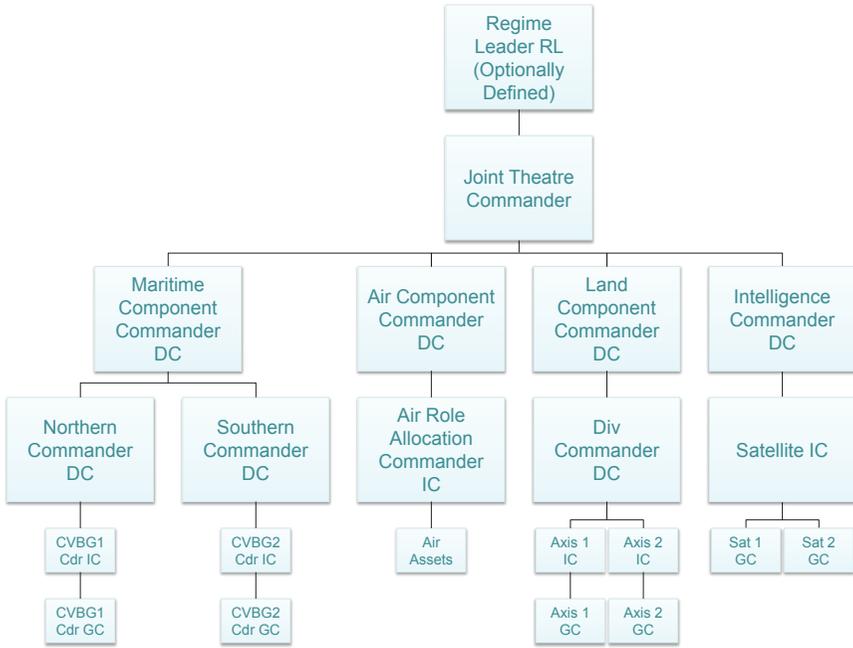


Figure 5.6: A typical command structure represented in the COMAND model.

The approach to deliberate planning in COMAND at the higher levels of this hierarchy is similar to that described for CLARION. However, in COMAND we have introduced the idea of a *campaign state vector* (CSV). The CSV is a measure of how well the overall campaign is progressing in each of the domains (land, air, and maritime), so that plans at the campaign level can be re-adjusted dynamically as the simulation progresses. The conditions for a plan to start are now expanded to include consideration of the CSV, and other events related to this new joint domain, including:

- events triggered at a certain time into the simulation;

- losses exceeding a threshold value;
- the air, land or maritime CSV is better or worse than a threshold value;
- a commander has been attacked, or has launched an attack;
- a commander has succeeded in a mission;
- stocks of weapons exceed or are less than a certain value;
- a maritime unit has been destroyed;
- a minefield is detected, or swept; and
- over target requirements for aircraft are greater or less than a threshold value.

The representation of the land campaign in COMAND is highly aggregated and is structured so that it can be calibrated to the more detailed representation in CLARION offline. In chapter 6, I will describe in detail how COMAND was able to successfully replicate real command and operational outcomes.

DIAMOND

DIAMOND is a closed form constructive simulation of peace-keeping, peace enforcement and humanitarian aid operations (PSO). A simple node and arc network provides a graphical representation of the region and environment, with represen-

tation of key areas of interest, areas of sea or lake, and the airspace above. Facilities, such as airports and civilian shelters can also be represented.

The model represents the main actors and contributors to PSO by the use of *entities*. These represent the capabilities and behaviours of military units, civilians, non-military organisations, and the leaders or commanders for each. Entities interact with each other and the environment and exchange or consume key commodities such as food, fuel, and ammunition. The simulation incorporates a mechanism to organise entities into common parties that represent specific organisations or common groups within a scenario. These could be, for example, an aid organisation, a military unit, a civilian group led by an activist, or an insurgent group. These parties have an appropriate command structure and communications network to allow for the allocation of missions and flow of intelligence throughout the party, and these parties have relationships with one another which define their interactions (ranging from friendly to hostile).

Using a mission-based approach to the representation of command and control similar in concept to both CLARION and COMAND, the simulation includes a mechanism to represent each party's *concept of operations* by nesting objectives in a series of plans and for those objectives to consist of a series of missions that entities can carry out during a campaign. Commanders within a party allocate resources to achieve their objectives in line with the sequence of plans, and the simulation completes when a set number of parties achieve their end state conditions or when a predetermined period of time has elapsed.

As a simulation run progresses, each of the entities gains information about their environment and other entities through sensing, interactions and communication. This information is organised into a *local picture* (the CROP discussed in chapter 4) on the basis of which entities make informed decisions on how they should carry out their missions. DIAMOND also includes a mechanism (referred to as *negotiation*) for obtaining access (through a checkpoint or roadblock for example) to an area denied to one party by another and for allowing multiparty cooperation to achieve aims and objectives without having to rely entirely on their own resources.

Representing the Physical Environment

As already noted, the physical environment in DIAMOND is represented by a node and arc network. Nodes represent areas of operational interest, population centres and the locations of key infrastructure and terrain features. Arcs represent the routes between these nodes. An example node-arc network for DIAMOND is shown in figure 5.7.

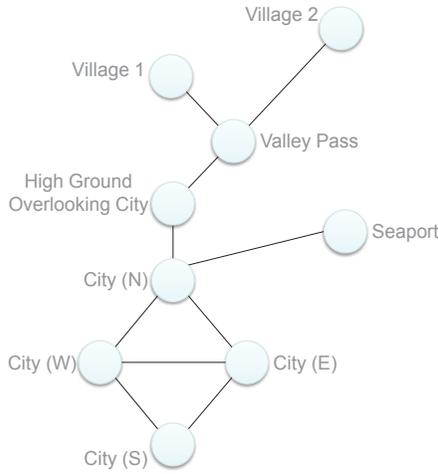


Figure 5.7: Example node and arc network representation of the physical environment.

Nodes can, depending on the nature of the scenario, represent whole cities or individual districts or regions within a city. They can be used to represent individual villages, but a more appropriate aggregation level would be a collection of local villages. Nodes are also used to mark areas of deep water, points along an air corridor, strategic junctions, and key terrain features. In this way, the model is able to capture the full air, maritime, and land context of the operation.

Arcs represent the routes between the nodes and each one has several channels which can include ground routes (road, rail, and cross country links), air corridors, inland waterways (canals, rivers, and lake crossings), close to shore waterways, and deep waterways. They can also be used to represent important infrastructure networks such as oil or water pipelines and electricity

cables. The anticipated length of each arc is around 10 to 30 km, although this can be much shorter where areas of interest are close to one another (e.g., the districts of a city)

The type of channel (and its capacity) determines which entities can move down that arc. For example, large ships cannot transit an arc connecting two water nodes with only an inland waterway channel (e.g., a canal), as they are prohibited from using any channel that is not a deep-sea waterway. For an environment represented as cities, towns, or districts with arcs between 10 to 30 km long, the appropriate entity size for military units is a battlegroup, air package,² or an individual ship.

Nodes and arcs both have a terrain type (called *culture*) which influences a variety of calculations within the simulation such as the effectiveness of sensors, the rate of attrition between two units engaged in combat, and movement rate. These culture types are: Urban, Suburban, Open Flat, Open Rolling, Open Mountainous, Scrub, Lightly Wooded, Densely Wooded, Mountainous, and Open Water. Weather is also represented to the extent of having a local, temporary effect. At each node it is possible to define facilities, which are key attributes of that area that any entity can interact with. These facilities include Hospitals, Shelter, Water, Targets, Food, Airports, and Seaports. Each facility is represented in terms of its ability to sustain damage and its ability to continue, given such damage. Facilities also have a local ability to repair themselves.

2. Battlegroup: approximately 3 to 4 companies, Air package: approximately 1 to 4 aircraft.

The Actors (Entities) Represented in the Model

The entities in the model can be considered to fall broadly into the four categories below:

Intervention Forces: These are the peacekeeping and peace enforcement forces with entities representing land, air, maritime, and special forces units operating under a UN or other international mandate. Supplementary police forces to assist a failed state are also covered under this category.

Factions: These consist of military and paramilitary forces of belligerent or warring factions who are not part of the peacekeeping or peace enforcement forces. The host nation's forces are also covered under the heading of factions. The entities include land, air, maritime, and special forces units.

Non-military organisations (NMOs): NMOs include monitors and observers, commercial companies, governmental and international humanitarian agencies, and non-governmental organisations.

Civilians: Civilians include neutral civilians and those associated with individual factions, internally displaced persons, refugees, and evacuees.

Although various types of commander are specified it is implicit for entities, including civilians, that they can make their own decisions if they have no direction from a superior. They have their own local CROP and are capable of making decisions for their own survival and to achieve their missions. The higher level commanders take into account broader considerations,

such as deciding which stage of a campaign plan should be followed, allocating resources to missions or directing a number of subordinate entities to work together to achieve a common goal. Commanders here represent military headquarters, local government, individuals, and in some cases the intangible collective actions of a set of common entities (e.g., refugees) as appropriate to the group being considered.

Sensing and Communication

In DIAMOND, sensing and communication cover the processes by which entities directly acquire information about other entities, events, and the environment. Sensing covers three processes: direct observation, use of a sensor such as radar, and information derived from interactions with other entities and the environment. The representation of sensors has been kept as simple as possible. For example, a British battlegroup can have numerous visual, infra-red, and radar sensors plus the eyes and ears of over 500 soldiers. This can be represented as a single sensor package.

In DIAMOND, the surrounding culture type of any target entity, the size of that entity and the local weather conditions modifies the range at which it can be detected or identified. Determining whether a detection is a target to be attacked, or a civilian group to be supported (for example) is a key aspect in this operational context. The ability of the sensor to resolve such issues at various ranges is shown in table 5.2.

Resolution	Definition
Detection	The location of a detected entity is available. No further information is available on the entity.
Status Recognition	The location of a detected entity is available and further clarification on whether it is a civilian or military entity.
Recognition	The location of a detected entity is available, further clarification on whether it is a civilian or military entity and the type of components it is made up of (unit type identification), e.g. Armour, Infantry, etc.
Identification	The location of a detected entity is available, further clarification on whether it is a civilian or military entity, the type of components it is made up of (unit type identification) and the entity's unique identifier and the party to which it belongs.
Analysis	The location of a detected entity is available, further clarification on whether it is a civilian or military entity, the type of components it is made up of (unit type identification), the entity's unique identifier, the party to which it belongs and the current status of the entity (unit strength, available food stocks etc.) and the activity it is engaged in. For DIAMOND, Analysis also counts as visual recognition for the purposes of Rules of Engagement.

Table 5.2: Definition of sensor resolution categories.

All information received by an entity (whether through direct sensing or sharing of information) is assimilated into its local picture. The representation of a local picture, and perceptions based upon it, are important aspects of DIAMOND, as all entities decide what to do in the simulation on the basis of the information available to them. If this information is incomplete or out of date the entity's actions may be different, compared to their actions based on complete and current information. The local picture in DIAMOND (the CROP discussed in chapter 4) is an aggregation of all the information made available to that entity. Each piece of information in this local picture has an assessed resolution level, a degree of credibility, and a record of when it was collected. DIAMOND also represents a number of communications networks allowing entities to share information. Some of these communication networks are based on the capabilities of individual parties (such as a particular insurgent grouping exploiting easily available

communications technology), while others (such as commercial news stations) are global. Messages communicated include, for example, orders, status reports, requests for assistance, intelligence, local picture information, and media broadcasts.

Missions and Decision-Making

The activities of entities within the environment are governed by two criteria. Firstly, the missions represented in the model that entities are able to perform and secondly, the decision-making processes in each party that determine how and when those missions should be carried out.

Following the mission-based approach to command, there are twelve discrete missions defined in the model. They are: Transport, Intelligence, Move, Engineering, Defend, Reserve, Evacuate, Escort, Presence, Strike, Secure, and Deny Movement. The majority of these missions cover general tasks that any entity in the simulation could undertake (Transport, Intelligence, Move, Engineering, Defend, and Reserve). The other missions are those that are likely to be specific to either the peacekeeping forces (Evacuate, Escort, Presence, and Strike) or to the belligerent factions (Secure and Deny Movement). This is not to prevent the missions being interchangeable between the different parties within DIAMOND but to indicate that the design has focused on providing specific tasks associated with the principal actors involved in PSO. Each of the missions is interpreted by the entities that perform them as a series of activities. For example, the transport mission consists of the following sequence: plan, move, commodity exchange (i.e., load), move, commodity exchange (i.e., unload), reserve (i.e.,

become available for a new task), and communicate (i.e., report to superior commander that the entity is now available for new missions).

As with CLARION and COMAND, the missions themselves are organised into concurrent and sequential strings, referred to as plans. For example, a plan may include a mission to secure an area after which several transport and presence missions may occur concurrently. The entities undertaking the missions within the plan report at regular intervals on whether they are succeeding or failing and their superiors may allocate additional resources (if they have them) to move failing missions back towards success. For DIAMOND, the relationship between plans, missions, and activities is shown in figure 5.8.

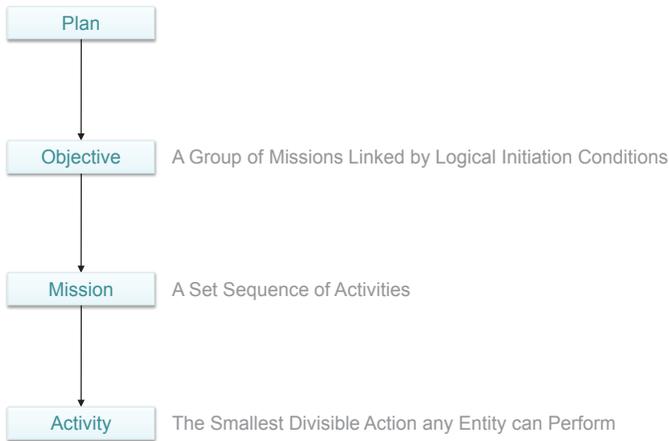


Figure 5.8: Relationship between plans, objectives, missions, and activities.

Monitoring the overall progress of the plan is the Joint Theatre Commander (JTC) or his non-military equivalent. His/her perceptions include a campaign state vector (CSV), similar in

concept to that employed in the COMAND model, and indicating whether the plan is succeeding or failing. Each plan has an associated set of initiation conditions and end conditions, which may be time dependent and/or success dependent. If a plan is failing (or has completed) the commander (or civilian equivalent) will decide which is the next most appropriate plan to follow. This sequence of plans forms the party's concept of operations, as shown in figure 5.9. The choice of the sequence of plans adapts as the simulation progresses, and may, as indicated in figure 5.9, end in success or failure.

Blue Party Concept of Operations

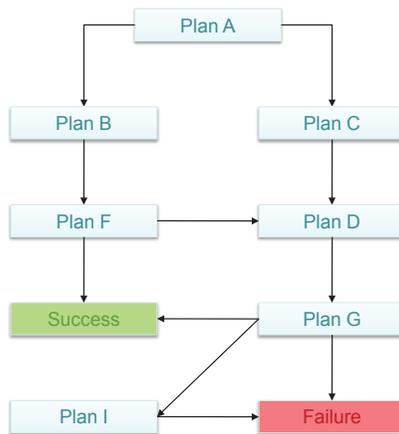


Figure 5.9: Example of a party's concept of operations.

Relationships

In models of warfighting, typically only two sides are represented. This is a suitable assumption for most conventional battles. However, in non-warfighting operations this assumption

is not valid, as there are often a large number of participants, none of which can be classified purely as hostile to each other. For example, in the context of Bosnia there were three main armed factions, their respective civilian populations and the peacekeeping forces. In the context of Somalia there were many warlords vying for control, the embattled civilians, the multinational peacekeeping forces, and United Nations personnel, all of whom were of strategic importance to the operation at one time or another. Very quickly it becomes obvious that any successful attempt to model non-warfighting operations requires a multi-sided approach. It was decided that each side in the simulation would be identified as a separate party and that the relationships between those parties would be used to describe their affiliations, rather than aggregating like-minded parties into distinct sides.

In accepting that a multi-sided model is required, it is necessary to identify the relationships that will be required to describe the affiliations of each party. Again, in modelling of warfighting, only one type of relationship is modelled, that of hostility between parties. In non-warfighting models a greater range of relationships is required. A five point scale is used to represent the range: Hostile, Uncooperative, Neutral, Sympathetic (cooperative), and Friendly. It was also recognised that a relationship between two parties does not have to be symmetric. For example, a non-military organisation may consider its relationship with a belligerent faction as neutral whereas that faction may adopt an uncooperative or even hostile stance in return. In DIAMOND we currently assume that a party will always at least know the stance of other parties towards them, even if it is an asymmetric relationship. These relationships can change and adapt within a given simulation run.

Figure 5.10 shows an example of how combat works within DIAMOND. The red armoured units (the rectangles³ enclosing ellipses in figure 5.10) advance into the node, attacking the civilians and industrial facilities. They do not attack the medical facilities as their rules of engagement do not permit them to do this. The blue infantry forces are shown as rectangles enclosing crosses in figure 5.10. The relationship between the red and blue forces is such that normally they would not engage each other. However, the rules of engagement for the blue forces allow them to go to the defence of the civilian population and hence start to attack the red forces. As a result of this, the red forces switch their attention to the blue forces since they present the biggest threat. The combat will end when either of the forces withdraws. If it is the blue force that withdraws then red will return to attacking the civilians and industry.

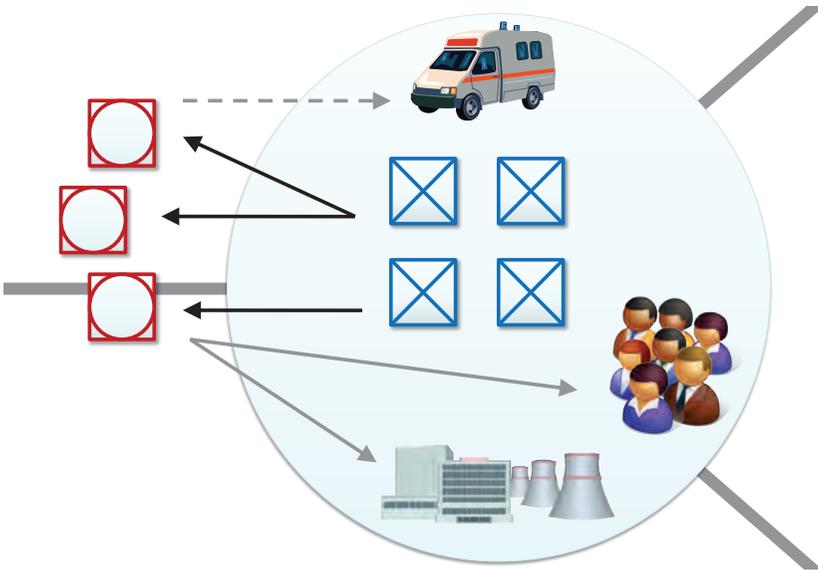


Figure 5.10: Example of a complex non-linear interaction within the model between red and blue forces, involving also the effect of civilians, and medical and industrial facilities.

3. Using standard military notation.

The previous example could be modified such that the red forces only attacked the industrial facilities. In this case, the rules of engagement for blue would not allow them to engage red as the red forces were not attacking civilians.

DIAMOND, as with all of our models, has undergone a number of validation efforts, and is now used in studies related to the peace support operations context. In the next chapter I will discuss the subject of model validation in more depth, and give some examples of how we carry it out.

