Adaptive Fleet Literature Review

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Presented to:
Dr. Peter Dobias and Cheryl Eisler
MARPAC Operational Research Team,
Defence Research and Development Canada – Centre for Operational Research and Analysis
PO Box 1700 STN Forces
Victoria, BC V9A 7N2

Prepared by:
International Safety Research
38 Colonnade Road North
Ottawa, Ontario
Canada K2E 7J6

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Abstract

The Maritime and Air Systems Section of the Defence Research and Development Canada’s (DRDC) Centre for Operational Research and Analysis (CORA), under DRDC Project 01AA, supports a force structure and concept development paradigm for the Royal Canadian Navy (RCN). One of the possible approaches to force structure planning in uncertain future is based on the Complex Adaptive System (CAS) approach. In order to ensure that the work reflects the state-of-the-art, a comprehensive literature review of related research was required.

CAS are understood as dynamic systems composed of mutually interacting subsystems with non-linear feedback; these interactions give rise to emergent behaviour that cannot be explained by decomposing the system into its sub-components. Such complex systems typically adapt to the changing environment. Through application of the CAS approach to the design of a future naval force structure, it is expected that a fleet structure that is better able to handle the variety of future mission demands will be developed.

The objective of this work was to conduct a search and review of literature describing a) the application of the CAS paradigm within the naval domain, and b) the general application of the CAS approach that can be tailored to the naval domain.

An extensive literature search was conducted that resulted in the identification of 54 papers. After a thorough review of the literature, 15 of these papers were rated as directly applicable and 12 were rated as potentially applicable. Papers were grouped together according to content; once this was complete, a topic area that encapsulated each group of papers was identified. The topic areas include: a) Future Operational Environment Analysis, b) Force Structure/Force Generation, c) Modelling & Simulation, and d) Command and Control. This paper provides an extensive description of each applicable paper, and provides a summary for each topic area, focussing on the commonalities and differences amongst the literature in each topic area.
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| Reviewed by                    | Devin Duncan                    |
| Approved by                    | Devin Duncan                    |
| Approved for Corporate Release by | Ian