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- [2] J Moffat (2002). *Command and Control in the Information Age: Representing its Impact*. The Stationery Office, London, UK.

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CHAPTER 6

VALIDATION OF OUR SIMULATION MODELS

What does it mean to say that a simulation model is valid? The simulation models I discussed in the previous chapter are not of the temporary nature, which might be constructed as part of a problem formulation, or as an initial exploration of the problem space. They are what might be called *expert models*. They represent our distilled understanding of how a particular system, or system of systems, actually works in detail, and they give quantitative predictions which can be compared with experimental evidence. From a scientific perspective, they are our *theories*, and whether a model is valid is equivalent to the question of whether a scientific theory is valid. I will return to this point later. Before discussing the nature of validation, however, I want to describe in more generic terms the basic structure of our *models as theories*.

The Generic Structure of our Models as Theories

In the previous chapter, I laid out in some detail how the mission-based approach to command and control is implemented in our higher level system of systems models (CLARION, COMAND, and DIAMOND). The agent structure which we have developed is first of all based on the construct of a *layered agent*. Research on such layering of agents, discussed for example in [1], looks at the problem of modelling agents within a multi-agent environment from the perspective of an individual agent. In this *agent-centred* view, an agent system is looked upon as consisting of an agent and its perceived environment. The environment is described within the agent by a number of states which are accessible to the agent. The agent updates this representation by perceiving changes in the environment. Actions performed by the agent cause transitions between states.

Such agent models are based on the idea of *deliberative agents*. This representation is based in turn on Simon and Newell's physical symbol system hypothesis [1, 2]. The key assumption is thus that such agents maintain an internal representation of the world, and there is an explicit mental state which can be modified by some form of symbolic reasoning. *Beliefs* of an agent represent its expectations about the current state of the world, and about the likelihood of a course of action achieving certain effects. *Desires* specify preferences for particular world states or courses of action—some desires may be incompatible. The weak and possibly inconsistent nature of Desires leads to the idea of *Goals*. These are a consistent subset of Desires which the agent might pursue. Even if the Goals are consistent, however, it is often necessary to select a particular Goal (or

set of Goals) to commit to. It is this process which is called the *formation of intentions*. We use this as a basis for our representation of *intent*—i.e., the intent of a commander.

The development of increasingly sophisticated belief-desire-intention (BDI) based architectures leads in its fullest form to the idea of layered agents, as a generic structure for the representation of artificial intelligence (which can then be applied to artefacts such as mobile robots). In Muller's approach [1], these layers correspond to a higher level *cooperative planning layer* (e.g., the robot looks ahead, in collaboration with other robots, to avoid collisions and plan its route); a *scheduling layer* to turn this into a schedule of lower level operations for the individual robot, and a *local planning layer* (e.g., the robot selects from a small set of alternative possible operations which are functionally defined). In our models, these local alternatives are based on the idea of a *mission* to be carried out by the agent. This represents one from a small set of alternative specific tasks. Taking CLARION as an example, these are Secure, Defend, Fix, Search, MoveTo, Support, and Reserve. As we have also seen, these can be applied recursively at a number of different command levels. In DIAMOND, the missions include (for example) Evacuate, Escort, and Presence, reflecting the peace support operations environment of that model. In all three models (COMAND, CLARION, and DIAMOND), a plan at the cooperative planning layer consists of a branching string of such missions to be performed by subordinate or collaborating agents in order to achieve the agent's intent.

At the cooperative planning layer, a fitness function for the plan is defined (in some applications of the approach we call this the campaign state vector) which is a measure of whether the current plan is succeeding or failing. This then leads to the possible

selection of an alternative plan, as described in chapter 5. In the full representation of this process of deliberate planning, the choice of plan is implemented by a genetic algorithm [3]. We adopt here Bratman's approach [4] that intent corresponds to the current plan selected by the agent.

At the single agent level, the rapid planning model, as discussed in earlier chapters, puts the emphasis on situation awareness. The goal of this process is to provide the command agent with an understanding of what is happening in the outside world. In particular, the command agent tries to answer the question: Is the situation that I perceive in the outside world one that I recognise? Because if I do recognise the situation then my experience (long-term memory) tells me which mission I should adopt, given this situation. The focus of the process is thus on pattern matching—analysing the information available about the outside world and trying to match the perceived state of the world to one of an existing array of *patterns* held in the command agent's long-term memory. Each pattern is a representation of a *situation*, and each situation is linked directly to a course of action (a mission) appropriate to that situation. This linkage of a recognisable situation to appropriate course of action represents the command agent's experience and is what enables the command agent to make decisions rapidly without recourse to extensive option generation and evaluation. This formulation of the desired mission at the single agent level (the local planning layer of the layered agent representation) then has to be reconciled with the planning which is going on in the higher scheduling and co-operative planning layers. This

reconciliation is essentially achieved by bringing together the group perception which is driving the co-operative planning, and the individual agent situation assessment process.¹

Model Validation

Because our models are the equivalent of scientific theories or hypotheses, we can consider their validation from the point of view of Popper's approach to falsification. Thus, to quote from Michael Pidd [5] referring to Popper, "scientific method is best seen as theory driven rather than being driven by independent observation ... scientific work depends on the generation of hypotheses from which deductions can be made. These deductions can be tested by properly designed experiments that aim to show whether or not the deductions, and hence the hypotheses, are correct." Pidd [5] then points out that from this perspective, all knowledge is in some sense conjectural, since hypotheses can never be wholly proven to be true, but can only be decisively shown to be false. In Popper [6] we also have some guidance in a letter from Albert Einstein to Karl Popper.

Einstein, in translation, says "I think (like you) that theory cannot be fabricated out of the results of observation, but that it can only be invented." Coming back to simulation models, what this means is that [5] "in Popperian terms, a valid model is one that is unrefuted within some specific assumptions. Validation then is to be seen against the intended use of the model and not in an absolute sense."

1. A point originally made to me by Murray Gell-Mann at the Santa Fe Institute.

While working on aspects of mathematical logic at Edinburgh University, I also had an exchange of letters with Karl Popper. An example is shown at the end of this chapter. I discussed with him the development of a theory of probability on an axiomatic basis. This allows the *probability* of a theory being false to be properly considered as an idea. Ironically, as a theory becomes more general in its application, the possible set of experiments which might falsify it increases, and thus its probability of being false increases. At any given point in time, then, we have to consider that a theory is only valid within a certain domain of application, based on the experimental evidence thus far.

Since our expert models undergo a continuing process of refinement and scrutiny by both expert analysts and in-house military advisors, our point of view is nearest to that of Balci, [7, 8] and lies within the context of building increasing trust in the model, the analysis based upon it, and the interaction between the analyst and the customer [9], thereby establishing the valid domain of application. Our key building blocks in this process are establishing validity at two different levels, as follows:

- Level 1: Given the input assumptions, the emergent behaviour of the model conforms with expert military judgement.
- Level 2: The model successfully replicates a number of historical case studies of conflict.

This Level 2 validation process was applied to both the COMAND and SIMBAT models, and I will now take you through the results for the historical case of the Falklands War,

1982. In carrying out such comparisons, our aim is to test whether the dynamic outcome of the conflict lies within the *fan* of simulation outputs from our stochastic models. Of course, the conflict itself is just one replication of reality, and we do not know whether it is typical or not.

The COMAND Simulation Model

As introduced in chapter 5, COMAND is a stochastic, campaign-level, intelligent agent simulation of maritime, air, and land contributions to a joint campaign. The representation of the land battle is more aggregate than for the other domains and is calibrated offline to the higher resolution CLARION model. COMAND also represents a third side allowing the representation of neutral aircraft and ships. COMAND has been developed with a flexible command hierarchy that allows it to model any command structure or doctrine. These commanders are represented by intelligent agents. In COMAND each side has a joint commander who is in charge of the whole campaign, with component commanders who handle the details of the individual domains. The maritime hierarchy devolves below the maritime component commander to task group commanders who may be in charge of anything from a carrier battle-group to a single submarine. In real life most of the decision-making about the allocation of air power is handled within the Combined Air Operations Centre. This is represented in COMAND by a range of commanders, each of whom takes on the role of one of the cells within this headquarters; for example, one commander looks after air defence issues, while another tasks aircraft on strike missions. Land-based assets such as surface-to-air missile sites, or coastal batteries of anti-shipping missiles are handled in a similar way to maritime assets; a commander may be in charge of a group of systems.

Information Networks in COMAND

COMAND represents the flow of key types of information between commanders. These are

- orders and status reports which flow down and up, respectively, the command hierarchy;
- support requests: each commander can have a number of other commanders from whom he or she may request support; this may not necessarily follow the command hierarchy, reflecting the horizontal or peer-to-peer linking discussed in chapter 2; and
- information on enemy intent and location: the flow of such information takes the form of networks which may be available to all, allowing more transparency of intent, as also discussed in chapter 2.

Missions are the building blocks from which scenarios are created. They are used in all domains and are a task that a commander may be assigned to carry out. Missions fall into the categories of Attack, Escort, and Patrol. Using this mission-based approach to command, it is possible to represent the deliberate planning of senior commanders at the higher levels of the command hierarchy. As I described in detail in chapter 5, this course of action takes the form of a plan, containing one or more strings of missions, which is passed down the command hierarchy. The mission-based structure also allows the representation of rapid planning, where commanders must make quick, time-pressured, decisions about their immediate environment and the threat. Rapid planning is currently represented in the maritime domain in COMAND.

As also discussed in the previous chapter, the status of each domain (land, air, and maritime) is measured using campaign state vectors (CSVs). These are specific to each domain, but typically take the form of the ratio of the enemy's capability to friendly capability. For example, the maritime CSV is the ratio of each side's anti-surface warfare and anti-submarine warfare capability.

In rapid planning, each commander maintains a track table which gives him a degree of situation awareness. This track table, similar to the idea of the local CROP discussed in chapter 4, is developed using the group's own organic sensors (radars and sonars aboard ships, the dipping sonars of helicopter screens, etc.) and also through information sharing using any information networks to which the commander has access. Through these information networks a commander may have access to the sensors of maritime patrol aircraft, other task groups, airborne early warning aircraft, and satellites. Each track contains information such as platform type, bearing, and speed, and may be built up from a number of different sensors, each one providing a different piece of information. For simplicity, perfect track fusion (no ambiguity) is assumed in compiling the information. Each track is time-stamped and if it is not updated after a certain length of time then it is discarded.

In COMAND, the key to rapid planning is the commander's threat assessment, which is carried out based on his track table. If information is delayed, or incomplete, then he may make inappropriate decisions. A commander may be in one of two postures, either offensive or defensive, which are defined according to the particular mission he is carrying out. Once a track becomes a threat, an assessment is carried out in order for the commander to arrive at a course of action. The threat

assessment process involves taking the perceived capability of the threat and comparing it with his own. If the assessment is unfavourable then the commander may seek to evade the threat and request support from other commanders to prosecute the contact; if it is favourable then the commander may elect to attack the threat himself.

Comparison of COMAND and the Falkland Islands Conflict

A comparison between the 1982 Falkland Islands conflict and a COMAND simulation, using 160 replications, was carried out as part of the validation of COMAND at Level 2. Three main types of agent decision-making were represented in this comparison: a) In terms of the deliberate campaign plan for each side's maritime assets, this consisted of an initial string of missions. At various points, triggers were built into the plan, allowing it to branch to a new string of missions dependent on the situation at the trigger point (this might be the sinking or not of a major warship for example). b) In terms of rapid planning, maritime missions could be adapted to reflect local circumstances. For example a UK ship in transit to a patrol area could mount an attack of opportunity if its sensors detected such a threat and the attack was likely to succeed. c) Air missions were developed and prosecuted as a function of the sensor information on targets. For example all Argentinean air missions attacking the UK task force were created by the model in response to sensor information (mainly from maritime patrol aircraft and sensors based on the Falkland Islands).

Entity/group missions (the mission-based approach of chapter 5) are the building blocks of the scenario and are the key to COMAND's representation of the decisions made by the various commanders and the emergent effect of these decisions.

Broadly it was possible to represent all types of mission: for example, the retreat of the Argentinean Navy to port, following the loss of one of their ships; the regrouping of the various ships into a single amphibious landing force and its subsequent passage to San Carlos.

It is not currently possible in COMAND to have different rules of engagement (RoE) in different areas of the battlespace. In the real conflict, hostilities began on 25th April at South Georgia when the Argentinean submarine Santa Fe was sunk. When RoE are changed in COMAND to allow this to happen they are applied over the whole geographical area of the scenario. The result is that hostilities commence around the Falklands themselves slightly earlier in the model than in reality.

The representation of sensors, which feed information about the environment to the commanders, was sufficient to meet model requirements. On the Argentinean side, the primary sensors were maritime patrol aircraft, the Narwal (an intelligence trawler), and various assets located on the islands, all of which were represented. On the UK side the primary sensors were the ship-based radars and communications electronic support measures, all of which were represented.

Since COMAND is a stochastic model, each case considered within the model produces what we referred to earlier as a fan of results, representing the set of possible dynamic evolutions of the conflict over time, when the assumptions within the model are held constant, and the 160 replications then represent the result of stochastic variation. Figure 6.1 compares the fan of simulation outputs of COMAND (showing the mean and 95% confidence limits of the stochastic variation) for the number of UK ships lost, as predicted by COMAND,

compared with the number of ships lost in reality. The actual line includes the six ships that were sunk (Sheffield, Ardent, Antelope, Atlantic Conveyor, Coventry, and Sir Galahad) and the three which were severely damaged (Glasgow, Sir Tristram, and Plymouth) to the extent that they played no further part in the war and could be counted as operational losses. Additional ships were hit in the conflict, but for this analysis they were deemed insufficiently damaged to be classed as operational losses. The figure shows four steps in the actual line; these are the loss of Sheffield on 4 May; the loss of Glasgow on 12 May; the three ships which were lost in San Carlos between 21 and 25 May plus the Atlantic Conveyor, and finally the two landing ships lost in the landing at Fitzroy and the loss of Plymouth in San Carlos Water.

Figure 6.1 shows that COMAND produces similar results to those which occurred in reality. These losses also occurred at roughly the same times, comparing model with reality, except for the fact that UK ships were lost slightly earlier than in the actual campaign during the period from late April to mid May. This was due to the representation of rules of engagement in the model, as I discussed earlier.

Implications for Deliberate and Rapid Planning

Comparisons such as these are testing not just the overall validity and domain of application of the model, but also, in particular, the validity of the representation of command and human decision-making within the model, founded on the mission-based approach. This is because the total casualties inflicted or sustained are caused by the combination of the number of engagements between units and the effectiveness

of each engagement. In this example, we have scaled back the effectiveness per engagement to those actually sustained during the conflict. The assumptions of the command process are a key driver in determining the number of engagements in the model. Thus the emergent behaviour which we measure from the COMAND model is a true test of the validity of our representation of planning and human decision-making.

Figure 6.1 shows the dynamic of UK losses² over time. In figure 6.2 we consider the geographical distribution of these losses, broken down by ship group. The groups have been simplified from reality for comparative purposes. Figure 6.2 shows that the losses inflicted on both the Carrier and the San Carlos groups in COMAND were similar to those inflicted in reality. The losses to the Paraquat group in COMAND (i.e., those ships involved in the UK effort to retake South Georgia) were caused because in a number of replications, UK forces take longer to sink the Argentinean vessel Santa Fe than in reality, which gives the submarine the opportunity to attack UK ships.

2. Note: In scientific analysis of this sort, concerned with casualties and death, deaths are dispassionately counted as quantified units as in any scientific endeavour. However, the practical purpose of analysis of this type is to expose to decision-makers the consequences of their actions, and in this, the human consequences also have to be considered.

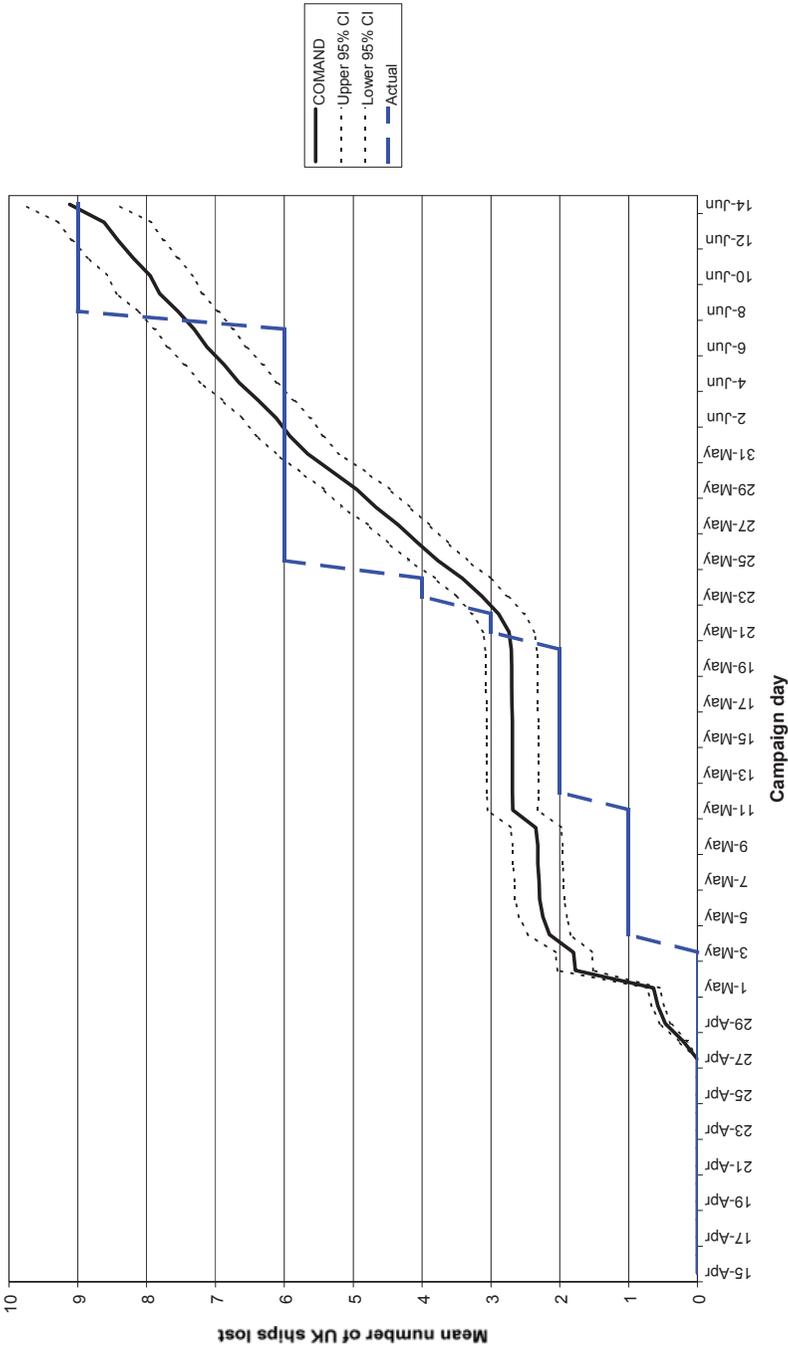


Figure 6.1: Cumulative number of UK ships lost over the time of conflict.

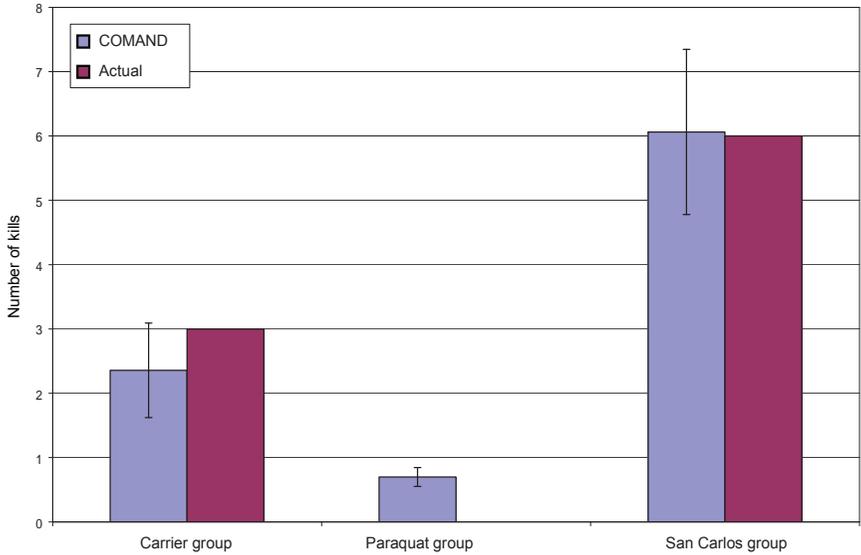


Figure 6.2: UK ship losses by ship group.

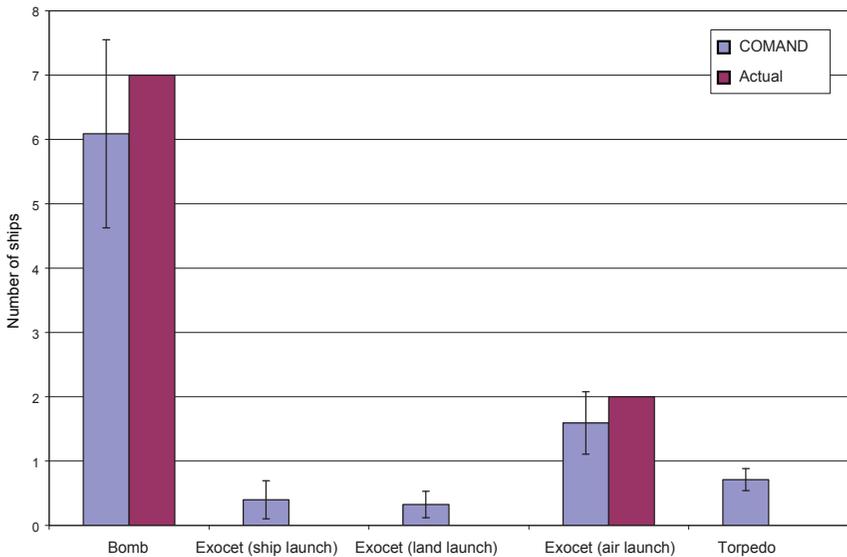


Figure 6.3: UK ship losses by weapon type.

Figure 6.3 compares UK ship losses by weapon type. In reality, UK ships were lost exclusively to iron bombs (7 ships) and air-launched Exocet missiles (2 ships). The simulation results match this reality closely.

In some of the COMAND simulations, the UK also lost ships to ship-launched Exocet. In the actual campaign the Argentinean Navy planned a pincer attack on the UK Carrier group, the southern arm consisting of the General Belgrano group and the northern arm consisting of a number of Exocet-equipped destroyers. The sinking of the Belgrano by the UK SSN Conqueror prevented this attack from taking place. In some of the replications of the COMAND simulation, the Belgrano is not sunk and the attack goes ahead, causing heavy UK ship losses.

In the simulation there is also a small possibility of losing a ship to land-launched Exocet missiles. In reality, Glamorgan was hit by a land-launched Exocet but survived. Results from COMAND additionally show that there is approximately a 70% chance of losing one ship to a torpedo attack by a submarine, the Santa Fe. In reality, this submarine was destroyed early in the campaign and the other submarines did not successfully attack any ships.

Figure 6.4 compares the cumulative number of Argentinean ships lost within COMAND with the number of ships lost in reality. In the actual campaign, the Argentinean forces lost seven ships—General Belgrano, Alférez Sobral, Comodoro Somellera, Narwal, Bahia Buen Suceso, Rio Carcarana, and Rio Iguazu. Of these seven however, only two were represented in COMAND—General Belgrano and Narwal, a trawler mod-

ified for intelligence collection, as the others were patrol boats and freighters. Figure 6.4 therefore shows the loss of only two ships—Belgrano on 2 May and Narwal on 9 May.

Figure 6.4 also shows the fan of outcomes from the COMAND simulation, matching closely to reality again.

Figure 6.5 compares the number of Argentinean aircraft lost, as predicted by COMAND, with the number of aircraft lost in reality. In reality, the Argentinean forces lost 70 aircraft but some aircraft types and causes of loss were not represented. These totalled 36 aircraft and consisted of support helicopters and transport aircraft. Their loss was primarily due to the special force attacks on Pebble Island and non-conflict losses. They are therefore discounted from the loss record. The Argentinean forces thus lost 34 aircraft, with the bulk of the losses being experienced whilst attacks were being mounted on the UK ships in San Carlos between 21st and 25th May, as shown in the figure.

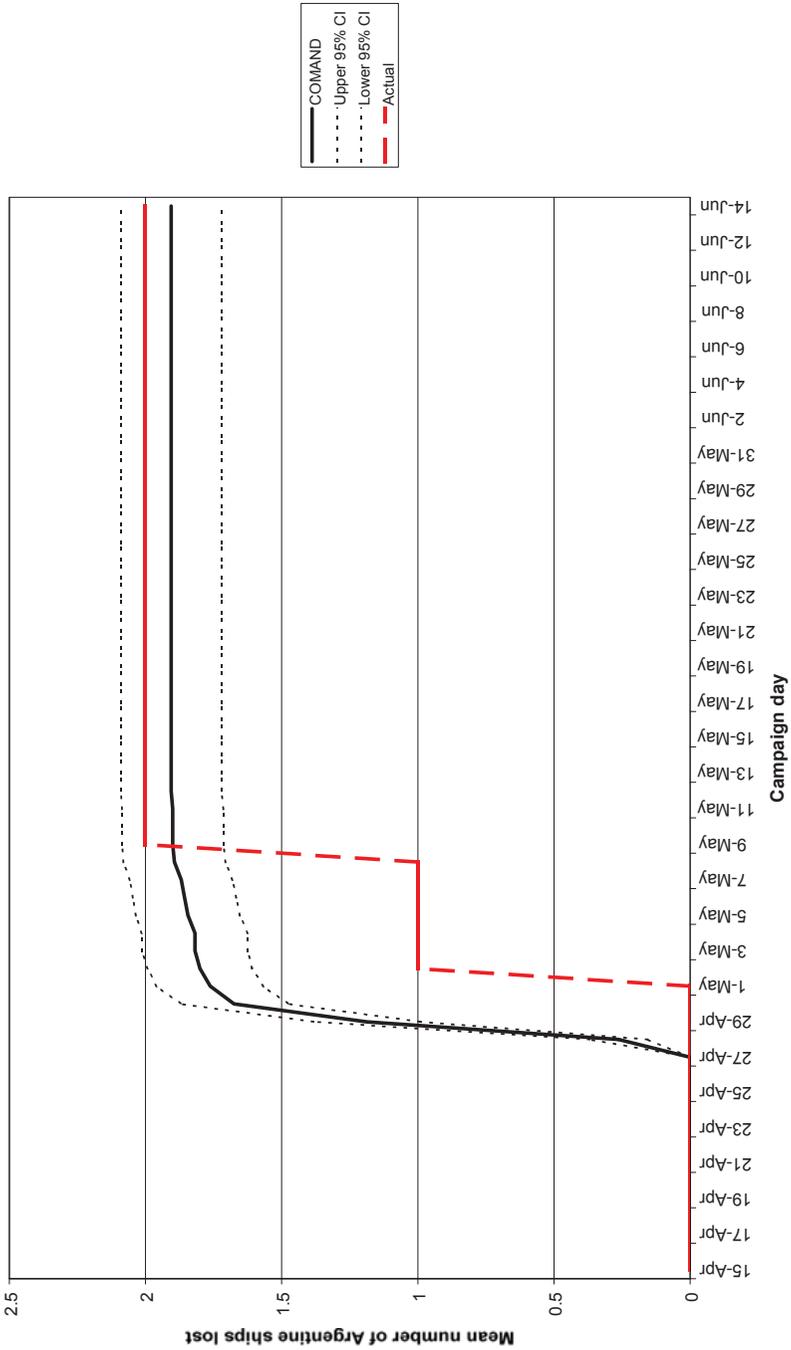


Figure 6.4: Cumulative Argentinean ship losses over time.

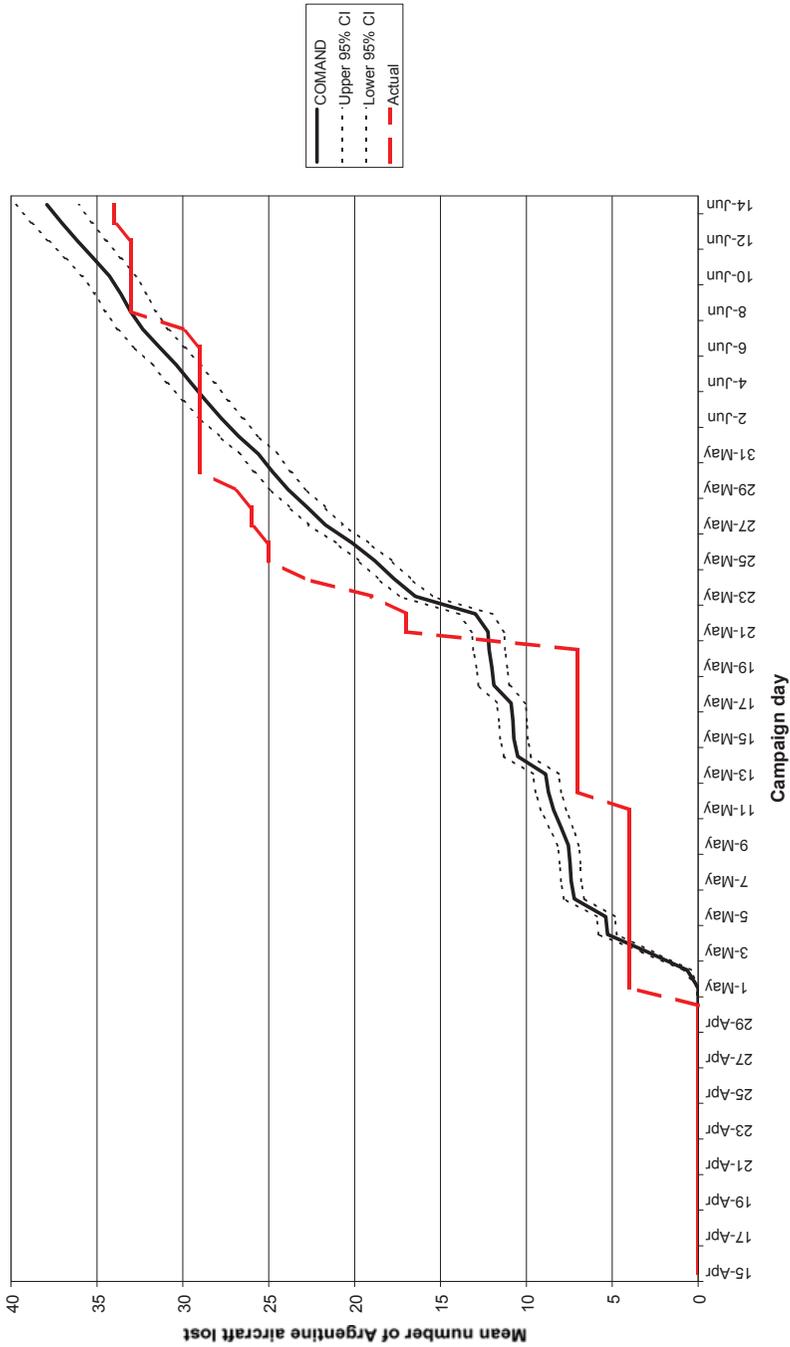


Figure 6.5: Cumulative Argentinean aircraft losses over time.

The cumulative number of losses predicted by COMAND was a little higher than in reality. This was due to a small number of replications in which UK ship losses in COMAND were either significantly lower, or occurred much later in the campaign, than in reality. In these cases, Argentinean aircraft were exposed to more SAM (surface-to-air missile) fire over the campaign as a whole than in reality.

The overall results indicate that the predicted timing of events is in accord with the actual flow of the campaign (except for the slightly early attrition of UK ships caused by the way in which rules of engagement are defined globally rather than locally). The size of casualties inflicted, in terms of ships or aircraft lost is also of the correct order.

The land battle in the Falkland Islands campaign was not represented in the COMAND simulation, since it was at too low a level of resolution for such a joint campaign level approach. As a separate exercise, a comparison was thus made between the battle of Goose Green and the SIMBAT tactical land combat model, which is based directly on the rapid planning process.

The SIMBAT Model

SIMBAT (Simple Battlegroup Model) is a simulation model which takes a balanced approach to decision-making at army battlegroup level by using the rapid planning process to model the local command decision-making and data input at each level in the command hierarchy to explicitly model higher level command. This method of modelling higher level command limits the number of hours SIMBAT can model, as no reappraisal of the whole battlefield takes place. Therefore there is no creation or adaptation of broad higher level plans, although

the rapid planning process in the higher level command cells can lead to a change in tactical stance in an agent. The rapid planning process thus reflects two different mechanisms: the first is the lower level response to local circumstances; the second is the need to resolve this with orders and intent from the superior commander in the command hierarchy.

This approach is specifically implemented in the agents as follows. At lower levels (e.g., platoon), one of three states or postures can be taken: Advance, Halt, or Retreat. Advance and Retreat are individual states of action. Halt consists of a number of sub-states defining various forms of Halt, to represent the protection and the situation of the units. These can be defined as defence, stood down, hasty defence, hasty defence stood down, deliberate defence, and deliberate defence stood down. These states are related to the higher level orders of Attack, Hold, or Defend. The posture is calculated from a combination of the local situation and higher level orders. To determine if a change in posture is required a decision on whether the current situation is “OK” or “Not OK” is taken as part of rapid planning [3]. If the situation is Not OK then the final step in deciding whether or not to change the posture, is to decide whether such a change is both feasible and desirable. This is partly the result of *command inertia*, as once in a posture, there is inertia built up, making it more difficult to move out. This reflects the reluctance of commanders to keep changing their minds and prevents units from continually switching between postures. A pattern matching process takes place, consisting of trying to match the perceived state of the world to situations in memory, derived from previous experience. If a match is made then a new preferred posture is suggested.

If a preferred posture is defined at the lower level then a posture selection process is required, in order to choose between this and the ordered posture derived from higher level orders. This selection is controlled by timings sent with these higher level orders. These timings control how long a lower level entity is allowed to stay in a preferred state and how long it then has to stay in the ordered posture before returning to a preferred state. The flexibility offered by this method allows the interaction of higher level and local command to be represented.

Comparison of the SIMBAT Model and the Battle of Goose Green

The battle of Goose Green was fought as part of the Falklands war, between the UK 2 PARA Battlegroup and a mixed force of Argentinean conscripts on 28/29th May 1982. The infantry battle started at midnight and finished at 20:00 the following evening. The Argentinean forces engaged were approximately equal in number to the British. The British force was highly trained and motivated. They were, however, fatigued from six days with little shelter on the cold slopes of Sussex Mountain, and by an 18 km march to the battlefield with little sleep. They were also shocked from an air attack on their ammunition point prior to the march. The British troops were opposed by Argentinean conscripts with barely four months training and little motivation. They were, however, fresh for battle, although shocked from low level tactical British air overflights and surprised by the British move to attack. The British force suffered casualties of 18 killed, the Argentinean force, 55 killed.

Human Factor Effects

The effect of changing human factor parameters of the agents (such as shock, surprise, and fatigue) was analysed using SIMBAT. The scenario was set using historical research from diaries, books, and interviews. Three levels of resultant force strength were designed on the basis of interviews with those who had fought in the campaign. Each level of force strength has parameter assumptions shown in table 6.1.

	Strong Force	Medium Force	Weak Force
Overall Effectiveness	1	0.5	0.21
Unit Participation	75%	50%	10%
Probability of being Shocked	0.01	0.5	1
Probability of being Surprised	0.01	0.5	1
Close Combat Trained	Yes	Yes	No
Fatigue Build up levels (per hour)	4% moving 2% static	4% moving 2% static	8% moving 4% static
Fatigue Recovery while at rest (per hour)	20%	20%	10%

Table 6.1: Parameter assumptions regarding levels of force strength.

For each possible combination of forces, 30 replications of the stochastic agent simulation were carried out and the fan of results calculated. For ease of comparison, the mean of these results is shown in table 6.2 for each of the cases considered.

	British Strong	British Medium	British Weak
Argentine Strong	British – 80 Argentine – 21 LER – 0.26	British – 80 Argentine – 13 LER – 0.16	British – 86 Argentine – 8 LER – 0.09
Argentine Medium	British – 80 Argentine – 30 LER – 0.37	British – 79 Argentine – 16 LER – 0.20	British – 72 Argentine – 6 LER – 0.08
Argentine Weak	British – 10 Argentine – 79 LER – 7.9	British – 12 Argentine – 52 LER – 4.33	British – 17 Argentine – 12 LER – 0.71

Table 6.2: Casualties predicted by the SIMBAT agent simulation for various force strengths.

The actual result of the battle can be seen to approximate the outcome of a medium British force versus weak Argentinean forces, as we would expect. The LER (loss exchange ratio) is the ratio of losses shown in each case and varies significantly as we vary the assumptions on each side.

Battle dynamics have historically been an area that conflict simulations have failed to successfully replicate. These dynamics were investigated by breaking down the battle into 5 separate phases and comparing the real events and timings with those of the simulation. The means of the resultant timings for each phase of the battle are compared with the real timings in table 6.3.

Event	Timing		
	Actual Battle	Strong British vs Weak Argentine	Medium British vs Weak Argentine
Burntside House and Hill Secure	0400	0230	0300
A Coy at Coronation Point, B and D Coy through Northern Positions	0630	0430	0430
A Coy held at Darwin Ridge, B and D Coy held at Middle Hill	0730	0600	0615
A Coy take Darwin Ridge, B and D Coy take Boca House	1030	1045	1115
Companies at their finish positions	1700	1830	1915
Proportion modelled time is away from Actual Battle	N/A	1.08	1.13

Table 6.3: Comparison of actual and SIMBAT agent simulation timings for key events.

The results show that the flow of the battle is well replicated by the scenario for British strong/medium forces versus weak Argentinean forces. Previous attempts to simulate this form of battle have always had a flow of time much faster than that which occurred in the actual conflict. In other words, events happened much earlier in the simulation than in the real conflict. Both the campaign level comparison (using COMAND) and the tactical level comparison (using SIMBAT) show that the introduction of a proper representation of command and control through the deliberate and rapid planning processes, coupled with a representation of human factor effects including shock, surprise, fatigue, and willingness to participate, slows down the battle dynamic to about the same level as in actual conflict.

In summary, for both the cases I have considered, spanning the range from the joint campaign level to the single environment tactical level, the overall casualties suffered are a combination of the number of engagements between the forces, and the effectiveness per engagement. As already discussed in each case, since we have scaled back the effectiveness per engagement to the values actually achieved in the real battles, the comparisons made here between simulated and actual casualties are a fair test of the command process represented in the models, since this directly affects the number of engagements. The results illustrated here thus build confidence that the models are correctly capturing the command and decision-making process, as well as the influence of information upon this.

Temporary address until December 1st:

BRANDEIS UNIVERSITY
WALTHAM, MASSACHUSETTS 02154

DEPARTMENT OF PHILOSOPHY,

Sept. 25th, 1969

Dear Mr Moffatt,

Many thanks for your letter of Sept. 16 1969 which reached me here yesterday. I am glad to have so careful a reader.

I do not have the various editions of L. Sc. D. here. After receipt of your letter I went to the library who had a first edn.

(Hutchinson) 1959. There (2) on p. 333, footnote, seem to read exactly as you put it. I should be very glad if you could give both the false and the correct formula, and the precise edition in which you found the false formula.

As to (63) on p 352, both your formula

Page 1 of a letter from Professor Karl Popper to the author discussing the logic of the scientific method.

thus there is no mistake
and the equivalence are, of course, correct, here.
 For we first deduce your implication, and
 then conclude that (by instantiation)

$$((c) p(c, b) = 1) \rightarrow p(a, b) = 1$$

$$((c) p(c, b) = 1) \rightarrow p(\bar{b}, b) \neq 0$$

which, together with your implication,
 yields the equivalence. *)

yours sincerely,

K. R. Popper

*) By turning round the order of the
 components of the equivalence, thus writing:

$$p(\bar{b}, b) \neq 0 \leftrightarrow ((c) p(c, b) = 1)$$

we are entitled to omit the outer pair of
 brackets in the second component since
 no ambiguity can arise from this. (Simi-
 larly, we are entitled, if we like, to insert
 brackets round the implicate of your
 implication.)

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CHAPTER 7

THE WARGAME INFRASTRUCTURE AND SIMULATION ENVIRONMENT

Chapter 5 introduced the modelling framework that is being developed and the algorithm enhancements that are moving our modelling capability towards the NEC mature state. This chapter will focus in more detail on one particular model, the Wargame Infrastructure and Simulation Environment (WISE). The place of WISE in the overall model structure is shown in figure 5.1. As noted there, it is a land focussed model (with representation of air and maritime support to land operations) at the system level, which can represent warfighting, peace support, or stabilisation operations. It has been developed so that it can be used both as a synthetic environment (SE) and as a closed form constructive simulation.¹ Recent developments, some of which we will present in this chapter, have brought WISE to the forefront as a significant addition to Dstl's modelling capability.

1. A synthetic environment consists of real and simulated people interacting with simulated environments. A closed form constructive simulation consists of simulated people (i.e., computer algorithms) interacting with simulated environments, with no human intervention during the model run.

The basic conceptual framework within WISE allows for force elements to be represented either as individual entities (such as a single tank with a commander and crew) or as aggregated units (such as a company, with a company commander), with a scenario typically having a mixture of the two. For example, division level scenarios may represent unmanned air vehicles as individual entities, working together with aggregated tank squadrons and infantry companies. In contrast, a study at brigade level may require a representation of aggregated platoons as well as entity based force elements.

Scenarios of future possible military situations represented within WISE often correspond to a small part (a vignette) of a larger scenario within a campaign level model such as CLARION, although this is not a prerequisite. The flexibility of the modelling approach allows for scenarios to range in scope from army divisional level to company level. When used in SE, or wargaming mode, WISE is typically used to facilitate discussion on a topic of interest and as such is able to provide insight into a number of *lines of development*² such as equipment, training, and organisation. Orders and decisions produced during a particular wargaming experimental intervention can be captured and used as input to facilitate analysis within the closed form, constructive simulation mode. The use of the wargaming mode allows a rich and detailed exploration of a particular future scenario. This is complemented by the closed form simulation mode which allows for a number of excursions to be made around that particular future scenario, to investigate the robustness of the results to perturbations.

2. The purpose of defence lines of development (DLOD) is to provide a pan-defence taxonomy to enable the coherent, through life development and management of defence capability. The DLOD are not in order of importance and have equal value.

Overview of WISE

WISE is a stochastic, event driven model that allows decisions to be made by players, software algorithms, or a combination of both. By using players rather than software algorithms to make decisions, WISE is played as an SE, whereas with software representing human decision-making, WISE is run as a closed form, constructive simulation. Architecturally WISE is a personal computer (PC) based system, written in C++ utilising a number of open source software products under the RedHat Enterprise Linux operating system, with a modelling approach centred on the use of software agents within a distributed network. The use of agents allows a loose coupling between WISE system components which in turn enhances the capability of WISE to represent various approaches to command decision-making. This becomes increasingly important at the higher levels of NEC command approach discussed in chapter 3.

WISE can be viewed as a series of layered products that together provide the overall modelling capability as illustrated in figure 7.1.

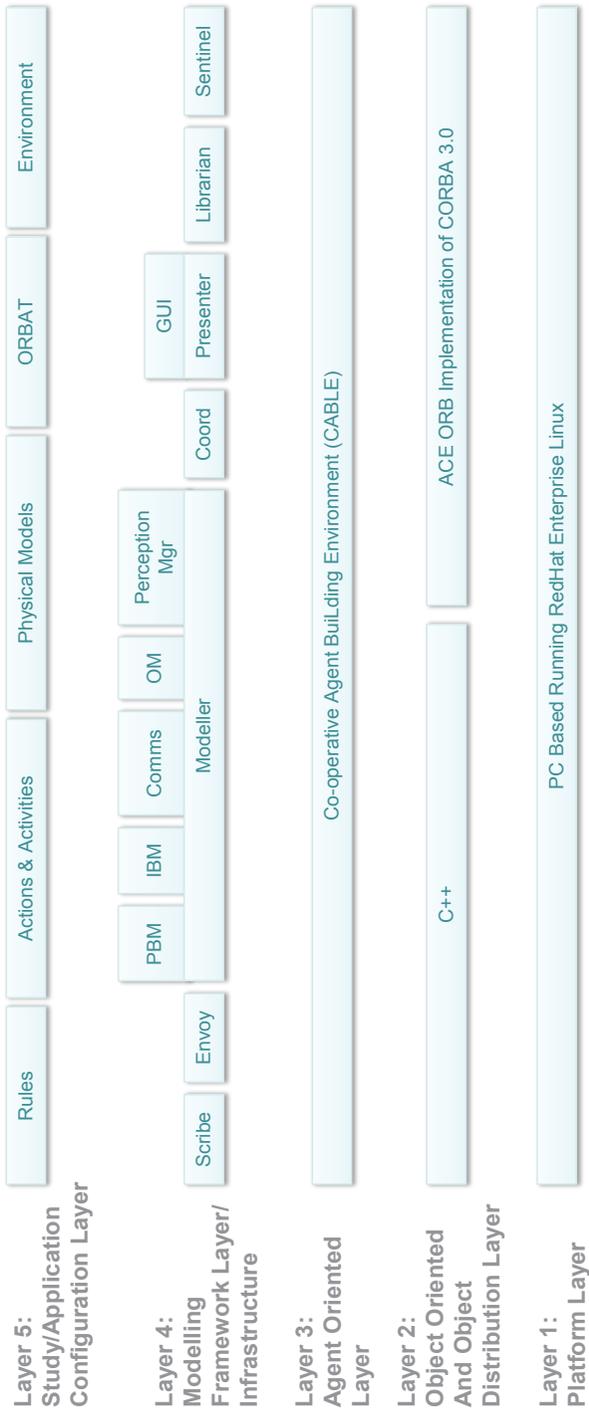


Figure 7.1: WISE architecture layers.

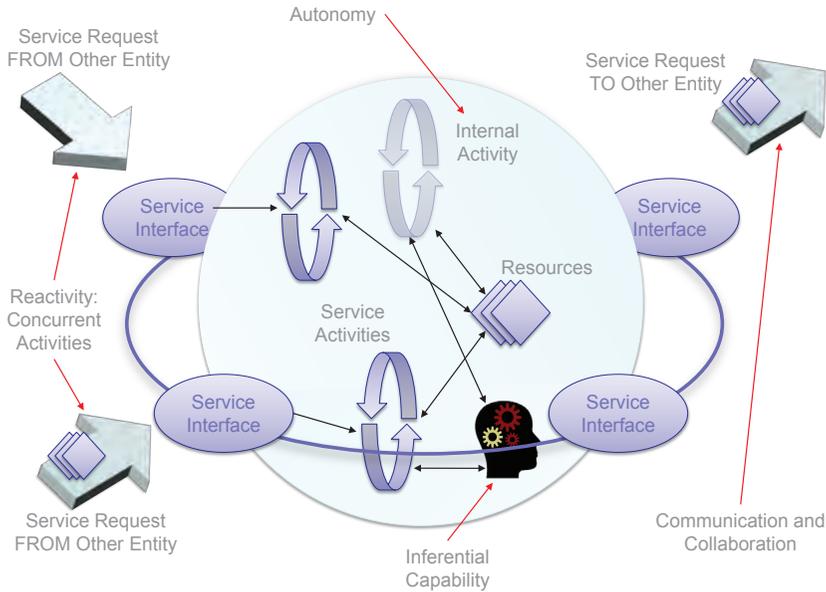


Figure 7.2: Diagrammatic view of an agent.

Software agents within WISE are developed using the Cooperative Agent Building Environment (CABLE) [1], a generic software agent framework that can be used to develop and execute distributed applications based on multiple, cooperating agents. CABLE provides the developer with an Agent Definition Language (ADL) which is used to define services that agents will provide, and the sensible ordering of actions (method invocation) once the service has been requested, as illustrated in figure 7.2.

Once the agent has been defined using the ADL a language parser known as the CABLE Scribe is used to compile the agent definitions into the target application code. In the case of WISE this is the C++ language. Distribution is achieved through interfacing CABLE with the Adaptive Communication

Environment (ACE) Object Request Broker (ORB) which is based on the Common Object Request Broker Architecture (CORBA) 3.0 standard. An ORB is responsible for handling messages between WISE agents.

Within WISE, packets of information flowing between these agents are called *interactions* and are essentially an internal WISE information protocol. There are four types of interaction used during a WISE execution: *organisation interactions*; *physical interactions*; *event notification interactions*; and *schedule interactions*. The structure of each interaction is different in that organisation interactions convey information to other organisations and players (e.g., reports, requests for re-supply), whereas physical interactions contain instructions that can be interpreted by physical behaviour models within WISE. Player interactions will comprise either organisation interactions or physical interactions. Event notifications are used by the physical models to publish the occurrence of an event that may affect itself, or other physical models. Schedule interactions are used when an event is to be scheduled with the WISE coordinator agent.

The WISE modelling framework layer (see figure 7.1) is the bedrock of the WISE capability and allows analysts to configure modelling agents to represent the required functionality for a study. In addition to this layer there are some standard modelling agents that are able to log data during an execution, enable participation within a federation linked together by the High Level Architecture³ (HLA) protocol, register events for future

3. The High Level Architecture (HLA) is a general purpose architecture for distributed computer simulation systems. Using HLA, computer simulations can communicate to other computer simulations regardless of the computing platforms. Communication between simulations is managed by a Run-Time Infrastructure (RTI).

execution, provide distributed coordination to ensure causality, display objects on the graphical user interface, and save and restore the state of the configuration when requested. The framework also includes the Modeller, an agent that is responsible for selecting the study agents from the study layer that are appropriate for the execution configuration selected by the user. These configured models run in parallel with the remainder of the framework agents (shown in figure 7.1), the Intelligent Behaviour Modeller (IBM), Physical Behaviour Modeller (PBM), Communications Manager (Comms), Organisation Manager (OM), and the Perception Manager (PCM). The Modeller is also responsible for recruiting the Master Events List (MEL) agent that allows events to be injected into the system to stimulate modelling agents or provide specific inputs to players. The MEL agent is technically a physical model and as such sits within the Physical Behaviour Modeller block. Figure 7.3 shows the main control panel for WISE which allows the analyst to configure the model and data outputs and launch player displays if required. All of this functionality ensures that WISE can be used not just as an SE yielding anecdotal insights, but as a serious analysis tool.

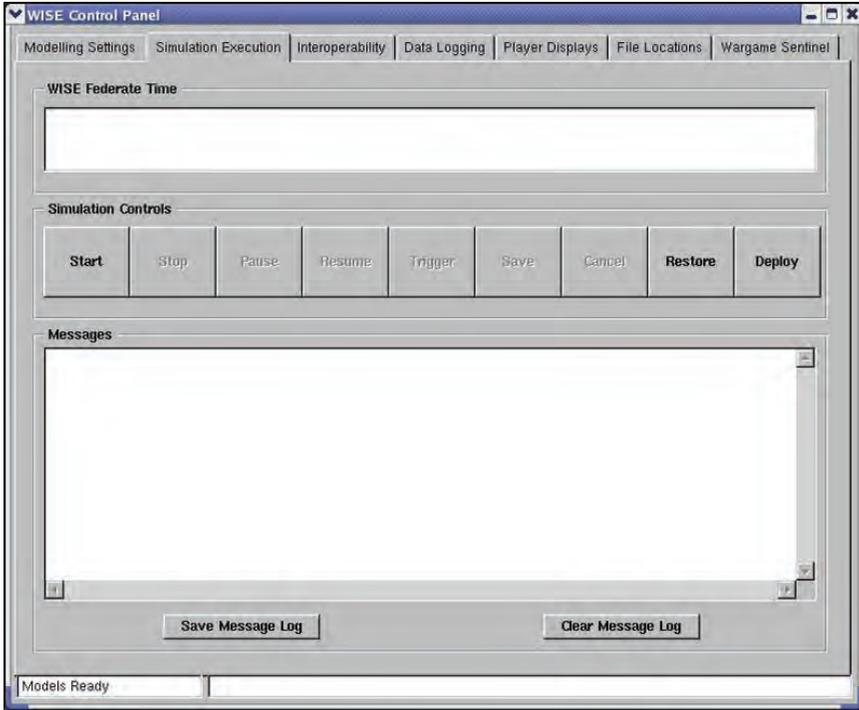


Figure 7.3: The WISE control panel, allowing configuration of the model, data and displays, as shown by the tags along the top of the panel.

The architecture of WISE had to ensure that it could represent a sufficiently rich command and control capability as required by the UK MoD Modelling strategy [2], and as spelt out here:

- *The ability to represent C2 at all levels:* The spectrum of operations, reflecting a more explicit political and military context, means political leaders will take a more active role in the decision-making process. Models should allow high level policy decisions to impact the

use of assets even at the tactical level since in non-war-fighting operations individual tactical assets may have strategic importance.

- *The need to represent the C2 structure flexibly:* Flexible structures are required to cope with new organisational force structures, ad hoc force packages and ad hoc coalitions.
- *The need to represent joint C2:* Increasingly operations are of a joint or multinational nature and the inter-relationships between services, coalition partners and non-governmental organisations need to be considered.

Organisations as the Building Blocks

The result of these requirements was a concept that considered building blocks based on *organisations*, organisational roles and physical resources. WISE avoids the explicit representation of equipment types and force elements by considering force elements as organisations that have roles and resources. As such any scenario could consist of a number of organisations, associated decision-making roles and physical resources. These characteristics can then be used to describe any force element or equipment type to be represented within a scenario. For example, it is possible to consider an organisation that represents Challenger 2 tanks as an aggregated group of physical resources and with an associated squadron commander role, or an organisation that represents an individual Challenger 2 tank as a physical resource, e.g., Tank1 with associated roles of commander, gunner, loader/signaller, and driver. Each role can be assigned an appropriate model for its required human behavioural representation.

Organisations and Roles

An organisation can be assigned any number of *roles*. Each role within the organisation undertakes processing on receipt of information to update the organisation's operational picture (the CROP discussed in chapter 4), which is based on a perception of the environment and is used to drive its decision-making. Roles can also be assigned to physical resources associated with an organisation. This allows attacks on physical resources to directly affect the processing capabilities of an organisation. For example, if a force commander is making decisions from a command vehicle that is destroyed through enemy action, an important decision-making function is removed from the organisation.

Information arriving at an organisation is processed and stored within an organisation's perception. *Domain objects* are used as a means of representing data about the domain of operation within an organisation's perception. Domain objects are organised into inheritance hierarchies to reduce the need for repetition, and are an example of frame-based knowledge structuring [3]. All objects that are to be represented in the scenario are described by a domain object, and this provides a means by which any type of object can be considered, whether it is the United Nations, an individual tank, or a sensor. An example extract from the domain object hierarchy is shown in figure 7.4. The domain objects in figure 7.4, such as *Organisation* or *LogisticsDescriptor*, are all inherited from *DomainObject*.

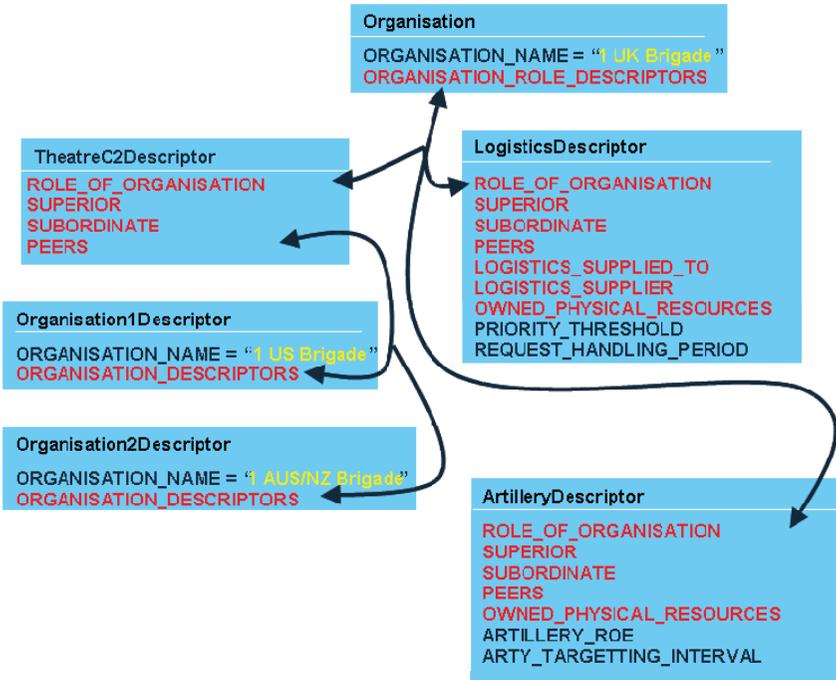


Figure 7.4: Extract from the WISE domain object hierarchy.

Relationships between Organisations

Attributes within the domain objects are shown in figure 7.4. These allow data to be stored against each attribute. Relationships can occur between domain objects of the same or different types. The double-headed arrows signify that relationships are inverse, e.g., if organisation *A* is specified as a subordinate organisation in the *SUBORDINATES* relationship of organisation *B* then organisation *B* will be specified as a superior organisation in the *SUPERIOR* relationship of organisation *A*.

Through such relationships the analyst has the ability to logically link domain objects to allow the creation of any type of command structure. Figure 7.4 includes the *Superior*, *Subordinate*, and *Peer* relationships. These relationships can be used to provide a link to any other type of organisation object and effectively define the command structure. Because each organisation descriptor contains the relationships, it is possible to define multiple hierarchies for a single organisation. For example an organisation designated as “1_UK_Brigade” could have separate organisation role descriptors for artillery and for the command of companies and squadrons.

Information Flows between Organisations

The C2 links between organisations allow for information flows during a scenario. It is possible for links to be broken and re-assigned dynamically during a wargame or simulation giving an ability for analysts to represent, for example, the formation and break up of self-synchronising, agile task organised groups. Each C2 link has delays associated with the passage of information which can be used to represent physical communications delays or delays as a result of C2 staff processes or functions.

Representing Situation Awareness and Shared Awareness

The cycle of processing within an organisation is representative of a situation assessment process leading to an end state that represents the organisation’s situation awareness. A *role* within an organisation can be represented by any appropriate human decision-making model, such as the rapid or deliberate planning processes introduced in chapter 2, or by a human

player. When multiple roles are defined for an organisation, WISE is implicitly representing *shared situation awareness* within the organisation.

In order to distinguish between different levels of situation awareness within an organisation, WISE expresses this within the context of the model of situation awareness proposed by Endsley [4]. Endsley distinguishes between situation awareness and situation assessment by defining situation awareness as a state of knowledge and situation assessment as the processes used to achieve situation awareness. In Endsley's approach, situation awareness itself is characterised by three levels. Level 1 represents a perception of elements in the environment within a given volume of time and space, Level 2 represents the comprehension of their meaning, and Level 3 the projection of future status.

All decision-making within WISE is based on the organisation's perception of the environment, which is essentially a representation of Level 1 situation awareness within Endsley's model. Players within the wargame are presented with a fused organisational picture from which they would develop Level 2 and Level 3 situation awareness. Within a constructive simulation run this would be undertaken by the rapid or deliberate planners.

Examples of common relevant operational pictures (CROP) with different perceptions, taken from a recent study using WISE [5] are shown in figures 7.5, 7.6, and 7.7. Figure 7.5 shows the ground truth display screenshot from WISE and illustrates the actual position of all organisations within the screenshot area. With the exception of three enemy red unmanned air vehicles (UAVs) entering the named area of interest (NAI) and one unit

to the north-east of the area, a ground truth view shows that all red reconnaissance elements in the area have been destroyed (units marked with a black X).

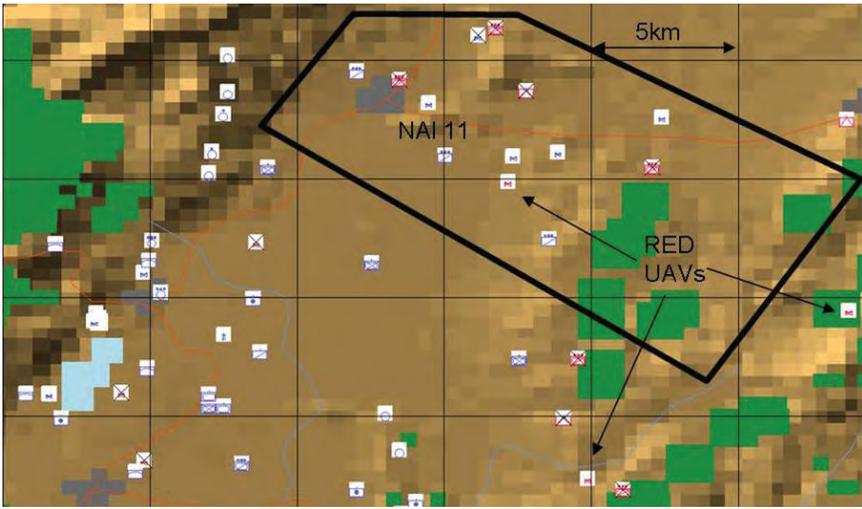


Figure 7.5: Ground truth CROP of red reconnaissance line and blue advance.

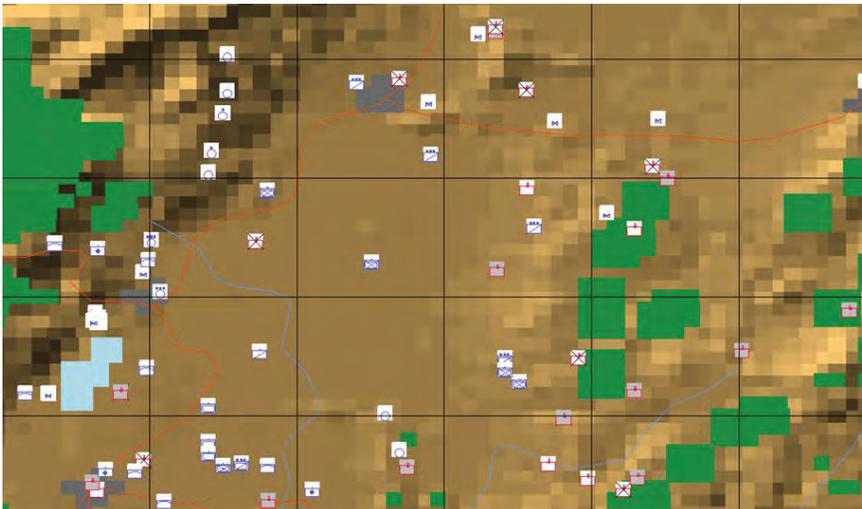


Figure 7.6: Blue perceived CROP of red reconnaissance line and blue advance.

The blue commander's perception of his sensor focus, including intelligence, surveillance, target acquisition, and reconnaissance (ISTAR), is shown in figure 7.6. Blue's perception of red is close to that of ground truth, and results from blue's comprehensive and coherent ISTAR plan; however, the perception of own force positions differs markedly from ground truth. The screen shot also shows the beginnings of battle damage assessment reports being received from the sensors (shown by the presence of black X's on the blue perception).

In contrast to the blue perception, the red commander, who had less sensor capability, had a far poorer feel for what blue was doing or the levels of attrition being achieved against blue. Figure 7.7 shows the red divisional commander's perception of the battle at the same time as the previous screen shots.

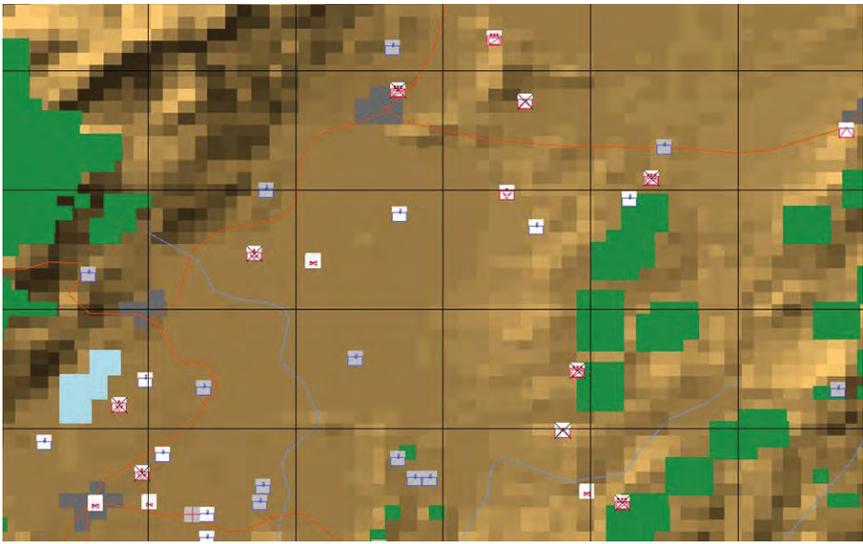


Figure 7.7: Red perceived CROP of red reconnaissance line and blue advance.

During a constructive simulation run, or for selected organisations during a wargame experimental intervention, the resulting Level 1 situation awareness is made available to an organisation following fusion of the information in the interactions. The organisation will then invoke either a rapid planner or deliberate planner [6], to undertake Level 2 and Level 3 situation awareness, leading to a course of action being selected by either of the planners.

Invocation of the rapid planner is not only done on a periodic time basis but when there is a change in the situation, e.g., a new acquisition. In its present form the presented picture is used by the rapid planner to calculate the current perceived combat power ratio between the organisation undertaking the planning and all acquisitions of interest, from both a spatial and temporal aspect. Once the combat power ratio is calculated, it is used to select the appropriate course of action, such as: `WITHDRAW`, `HASTY_DEFENCE`. Work currently in progress will replace this with an extended form of the rapid planner capable of coping with multiple cues, as we discuss later on in this chapter.

The architecture of WISE results in a capability that is readily flexible and able to provide modelling abstractions suitable for a wide range of studies. Figure 7.8 shows a screenshot of WISE as seen by one of the players in the SE mode.

Analysing Higher Levels of Shared Situation Awareness and Command Agility

In SE mode, WISE offers sufficient C2 modelling flexibility to be able to analyse varying aspects of all of the NEC epochs shown in figure 7.9 (taken from chapter 4).

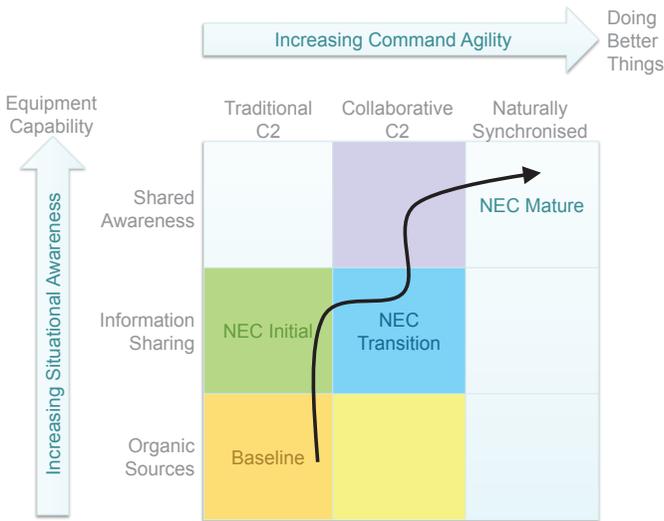


Figure 7.9: The relationship between command agility and levels of shared situation awareness.

However, despite the inclusion of the rapid and deliberate planners, there are still challenges in modelling these epochs within constructive simulation mode which presents the analyst with difficulties in considering higher levels of NEC command, especially the effect of shared situation awareness, and natural, or self-synchronisation. To help capture these higher levels of NEC command, our recent research activities have focused

on improving the WISE modelling capability in three ways, each leading to less scripted and more proactive responses to changes in the simulated environment.

Decision-Making

Firstly there have been improvements to the basic rapid planner which now allow for any number of cues to be defined, rather than just combat power ratios. Course of action selection is also now done according to the context of the overall mission assigned, characteristics concerning the commander that drive this selection, and forecasting of possible future cue values and likely mission states. The latter is important as it allows for the possibility of proactive rather than reactive actions occurring.

Secondly there has been research conducted to allow modelling of the dynamic creation and dissolving of task organised groups, and the associated group behaviour, with the aim of representing improved execution of a course of action from the rapid and deliberate planners.

Thirdly, research into collective behaviours has been undertaken which is aimed at improving the way in which models undertake what is essentially the process of situation assessment, leading to comprehension and projection within the Endsley situation awareness model, especially as applied to the more irregular groupings likely to be encountered in the 21st Century complex endeavours discussed in chapter 2 and reference [7]. This then leads onto an assessment of likely enemy intent which can be used as input data to the deliberate planning process, thereby reducing the need for this data to be presented to the deliberate planner prior to a simulation study, or it can be used as input data into the extended rapid planner in

the form of cues for consideration in course of action selection. Each of these research initiatives complement each other and together move the constructive simulation modelling capability closer to being able to represent more mature levels of NEC, and leading to simulated force elements that can self-synchronise if necessary to achieve an effect.

The Extended Rapid Planner

The extended rapid planner can now be configured to respond to data defined environmental cues⁴ (e.g., perceived enemy casualties, logistics state, combat power ratio) and then use these cues to match its experience with an appropriate course of action. Within WISE the rapid planner is presented with cues from the organisation's perception, following fusion of data presented to the organisation through the set of interactions as illustrated in figure 7.10.

4. Within cognitive psychology a mental structure containing knowledge relating to a particular object (which could be a situation) is called a schema. When observations are received the schema can be activated by triggering schema categories putting all the knowledge of the situation at the decision makers' disposal. Within the rapid planner a cue is equivalent to a schema category.

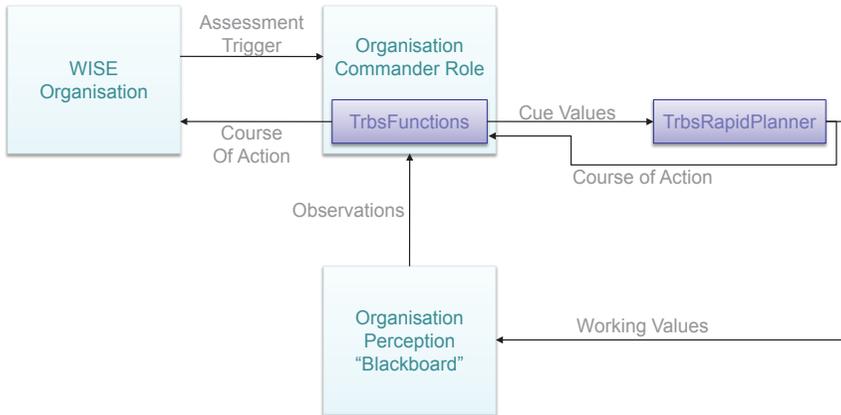


Figure 7.10: Architectural implementation of rapid planner within WISE.

On receipt of cue values to be assessed from WISE, the rapid planner then follows the following four stages:

- Stage 1: Observation analysis and parameter estimation;
- Stage 2: Assessment of the current situation;
- Stage 3: Pattern matching selection of a preferred course of action; and
- Stage 4: Allowing a change of course of action.

These are described in detail in reference [6]. To decide which course of action to take all the cues must be looked at together. Each cue will have a fuzzy state and depending on the combination of fuzzy states (e.g., high for cue 1, low for cue 2, low for cue 3) an appropriate course of action will be chosen.

Agile Task Organised Grouping

Algorithms have now been developed to allow a hierarchical heterogeneous collection of organisations to self-organise themselves following the creation or dissolution of agile task organised groups whilst maintaining sensible formations as they navigate around obstacles. When an organisation is added to or removed from the formation, the formation adjusts itself to accommodate the changes. Full detail of the algorithms is given in references [9, 10].

The relative position of the organisations is controlled by velocity components. There are two of these: a radial component that ensures the correct separation, and a tangential component which ensures the correct angular separation. Member i of a formation exerts a velocity

$$\mathbf{v}_{ij} = \left(-\frac{a}{r^\alpha} + \frac{b}{r^\beta} \right) \hat{\mathbf{r}}$$

on member j , where r is the distance between them and a , b , α , and β , all positive, are constants. If the organisations are too close, then the velocity moves them apart, and if they are too far apart, the velocity moves them together. Entities i and j may be the same type or different types; the values of the four constants depend on the two organisation types, and are not necessarily reciprocal. Typically, the organisations only exert velocities on others at the same or lower levels in the hierarchy, but not on organisations at higher levels.

Different types of organisation have different optimum orientations with respect to the command organisation; some, for example, should be behind, and others in front. Suppose that

the optimum angle between the entity and the headquarters unit (HQ) is θ , and the angle currently is ϕ , then there is a velocity acting on the organisation of magnitude

$$\frac{c(\theta - \phi)}{r}$$

with a constant c , and direction normal to the vector joining the organisation to the command unit directed so as to reduce the deficit. The expression is divided by the separation, r , so that when an organisation is far from the rest of the formation, its first priority is to adopt the appropriate separation, and only as the separation reduces does it begin to adopt the appropriate orientation. The parameters c and θ are, in general, different for each organisation type, but are the same for all organisations of the same type, even if they have different command organisations; all organisations of the same type and subordinate formations of the same type are interchangeable.

There are a number of velocity components acting on each organisation. The formation adjusts itself until the sum of those components is zero for each organisation. If an organisation is added or removed, then the formation re-adjusts itself until equilibrium is again achieved. The velocity of each organisation found by the disposition algorithm may be modified in the presence of obstacles. The formation attempts to retain its structure; however, if it has to pass through a gap narrower than the width of the formation, it is disrupted. The basic principle is that each organisation looks ahead. If it sees an obstacle, defined as an area across which it must not travel, then it rotates its velocity vector so as to avoid the obstacle. In order to allow the formation to retain its structure, each organisation

adds an extension to each obstacle whose size is typically the separation between it and the lowest level organisation in the hierarchy in open space.

Situation Assessment

Research on identifying collective behaviour [11] is aiming to improve the representation of the situation assessment process, particularly in the types of complex endeavour which are the challenge for the 21st Century, by allowing simulated forces to exploit information. Here, groupings of enemy elements are likely to be much more irregular and hard to define in terms of their intent, resulting in measures of situation awareness that relate to Endsley Levels 2 and 3, as defined in reference [4]. When these measures are used as inputs to the rapid planner they should result in improved behaviour representation within both wargame and constructive simulation modes.

The approach utilises a *Minimum Spanning Tree* based algorithm [12, 13] to model the fusion of indicators deemed to be important in determining collective behaviour and proceeds as follows:

- A fully connected bi-directional weighted graph with N vertices and $N \times \left(\frac{N-1}{2} \right)$ edges is constructed. The vertices represent acquisitions of WISE organisations, and the weights of the edges are a measure of how well two organisations are related.

- A Minimum Spanning Tree is built using Dijkstra's Algorithm [14] whereby the organisations are all connected in such a way that the sum of the edge weights is the minimum possible.
- A density approximation of the distribution of this minimal set of edges is computed using Gaussian Parzen Window estimation [15]. The edges that have a value above some predefined cut-off threshold are removed. The resulting *forests* (that is, collections of non-cyclic trees) represent clusters of organisations that are assessed to be behaving in a collective way.

Figure 7.11 illustrates the algorithm pictorially. The top image represents the fully connected graph. The bottom left image represents the Minimum Spanning Tree and the bottom right image represents the forests that remain after removing the edges above the cut-off value.

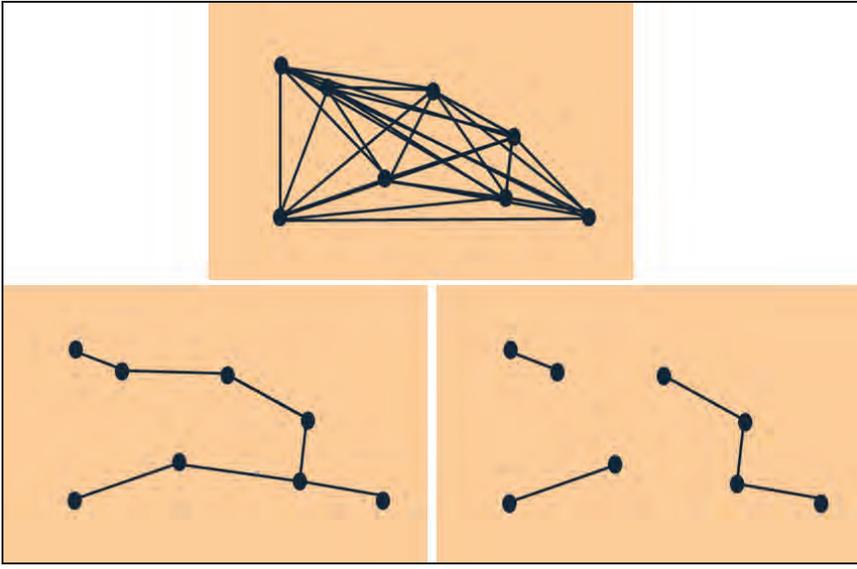


Figure 7.11: Minimum spanning tree (MST) algorithm.

The edge weights are free variables that can be defined for a specific application (e.g., for indicators of separation distance, velocity difference, density of communications traffic). In addition, the method allows for the fusion of indicators to be easily modelled and for indicators to be weighted, thereby reflecting the importance of their contribution to the definition of collective behaviour. The initial version of the algorithm uses indicators concerned with differences in *distance* (geographical location), *speed* and *heading*⁵ for a pair of organisations. Each indicator is normalised in the range $[0,1]$ by dividing by the maximum observed value for that indicator in order that an

5. With care taken to ensure that differences are taken in the minor sector so that the difference in heading between an agent travelling at 1° and one travelling at 359° is 2° and not 358° .

indicator does not dominate due to differences in unit (e.g., *distance* in metres is likely to be a much larger value than *heading* in degrees).

The edge-weight ($EW_{i,j}$) of the graph (that is, a measure of *relatedness* between any two organisations, i and j) is:

$$EW_{i,j} = \left(\alpha \times \frac{d_{i,j}}{\max_{i \neq j \in N} \{d_{i,j}\}} \right) + \left(\beta \times \frac{|\Delta s_{i,j}|}{\max_{i \neq j \in N} \{\Delta s_{i,j}\}} \right) + \left(\gamma \times \frac{|\Delta h_{i,j}|}{\max_{i \neq j \in N} \{\Delta h_{i,j}\}} \right)$$

Given that there are N organisations: $d_{i,j}$ is defined as the *distance* between the two organisations and $\max\{d_{i,j}\}$ is the maximum *distance* over all pairs of organisations; similarly $\Delta s_{i,j}$ and $\Delta h_{i,j}$ are the respective differences in *speed* and *heading* between all pairs of organisations.

The parameters α , β , and γ are weights which can be adjusted according to how important each indicator is considered to be. For instance, *speed* and *heading* will be more discriminatory for clusters which are co-located. In contrast, when organisations are spread over a wide geographical area with varying *speeds* and *headings*, each indicator becomes important when trying to group organisations together. The weights adapt dynamically with each execution of the algorithm, based upon the corresponding indicator's standard deviation and range [11].

The resulting output of this part of the situation assessment process is a form of picture comprehension in that the rapid planner can be presented with a cue that indicates the speed, heading and geographical spread of possible clusters of, for example, enemy force within the CROP, thereby forming an element of Level 2 situation awareness (comprehension)

as defined by Endsley [4]. The same approach could also be applied to clusters of refugees or other parties within the CROP. *Party* here is used in the same sense as in chapter 5 when discussing the DIAMOND model, and essentially means a group with a common intent and local information networking.

Having hypothesised which organisations are clustered together, it is useful to provide some means by which to measure the confidence that the algorithm has been attributed in these clusters and to indicate their general intent. If the *speeds* and *headings* of the organisations within each cluster are similar, this is used as an indication that they do indeed belong in the same cluster. In contrast, if there is a wide spread of *speeds* and *headings* of the organisations within the same cluster, then there is a lower confidence in the cluster. Based on this premise, the confidence in a hypothesised cluster (a set C , which defines a subset of organisations that are grouped together) is calculated as follows:

$$Confidence_C = \left(\frac{\beta \times \sigma(s_{i,j})}{\max\{s_{i,j}\} - \min\{s_{i,j}\}} + \frac{\gamma \times \sigma(h_{i,j})}{\max\{h_{i,j}\} - \min\{h_{i,j}\}} \right)^{-1}$$

given $s_{i,j}, h_{i,j} \in C$.

In other words, the standard deviation of the *speed* and the *heading* are normalised by the range of values for each property. β and γ are the values used to weight the indicators as described earlier.

It is desirable to normalise the possible values of confidence. This can be done by considering the range of values that the denominator can take [16]. For a cluster of P organisations, the confidence lies in the range defined by:

$$\frac{2}{\beta + \gamma} \leq \textit{Confidence} \leq \frac{\sqrt{2P}}{\beta + \gamma}$$

As noted in [16], the upper limit is dependent on the cluster size P . Therefore, the raw confidence score is scaled to take into account the cluster size, placing more confidence in smaller clusters. Let the minimum and maximum possible confidences be \textit{MIN} and \textit{MAX} respectively; a normalised score in the range $[0,1]$ is given by:

$$\frac{\textit{Confidence} - \textit{MIN}}{\textit{MAX} - \textit{MIN}}$$

Note that when $P = 2$, $\textit{Confidence} = \textit{MIN} = \textit{MAX}$ so that the normalised confidence is undefined. Thus the cluster size P has to be at least 3.

Having hypothesised clusters of force within the CROP, and the confidence in them, it now remains to infer the intent for a given cluster. Given M clusters and N possible destination objectives, there is a requirement for a method by which each cluster-objective pair can be scored to represent the likelihood that a specific cluster is moving towards an objective. Currently, intent is inferred with respect to the position of fixed objectives; these may be, for example, important geographical features, towns, or key fixed infrastructures. The positions of objectives are passed as input parameters to the algorithm. The prediction of intent, or likelihood scoring, is calculated dynamically; thus confidence in the intended objective varies as a function of time.

Daglish [17] proposes a method of *likelihood scoring* for a set of targets, for which we can substitute objectives, defined by their locations. Briefly, the method can be described with reference

to figure 7.12. All angles are measured in an anti-clockwise direction from the positive x -axis. The *direction of movement*, representing the direction of a cluster, is defined by the angle ω and is taken to be the mean *heading* of the agents in that cluster.

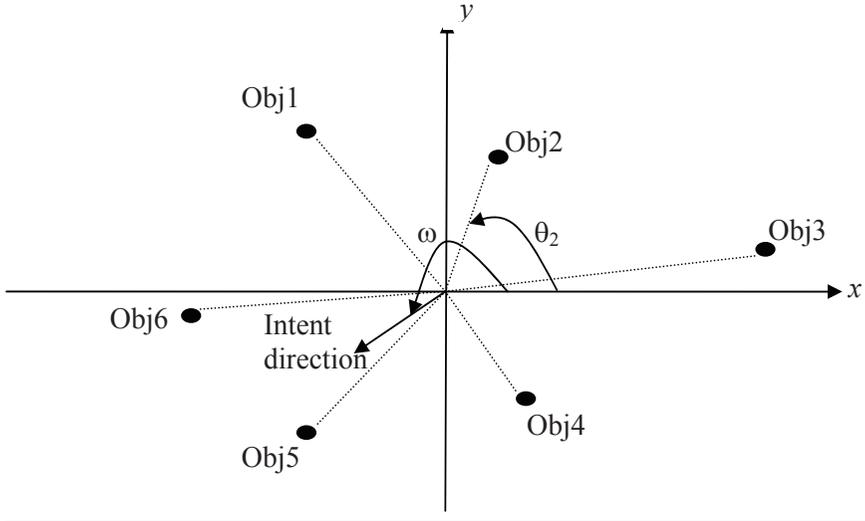


Figure 7.12: Inferring intent with respect to possible objective locations.

A family of functions is defined to give an indication of intent with respect to an objective. Put another way, it calculates the likelihood that the cluster is moving towards an objective:

$${}^n_{\omega}\tau(\theta_i) = \frac{1}{2} [1 + \cos^{2n+1}(\omega - \theta_i)]$$

for $n = \{0,1,2,3,\dots\}$, then:

$$(\omega - \theta_i) \in [-\pi, +\pi];$$

$$\theta_i \in [\omega - \pi, \omega + \pi];$$

$${}_{\omega}^n\tau \in [0,1]$$

given that ω is the direction of movement of a cluster and θ_i is the angle between the positive x -axis and the line that links Obj i and the origin, measured in an anti-clockwise direction as shown in figure 7.12 for Objective 2.

Figure 7.13 shows a selection of members of this family of *naïve target commitment* functions ${}_{\omega}^n\tau(\theta_i)$, given $\theta_i \in [\omega - \pi, \omega + \pi]$ for any angle ω and illustrates the tripartite tendency of the curve, which corresponds to the classes defined below. This tendency becomes more pronounced as n increases. When considering a single direction of movement against a single objective location, the significant values of τ , determined by the value of $(\omega - \theta)$ are as follows:

- ${}_{\omega}^n\tau = 1 \Rightarrow$ The direction of intent *is* the objective location
- ${}_{\omega}^n\tau = \frac{1}{2} \Rightarrow$ It is *undecided* whether the direction of intent is aligned with the objective location
- ${}_{\omega}^n\tau = 0 \Rightarrow$ The direction of intent is *not* the objective location

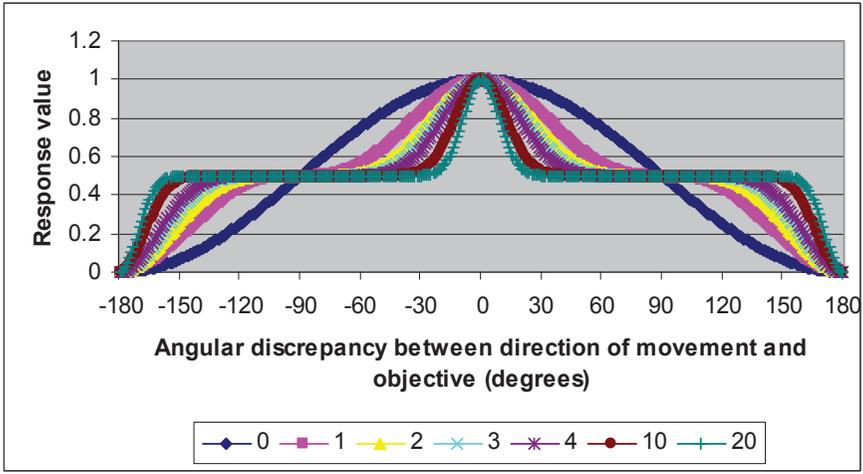


Figure 7.13: Naive target commitment functions.

As n increases, the shoulders of the curve shown in figure 7.13 become wider, and, in contrast, when n is small the class defined

by ${}^n_{\omega}\tau = \frac{1}{2}$ is also small. The choice of the value of n will thus

determine the degree of sensitivity of the function. With increasing n the bins corresponding to $\tau = 0$ and $\tau = 1$ become narrower.

The choice was made to use $n = 10$ as a *proof of principle* to show the function of the algorithm in inferring intent. A wider plateau results in a higher likelihood that those clusters sent to the $\tau = 0$ and $\tau = 1$ classes are correct, and increasing n from 10 to 20 has only a small effect upon the length of the plateau. It is intended that future development of the algorithm will attempt to assign n dynamically. It could be argued, for instance, that the choice of n should be allowed to vary depending upon the

scenario, especially where the degree of accuracy may become more critical. For instance, for high or very high values of n , marginal hostile intent could be masked by the extent of this plateau.⁶

In addition to an indication of intent, the destination objectives can be prioritised relative to the naïvely perceived commitments of any given cluster according to:

$$T_i = \frac{1 + \cos^{2n+1}(\omega - \theta_i)}{N + \sum_{j=0}^{N-1} \cos^{2n+1}(\omega - \theta_j)}$$

for $n = \{0,1,2,3,\dots\}$ and where N is the total number of objectives. Note that $\sum_{i=0}^{N-1} T_i = 1$, such that the set $\{T_i\}_0^{N-1}$ is termed a

set of *ranking commitments* for the given set of objective locations. That is, the ranking commitments suggest where the attention of the commander (within the simulation model) should lie and the relative importance of these priorities. This will allow decisions to be made with regards to allocation of assets (*force priorities*). The resulting output of this part of the situation assessment process is an assessment of the projection of the future status of, for example, possibly threatening force clusters and their associated organisations, thereby forming an element of Level 3 situation awareness (projection) as defined by Endsley [4]. By using the output from this assessment the extended rapid planner can be presented with a cue that indicates the

6. False inferences of this type would not present so much of a problem for those clusters that are classified as *undecided* rather than *non-threatening* (that is, those for which $\frac{n}{\omega \mathcal{T}}$ tends to zero).

intent and an assessment of which threatening force clusters should be given priority attention, leading to improvements in the selection of courses of action and more agile behaviour.

Measuring and Quantifying Situation Awareness: An Illustration

We finish this chapter with an illustration related to measuring the effectiveness of command information systems (CIS) at the battlegroup level [18]. The overall aim of the work was to develop and test a method for quantifying the effect of a digitised CIS on situation awareness and force effectiveness within a battlegroup level vignette (a part of a larger scale future scenario). Two cases were defined. The *control case* represents a battlegroup fighting with insecure analogue communications equipment and using traditional mapping products to plan and conduct the operation. The *treatment case* represents a battlegroup fighting with secure, encrypted digital communications equipment and appropriate supporting battlefield information systems applications, with digital mapping and own side position reporting relayed automatically through a *blue force tracker*⁷ and reported through the digital mapping. Each of the cases was wargamed and then a number of constructive simulation runs of each WISE game were undertaken. The Mann-Whitney U-Test was used to determine whether the force effectiveness measures from the two cases were different at the 95% significance level and the Spearman rank correlation test was used to determine if the situation awareness and force effectiveness measures were correlated. Both tests assumed that the output data were non-parametric.

7. Which shows in plan view the locations of all relevant blue units.

The research hypothesis was “the digitisation of a battlegroup headquarters, subordinates, and battlegroup enablers would affect the timely delivery of appropriate effects, leading to changes in blue force effectiveness.” For the purpose of the study, there was no presumption that digitisation (the treatment case) would improve force effectiveness relative to the control case, hence this was a two-tailed hypothesis. The null hypothesis was that there would be no change in blue force effectiveness as a result of digitisation of a battlegroup headquarters, its subordinates and battlegroup enablers. The following measures of C2 and force effectiveness⁸ were used to test the hypothesis:

- measurement of situation awareness within the battlegroup headquarters, corresponding to a measure of C2 effectiveness (MoCE); and
- Measures of force effectiveness (MoFE) using casualties to blue and red and the overall red:blue loss exchange ratio.

To measure situation awareness, the study developed both a quantitative method and also used an existing method, the *situational awareness rating technique* (SART) [19] to derive an independent score. The SART score was cross-checked with the quantitatively derived measure from the combat model as a means of ensuring some level of confidence in the quantitative measure.

8. These measures are consistent with definitions described in the *NATO Code of Best Practice for C2 Assessment* (Moffat et al. (2002) US DoD CCRP, Washington DC, USA).

Metrics were developed for the three levels of situation awareness as defined by Endsley [4]. For the analysis discussed here, only Endsley's Level 1 was used to derive the battlegroup headquarters operating picture and its relationship to force effectiveness, reflecting the quality of information at the battlegroup headquarters, leading to a measure representing accuracy and completeness⁹. The methods for calculating situation awareness used information within the perception of the battlegroup headquarters organisation, along with ground truth, to calculate an objective measurement of situation awareness within the battlegroup headquarters at the defined levels. These measures for Level 1 awareness at individual time steps within each constructive simulation replication were combined to give an overall measure which was then used to compare with our metric for force effectiveness.

To calculate the Level 1 situation awareness, an error term was defined for the distance measurement, which measured the *offset* in kilometres of a perceived location of an own or an enemy organisation, relative to its true ground truth location. Once levels of distance error, based on time and space considerations, are derived, an appropriate weighting for this error is derived from a utility function, calculating the possible threat in relation to the distance error in order to arrive at a Level 1 situation assessment product (see table 7.1).

9. As also highlighted in the *NATO Code of Best Practice for C2 Assessment (ibid)*.

Unit	Seen	Error in location	Error (weighted)	Product (Seen * weighted error)
T ₁	1	A	x	x
T ₂	0	B	y	0
...
T _n	1	C	z	z
Count of all units (N)	Count of units seen (n)			Total of Products (s)

Table 7.1: Information required to calculate Level 1 situation awareness.

The values are used to calculate Level 1 situation awareness as follows:

$$Level_1_SA = \frac{s}{N}$$

Where:

s = total of products from table 7.1;

N = count of all units from table 7.1.

Figure 7.14 shows a scatter plot of overall Level 1 situation awareness from both the analogue (control case) and digitised (treatment case) simulation runs against the overall loss exchange ratio (an MoFE). The results are taken from 10 replications of the analogue simulation runs and 10 replications of the digitised simulation runs. Figure 7.14 shows that there is a strong correlation between Level 1 situation awareness and force effectiveness. A Spearman Rank Test shows the correlation to be significant ($r = 0.84$, $n = 10$, $p = 0.01$). Although figure 7.14 shows a linear relationship, it is expected that as

more cases are considered with increased situation awareness, the result would not continue to be linear but show a diminishing returns effect.

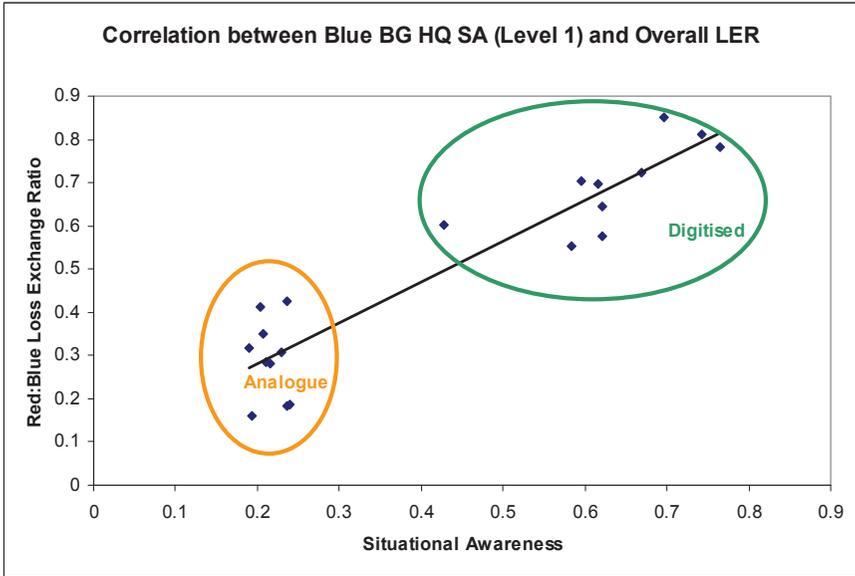


Figure 7.14: Plot of Level 1 situation awareness against red to blue loss exchange ratio for analogue and digitised cases showing correlation.

Summary

Within this chapter we have described the Wargame Infrastructure and Simulation Environment model and how it is being used as a test bed for the development of techniques to enable analytical assessment of agility and network enabled capability. The C2 modelling approach developed for use within WISE, coupled with a perception based modelling approach, makes it an ideal environment within which to develop and test these innovative ideas. These innovations are beginning to be

applied in support of studies and are advancing understanding in what is a challenging analytical environment. There are still issues to be addressed in enhancing these approaches, and further developments are planned for WISE together with a number of experiments utilising the ideas described in this chapter.

Much of the material on the recent algorithmic developments in the areas of collective behaviour and agility has been drawn from the referenced material following this chapter.

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CHAPTER 8

SHAPING UK DEFENCE POLICY

Informing Ministry of Defence (MoD) Decision-Making

In this final chapter, we move on from the contextual background and the key challenges arising from information age warfare, to a brief consideration of the advice that MoD decision-makers require, broadly referred to in the UK as the provision of evidence-based support to decision-making. Note, crucially, that the role of OA is to assist such decision-makers and not to usurp them. The decisions to be supported tend to fall into a number of overlapping categories. These are outlined below and followed by a commentary on how they are impacted both by the challenges described in chapter 1 and by the modelling developments described in chapters 2 through 7.

At the highest level are decisions related to *overall defence policy and force structure* as articulated, for example, in House of Commons Defence White Papers. These rely on analysis of a wide range of current and potential future operations and,

typically, involve trade-offs across all three armed forces (army, navy, and air force) in terms of capabilities, force structures, and associated costs.

Next come *high-level balance of investment (BoI) decisions* where a slightly narrower trade-space applies, such as the best force mix to conduct early entry operations or the optimum set of capabilities for attacking land-based targets. Importantly, the context for such studies comes from the overall defence policy work, and, in turn, the BoI work provides much of the data required for the former.

A third category is the support of individual *capability decisions*. So, for example, having decided that, say, an artillery system with certain attributes is required as part of the overall land-attack capability, which specific solution option best fits the bill? Again, context for such work in the form of scenarios can be provided from higher-level studies and the detailed *capability decision* studies provide data for the BoI work.

Finally, in this hierarchy comes more detailed work to assist with decisions related to the delivery of specific *capability solutions*. These normally operate within a very limited trade-space, often that for an individual equipment. Increasingly such decisions are not related solely to the capabilities of the equipment under consideration but also to wider factors across the Defence Lines of Development (DLoDs) including training, manning, logistics support, and infrastructure; as well as to its supportability through-life and from factory to foxhole.

In addition to this hierarchy of major types of decision-making, there is the requirement to support current *operational decision-making*—that is, supporting operational commanders with

their day-to-day decisions whilst actually on operations. Such decisions are typically taken in very time-constrained situations. These categories are by no means exclusive nor are they exhaustive, but they typify the range of types of decision-making that analysis needs to support.

General Points on Supporting Decision-Making

A number of observations are worth making across the range of decision-making categories before turning to more detailed observations in each category. First, as alluded to, context tends to flow from higher-level studies into lower-level ones. Similarly, data support for higher-level work usually comes from lower-level endeavours. One key consequence of this is that the models and methods that we adopt also need to inter-relate effectively to support this flow of information. In chapter 5, we have already described the key models in this hierarchy, and how they interrelate. Their organising principle is the representation of command and the related planning activities required to represent information age conflict.

A second key point is that we need to understand how confident we are in any evidence that is put forward—is it, for example, based on extensive modelling with well validated models? Validation (and verification) of our approaches is, therefore, vital if we are to use their outputs to underpin significant decisions. In chapter 6 we have already described in detail the extensive effort we go to in order to build confidence in the validity of our models across the modelling community, with customers and with wider stakeholders. This includes both review of the models and their behaviour by military experts, as well as the ability of such models to replicate the results of actual conflicts.

Thirdly, decision support needs to be tailored to the time when the decision needs to be taken. The extreme case is supporting operational commanders, who may well need the best advice possible in a matter of hours; however, the same principle applies throughout the modelling enterprise. Perfect advice provided after the decision has been taken is clearly not helpful!

Fourthly, our model suite must be capable of addressing all types of future operations as support to decision-making will be needed both for each individual scenario type and across the scenario-space as a whole. Challenge 1, concerning the need to represent a wide range of military operations, thus pervades our efforts in improving approaches to information age warfare.

And finally, wherever practicable, involvement of the decision-maker during the studies designed to support them is highly desirable. This helps to ensure the work is focused on the real issues faced by the decision-maker as well as provide opportunities to explain the provenance and detail of any methods, thereby generating confidence in the ultimate output.

Supporting Overall Defence Policy and Force Structure Decisions

Analysis supporting defence policy and force structure decisions is mainly undertaken for decision-makers in Policy and Strategy. The overall force development process is outlined in figure 8.1.

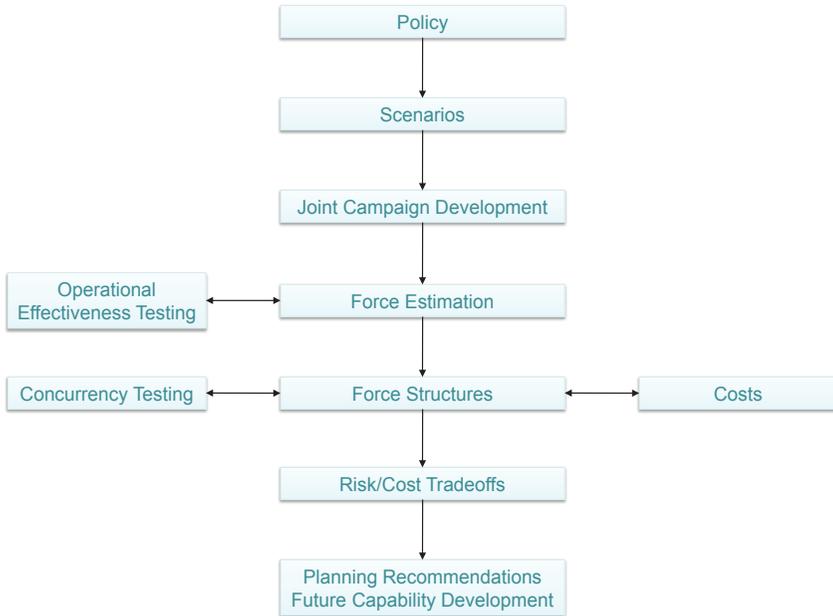


Figure 8.1: The force development process in the UK Ministry of Defence.

In broad terms, the overall planning requirements, as laid down in Defence Policy, are instantiated via Force Estimation and Campaign Development processes in a set of planning scenarios used across the modelling enterprise to ensure consistency and coherence as well as alignment to policy aspirations. It is at this point that the modelling suite kicks in, corresponding to the box labelled Operational Effectiveness Testing. This is where the actual outcomes of potential scenarios are determined, including potential excursions from any standard “reference” case to test alternative concepts of operations, tactics etc. Frequently, there is an important iteration back to the Campaign Development process, in particular in cases where the original reference case—determined largely by military judgement—proves to be untenable for some reason.

This might arise, for example, if the planners had been overly optimistic about blue's ability to progress in the campaign or if the modelling showed the campaign was not supportable at the required tempo of operations in logistics or command and control terms. The modelling, and the methods explained in earlier chapters, plays a key role in translating the largely judgemental work in the top part of the programme into a more evidence-based appraisal of individual campaigns. This, in turn, is used in the lower half of the diagram to inform overall decisions on force structure taking a larger set of scenarios into consideration.

For the modelling suite to be able to play its role in this process effectively, it is essential that the models appropriately reflect all aspects of future campaigns. Addressing the eight challenges laid out in chapter 1 is therefore critical, and much progress has been made, as elaborated earlier. In some areas the models are not yet fully able to represent the necessary factors, where our data and/or understanding are currently incomplete, such as in the assessment of non-kinetic effects (challenge 8) or the residual fog-of-war (challenge 6). In these cases it is necessary to pursue a vigorous research agenda to continue to develop our methods—and this is indeed in place—while ensuring that the architecture of our models is cognisant of potential future needs. In the interim, we need to utilise our modelling suite in tandem with other approaches, including military and scientific judgement and empirically-based evidence.

Supporting Higher-Level Balance-of-Investment Decisions

Such work is mainly undertaken for decision-makers in the Equipment Capability areas of MoD. Typically, a higher-level BoI study will utilise some form of integrating methodology, such as a linear programme, as illustrated in figure 8.2.

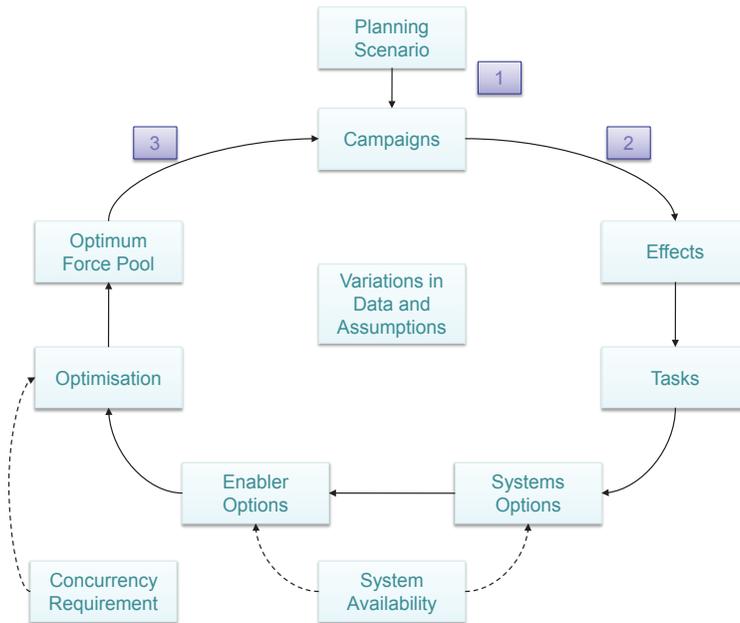


Figure 8.2: The cycle of variations in assumptions and data used in a strategic balance of investment analysis using linear programming.

The inherent uncertainties of the future environment mean that in addition to extensive variations in data and assumptions, this work is complemented by other strategic analysis looking, for example, at the role of agility in terms of covering the likely operational space.

The key role of the modelling suite in such studies is threefold. Firstly (box 1 of figure 8.2), as just discussed for the force structuring work, there is the need to produce viable reference campaigns that instantiate the planning assumptions in a credible fashion. Secondly (box 2 of figure 8.2), those reference campaigns need to be disassembled into their key components in a form that an optimisation method can then trade between. Key linkages between campaign elements can also be determined at this stage to ensure they are not lost in the optimisation process. Examples might include the need for particular command and control capabilities or surveillance means to support particular activities. Finally (box 3 of figure 8.2), the models also play a key role in checking that any optimised solution really can still achieve the required campaign success. Typically, this is done by running the optimised solution through the campaign models and, if required, iterating the process for example by capturing extra constraints in a re-run of the optimisation method, by adding extra tasks or linkages between them and so on.

As with force structure development, the modelling suite needs to address the eight challenges in order that both the campaign decomposition and the ultimate testing of optimised force structures can be done with confidence. Particularly important in this respect is the ability of our future models to address alternative ways of prosecuting the same campaign so that the impact of *doing better things* can be assessed, as well as *doing things better*. Challenges 3 (the impact of evolving technology) and 5 (human decision-making elements) are therefore particularly important. In both cases, the key is to move away from models that rely on prescribed approaches to scenarios, possibly with limited but preplanned branching, towards ones that can more fully select an appropriate course of action at any given point in time.

Supporting Capability Decisions

Such work is mainly undertaken for decision-makers in the Equipment Capability and Procurement areas of MoD. Typically the trade-space and decisions being informed relate to specific equipment procurement decisions or bounded capability areas. Modelling of information age warfare in support of such decisions falls into two main areas. First, there is a need to understand and effectively model the specific trade-space associated with C2, specifically the gathering of information by sensors of all kinds—intelligence, surveillance, target acquisition, and reconnaissance (ISTAR)—and military decision-making. The understanding generated from such work underpins other studies that need a representation of these aspects, at all levels of the decision-making hierarchy. Furthermore, it supports trade-space decisions within the command and control and sensors domain; for example, what should be the balance between improved aids to command decision-making, and improved gathering of information? What is the impact of decision-making within military headquarters? An illustration of the trade-space and some of the modelling issues involved is given at figure 8.3.

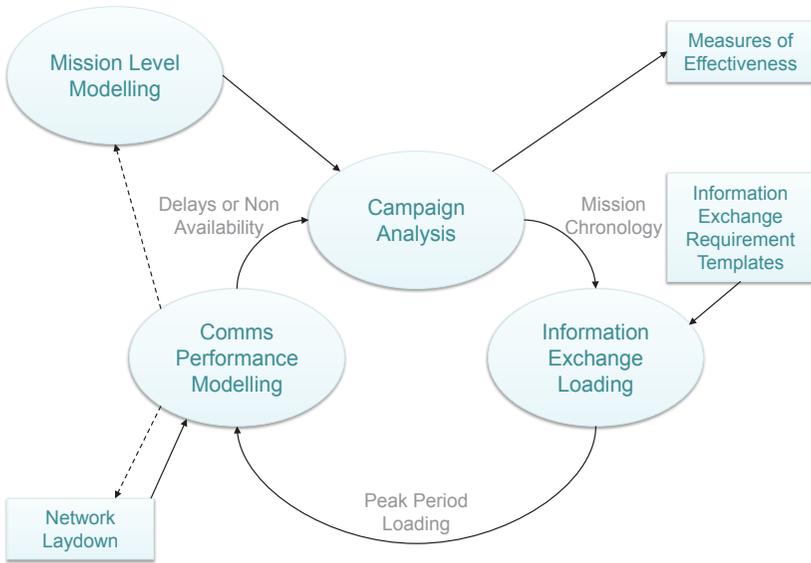


Figure 8.3: Issues involved in modelling the trade-offs within C2 and ISTAR.

Here, the modelling is effectively undertaken in two distinct, but mutually supporting, ways. The first relies on the construction of models that represent specific C2 and sensor collection processes and produce measures of C2 effectiveness in areas such as the delays or non-availability imposed by the particular communications architectures. The second set of models operate at campaign level and generate overall measures of effectiveness and campaign success drawing *inter alia* on the C2 measures. This modelling sits within the broader context of contextual information such as that from higher level force-structure level studies, and more detailed systems-level work in generating data and understanding.

An important point to note is that the campaign level models support both trade-space decisions *between* C2 and ISTAR elements **and** between {C2 and ISTAR} and all other capabilities. In the former case, the models can help to determine the best way of meeting C2 challenges in future operating environments—for example, in striking an appropriate balance between headquarters structures and the ISTAR assets that generate the overall picture of the situation on the battlefield. In the latter, the C2 or ISTAR capabilities can be traded with *effectors*—for example, what is the best balance between sensor assets and the weapons needed to prosecute the targets identified?

Challenges 4 to 6, those most specifically concerned with information age warfare, are particularly important to studies at this level. Sound understanding of information age warfare is a necessary precursor to implementing relevant models and populating them with data—much of the work described in earlier chapters has highlighted the advances in both understanding and in instantiating that understanding that have occurred in recent years.

Supporting Capability Solutions

The analysis of particular capability solutions is mainly undertaken for decision-makers within the procurement domain and often in support of a specific capability or equipment. Here, the level of fidelity required in the work is likely to be higher as the options to be discriminated between are typically much more similar than for decisions in the earlier categories. The need for extra fidelity is, however, frequently balanced by an ability to hold more things constant between options and thus we have a deeper but narrower trade-off space and need

for supporting modelling. Our previous discussion explicitly acknowledged the role of such studies both in informing their own trade-space and in providing data for higher-level, often more abstract studies.

A good example of such a system level study is the evaluation of the cost-benefit of tactical command information systems (CIS) discussed in detail in chapter 7. We have not explicitly focussed on the development of system costs and costing models, as that is not our purpose here, but in all such studies, a detailed costing of the various proposals would be made. In parallel, there is the requirement to develop a measure of the relative benefit that each of the proposed systems can offer. Here, low level modelling of communications networks can be used to derive measures of performance of the system (in terms of the ability to deliver the information in a timely manner, or measures of HQ situational awareness, for example). These can be used to compare, in performance terms, the ability of a new or improved system against the “do nothing” case of running on the current system. However, the key to success in such studies is the ability to relate these low level measures to higher level measures of effectiveness relating to the effects created on the battlespace by exploiting the CIS system (such as the likely red and blue casualty levels for example), as recommended in the NATO Code of Best Practice for C2 Assessment [1]. In the case of the tactical CIS example discussed in chapter 7, this link was made through using the WISE wargame and simulation.

Supporting Operational Commanders

Work in support of operational commanders is mainly undertaken for decision-makers in operational headquarters, often under severe time pressure (sometimes requiring a “good

enough” answer in a few hours for example). There are two key issues here. First is the ability to access understanding gained from more in-depth modelling. This is usually achieved by means of meta-models, look-up tables or similar systems for capturing the knowledge from more detailed work or by means of expert judgements from advisors in the headquarters (those judgements being underpinned by detailed knowledge of modelling capabilities, previous studies, and so on).

Second, is the ability to consider “what-if” options to support analysis of alternative courses of actions and their implications, both for own forces and for the enemy. Such fast analysis can be supported in a number of ways. One option is to utilise expert judgements or simple table-top games to examine options—where, as above, the understanding from previous work can be brought to bear. More formal methods of exploiting available knowledge can also be adopted, for example in the formulation of rules or simplified models that can conform to the pace required for operational decision-making. Finally, reachback methods can be adopted where time permits—or where prescience (or luck!) has enabled prior determination of likely options for consideration. In such cases the whole power of the available modelling suite illustrated in chapter 5 can be brought to bear outside the operational headquarters with the results and understanding then being communicated back to the commander in a timely fashion to support decision-making.

A final important point is that the decision-maker on operations typically *has* to make a decision—and thus will do so based on the best information available. The key to supporting such decisions is therefore clearly an ability to generate relevant advice and evidence in a timely fashion; however, an equally important facet is to know what level of confidence applies

to that evidence. Knowing how well the modelling represents the *real* information age world and being able to articulate that effectively and impartially is thus essential—understanding and tracking our progress with the eight challenges cited earlier is therefore much more than an academic exercise.

The Forward Agenda

A key insight into possible future challenges is given by the thoughts introduced in chapter 2—namely the trend towards more *complex* forms of warfare as societies transition from the industrial age to the information age. Concurrent with this transition is the need for increased *agility* in dealing with a wide set of uncertain futures.

The term *complex endeavours* developed by Alberts and Hayes, and introduced in chapter 2, has been used to characterise the complexity of problem spaces which are appropriate to information age conflict of the 21st Century involving coalitions of civil and military partners. In chapter 2 we identified a number of defining characteristics of a complex adaptive system and showed how the characteristics of a complex endeavour embody many of these thoughts, in fact showing that such endeavours are examples of complex adaptive systems; For example, the number and diversity of participants results in a correspondingly large number of *degrees of freedom* that, in turn, can generate a large number of different ways in which participants could interact.

Within the broader schema of operational research, we can classify likely challenges as *puzzles*, *problems*, and messes or *wicked problems* (a terminology originally developed by Russell Ackoff). Puzzles are those for which the question is clear and a

ready-to-hand algorithm is available to supply the answer (e.g., the scheduling of supplies from a warehouse to retail outlets). For problems, the question is still clear, but the solution, or set of alternative solutions, may be vaguely defined and challenging to deliver—there is no easy-to-hand approach. For wicked problems, neither the question nor the solution are well defined. This requires close working with the customer and stakeholders to crystallise the key issues, and then work through these as appropriate, developing understanding and solutions as required. Complex endeavours fall into the category of wicked problems.

From this perspective, a number of key points emerge:

- This is difficult intellectual territory—although much progress has been made, as detailed in chapters 2 through 7.
- We need to further develop the analytical skills required to deal with problems, and simulation models of these problems, which are inherently adaptive and nonlinear in their properties. For example, if a small change in the effectiveness of a system leads to a small change in the outcome, then that makes a straightforward story to tell. However, if the force is able to adapt to and nullify that change, then the outcome may be no different—and that makes a more complex story to tell, involving lines of development for the force such as training and doctrine in addition to just equipment, and thus addressing the whole capability of the force.

- A variety of interlinked simulation model approaches are required, building on our current hierarchy of methods described in chapter 5. Which of these matters will depend on the context of the decision being supported—there is no “one-size fits all.” The balance of complexity will be weighted towards the underpinning or system level models in this context.
- Much of this complexity is generated by humans in the model, whether they be military, civilians, insurgents, the Red Cross, or other actors. There is, thus, a major role for human factors research and experimentation to underpin future algorithms and provide relevant data.
- The world as a society does not stand still. Thus, our model developments must keep advancing within the context of helping our customers and stakeholders in government to understand issues such as the complexity of hybrid war where warfighting, peacekeeping and humanitarian assistance may all be intertwined and interlinked in a rapidly changing and dynamic environment. Future methods must be adaptable to such changes as well as fit for (current) purpose.

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CATALOG OF CCRP PUBLICATIONS

Coalition Command and Control

(Maurer, 1994)

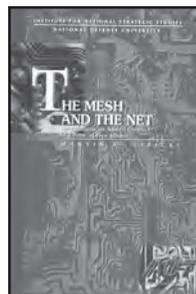
Peace operations differ in significant ways from traditional combat missions. As a result of these unique characteristics, command arrangements become far more complex. The stress on command and control arrangements and systems is further exacerbated by the mission's increased political sensitivity.



The Mesh and the Net

(Libicki, 1994)

Considers the continuous revolution in information technology as it can be applied to warfare in terms of capturing more information (mesh) and how people and their machines can be connected (net).



Command Arrangements for Peace Operations

(Alberts & Hayes, 1995)

By almost any measure, the U.S. experience shows that traditional C2 concepts, approaches, and doctrine are not particularly well suited for peace operations. This book (1) explores the reasons for this, (2) examines alternative command arrangement approaches, and (3) describes the attributes of effective command arrangements.

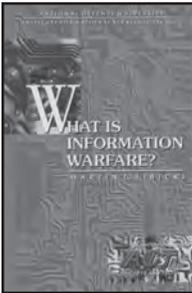




Standards: The Rough Road to the Common Byte

(Libicki, 1995)

The inability of computers to “talk” to one another is a major problem, especially for today’s high technology military forces. This study by the Center for Advanced Command Concepts and Technology looks at the growing but confusing body of information technology standards.



What Is Information Warfare?

(Libicki, 1995)

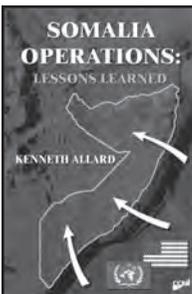
Is Information Warfare a nascent, perhaps embryonic art, or simply the newest version of a time-honored feature of warfare? Is it a new form of conflict that owes its existence to the burgeoning global information infrastructure, or an old one whose origin lies in the wetware of the human brain but has been given new life by the Information Age?



Operations Other Than War

(Alberts & Hayes, 1995)

This report documents the fourth in a series of workshops and roundtables organized by the INSS Center for Advanced Concepts and Technology (ACT). The workshop sought insights into the process of determining what technologies are required for OOTW. The group also examined the complexities of introducing relevant technologies and devices.



Somalia Operations: Lessons Learned

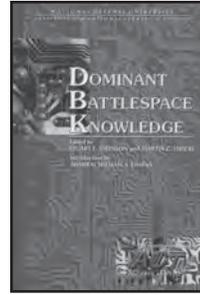
(Allard, 1995)

This book is Colonel Allard’s examination of the challenges and the successes of the U.S. peacekeeping mission to Somalia in 1992-1994. Key topics include planning, deployment, conduct of operations, and support.

Dominant Battlespace Knowledge

(Johnson & Libicki, 1996)

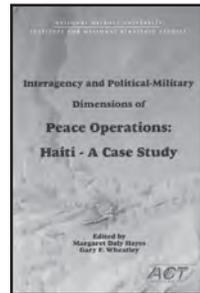
The papers collected here address the most critical aspects of that problem—to wit: If the United States develops the means to acquire dominant battlespace knowledge, how might that affect the way it goes to war, the circumstances under which force can and will be used, the purposes for its employment, and the resulting alterations of the global geomilitary environment?



Interagency and Political-Military Dimensions of Peace Operations: Haiti - A Case Study

(Hayes & Wheatley, 1996)

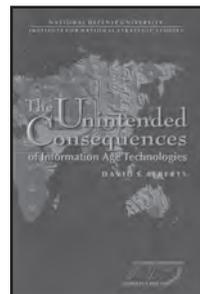
This report documents the fifth in a series of workshops and roundtables organized by the INSS Center for Advanced Concepts and Technology (ACT). Widely regarded as an operation that “went right,” Haiti offered an opportunity to explore interagency relations in an operation close to home that had high visibility and a greater degree of interagency civilian-military coordination and planning than the other operations examined to date.



The Unintended Consequences of the Information Age

(Alberts, 1996)

The purpose of this analysis is to identify a strategy for introducing and using Information Age technologies that accomplishes two things: first, the identification and avoidance of adverse unintended consequences associated with the introduction and utilization of information technologies; and second, the ability to recognize and capitalize on unexpected opportunities.

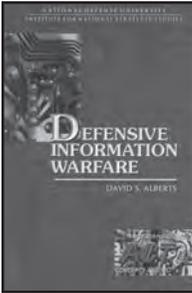




Joint Training for Information Managers

(Maxwell, 1996)

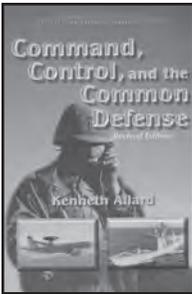
This book proposes new ideas about joint training for information managers over Command, Control, Communications, Computers, and Intelligence (C4I) tactical and strategic levels. It suggests a new way to approach the training of future communicators.



Defensive Information Warfare

(Alberts, 1996)

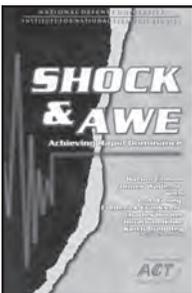
This overview of defensive information warfare is the result of an effort, undertaken at the request of the Deputy Secretary of Defense, to provide background material to participants in a series of interagency meetings to explore the nature of the problem and to identify areas of potential collaboration.



Command, Control, and the Common Defense

(Allard, 1996)

The author provides an unparalleled basis for assessing where we are and where we must go if we are to solve the joint and combined command and control challenges facing the U.S. military as it transitions into the 21st century.



Shock & Awe: Achieving Rapid Dominance

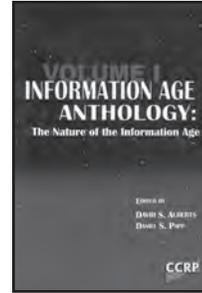
(Ullman & Wade, 1996)

The purpose of this book is to explore alternative concepts for structuring mission capability packages around which future U. S. military forces might be configured.

Information Age Anthology: Volume I

(Alberts & Papp, 1997)

In this volume, we examine some of the broader issues of the Information Age: what it is; how it affects commerce, business, and service; what it means for the government and the military; and how it affects international actors and the international system.



Complexity, Global Politics, and National Security

(Alberts & Czerwinski, 1997)

The charge given by the President of the NDU and RAND leadership was threefold: (1) push the envelope; (2) emphasize the policy and strategic dimensions of national defense with the implications for complexity theory; and (3) get the best talent available in academe.



Target Bosnia: Integrating Information Activities in Peace Operations

(Siegel, 1998)

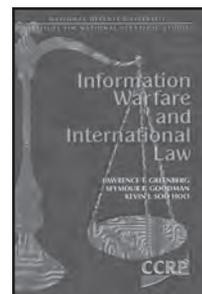
This book examines the place of PI and PSYOP in peace operations through the prism of NATO operations in Bosnia-Herzegovina.

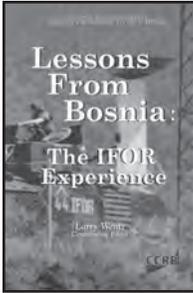


Information Warfare and International Law

(Greenberg, Goodman, & Soo Hoo, 1998)

The authors have surfaced and explored some profound issues that will shape the legal context within which information warfare may be waged and national information power exerted in the coming years.

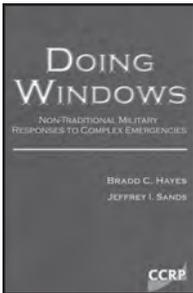




Lessons From Bosnia: The IFOR Experience

(Wentz, 1998)

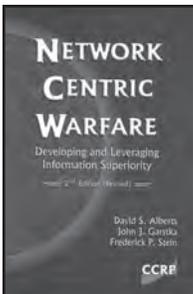
This book tells the story of the challenges faced and innovative actions taken by NATO and U.S. personnel to ensure that IFOR and Operation Joint Endeavor were military successes.



Doing Windows: Non-Traditional Military Responses to Complex Emergencies

(Hayes & Sands, 1999)

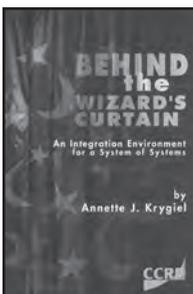
This book examines how military operations can support the long-term objective of achieving civil stability and durable peace in states embroiled in complex emergencies.



Network Centric Warfare

(Alberts, Garstka, & Stein, 1999)

It is hoped that this book will contribute to the preparations for NCW in two ways. First, by articulating the nature of the characteristics of Network Centric Warfare. Second, by suggesting a process for developing mission capability packages designed to transform NCW concepts into operational capabilities.



Behind the Wizard's Curtain

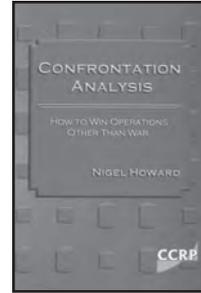
(Krygiel, 1999)

There is still much to do and more to learn and understand about developing and fielding an effective and durable infostructure as a foundation for the 21st century. Without successfully fielding systems of systems, we will not be able to implement emerging concepts in adaptive and agile C2, nor reap the benefits of NCW.

Confrontation Analysis: How to Win Operations Other Than War

(Howard, 1999)

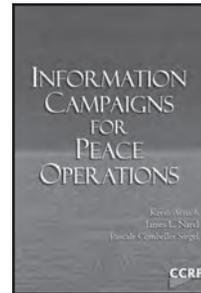
A peace operations campaign should be seen as a linked sequence of confrontations. The objective in each confrontation is to bring about certain “compliant” behavior on the part of other parties, until the campaign objective is reached.



Information Campaigns for Peace Operations

(Avruch, Narel, & Siegel, 2000)

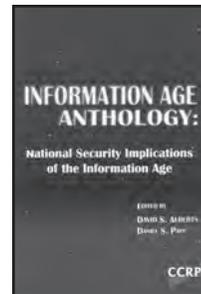
In its broadest sense, this report asks whether the notion of struggles for control over information identifiable in situations of conflict also has relevance for situations of third-party conflict management for peace operations.



Information Age Anthology: Volume II

(Alberts & Papp, 2000)

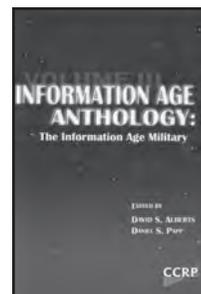
Is the Information Age bringing with it new challenges and threats, and if so, what are they? What dangers will these challenges and threats present? From where will they come? Is information warfare a reality?

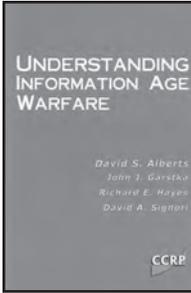


Information Age Anthology: Volume III

(Alberts & Papp, 2001)

In what ways will wars and the military that fight them be different in the Information Age than in earlier ages? What will this mean for the U.S. military? In this third volume of the Information Age Anthology, we turn finally to the task of exploring answers to these simply stated, but vexing questions that provided the impetus for the first two volumes of the Information Age Anthology.

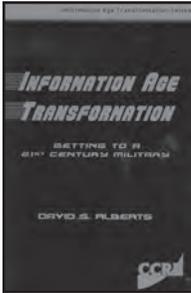




Understanding Information Age Warfare

(Alberts, Garstka, Hayes, & Signori, 2001)

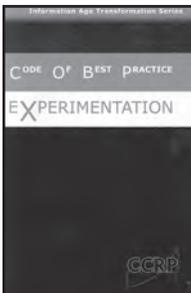
This book presents an alternative to the deterministic and linear strategies of the planning modernization that are now an artifact of the Industrial Age. The approach being advocated here begins with the premise that adaptation to the Information Age centers around the ability of an organization or an individual to utilize information.



Information Age Transformation

(Alberts, 2002)

This book is the first in a new series of CCRP books that will focus on the Information Age transformation of the Department of Defense. Accordingly, it deals with the issues associated with a very large governmental institution, a set of formidable impediments, both internal and external, and the nature of the changes being brought about by Information Age concepts and technologies.



Code of Best Practice for Experimentation

(CCRP, 2002)

Experimentation is the lynch pin in the DoD's strategy for transformation. Without a properly focused, well-balanced, rigorously designed, and expertly conducted program of experimentation, the DoD will not be able to take full advantage of the opportunities that Information Age concepts and technologies offer.



Lessons From Kosovo: The KFOR Experience

(Wentz, 2002)

Kosovo offered another unique opportunity for CCRP to conduct additional coalition C4ISR-focused research in the areas of coalition command and control, civil-military cooperation, information assurance, C4ISR interoperability, and information operations.

NATO Code of Best Practice for C2 Assessment

(NATO SAS-026, 2002)

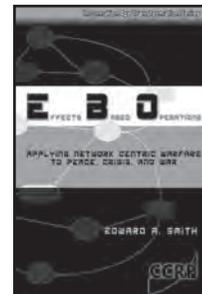
To the extent that they can be achieved, significantly reduced levels of fog and friction offer an opportunity for the military to develop new concepts of operations, new organisational forms, and new approaches to command and control, as well as to the processes that support it. Analysts will be increasingly called upon to work in this new conceptual dimension in order to examine the impact of new information-related capabilities coupled with new ways of organising and operating.



Effects Based Operations

(Smith, 2003)

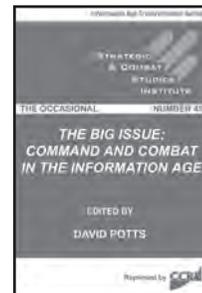
This third book of the Information Age Transformation Series speaks directly to what we are trying to accomplish on the “fields of battle” and argues for changes in the way we decide what effects we want to achieve and what means we will use to achieve them.

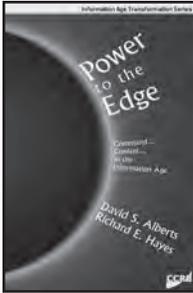


The Big Issue

(Potts, 2003)

This Occasional considers command and combat in the Information Age. It is an issue that takes us into the realms of the unknown. Defence thinkers everywhere are searching forward for the science and alchemy that will deliver operational success.

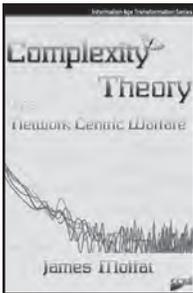




Power to the Edge: Command...Control... in the Information Age

(Alberts & Hayes, 2003)

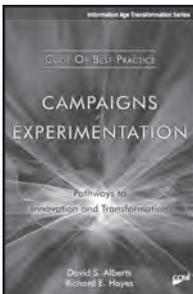
Power to the Edge articulates the principles being used to provide the ubiquitous network that people will trust and use, populate with information, and use to develop shared awareness, collaborate, and synchronize actions.



Complexity Theory and Network Centric Warfare

(Moffat, 2003)

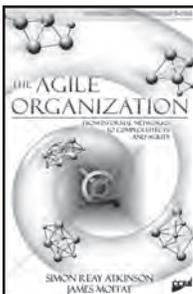
Professor Moffat articulates the mathematical models that demonstrate the relationship between warfare and the emergent behaviour of complex natural systems, and calculate and assess the likely outcomes.



Campaigns of Experimentation: Pathways to Innovation and Transformation

(Alberts & Hayes, 2005)

In this follow-on to the Code of Best Practice for Experimentation, the concept of a campaign of experimentation is explored in detail. Key issues of discussion include planning, execution, achieving synergy, and avoiding common errors and pitfalls.



The Agile Organization

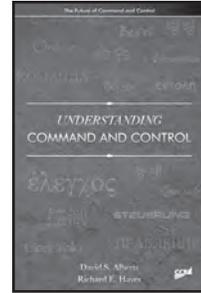
(Atkinson & Moffat, 2005)

This book contains observations, anecdotes, and historical vignettes illustrating how organizations and networks function and how the connections in nature, society, the sciences, and the military can be understood in order to create an agile organization.

Understanding Command and Control

(Alberts & Hayes, 2006)

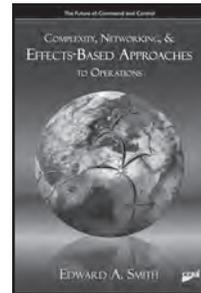
This is the first in a new series of books that will explore the future of Command and Control, including the definition of the words themselves. This book begins at the beginning: focusing on the problem(s) that Command and Control was designed (and has evolved) to solve.



Complexity, Networking, and Effects-Based Approaches to Operations

(Smith, 2006)

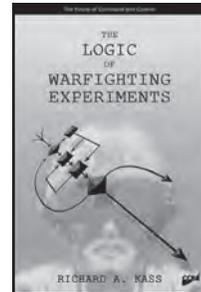
Ed Smith recounts his naval experiences and the complex problems he encountered that convinced him of the need for effects-based approaches and the improved infostructure needed to support them.



The Logic of Warfighting Experiments

(Kass, 2006)

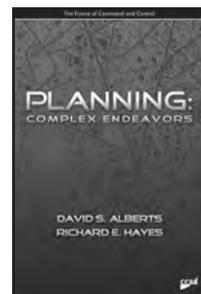
Experimentation has proven itself in science and technology, yielding dramatic advances. Robust experimentation methods from the sciences can be adapted and applied to military experimentation and will provide the foundation for continual advancement in military effectiveness.



Planning: Complex Endeavors

(Alberts & Hayes, 2007)

The purpose of this book is to present and explain an approach to planning that is appropriate for complex endeavors at a level of detail sufficient to formulate and conduct a campaign of experimentation to test, refine, and ultimately implement a new approach or set of approaches to planning.

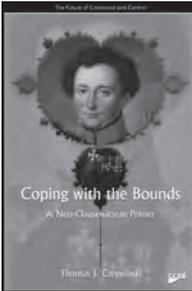




The International C2 Journal

Established 2006

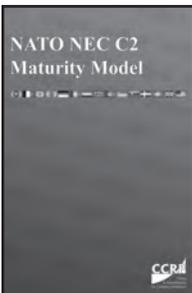
The International C2 Journal is one of the latest CCRP endeavors. This internationally directed and peer reviewed publication presents articles written by authors from all over the world in many diverse fields of Command and Control such as systems, human factors, experimentation, and operations.



Coping with the Bounds

(Czerwinski, 2008)

Originally published by NDU in 1998, the theme of this work is that conventional, or linear, analysis alone is not sufficient to cope with today's and tomorrow's problems, just as it was not capable of solving yesterday's. Its aim is to convince us to augment our efforts with nonlinear insights, and its hope is to provide a basic understanding of what that involves.



NATO NEC C2 Maturity Model

(SAS-065, 2010)

The NATO NEC C2 Maturity Model (N2C2M2) was developed to build on dearly won insights from the past, but goes beyond them in order that we can exploit Information Age approaches to address new mission challenges. This way of thinking about C2 is thus entirely compatible with current NATO Allied Command Transformation (ACT) thinking on Future Capable Forces which puts the emphasis on Mission Command within federated complex environments and ad hoc coalitions.



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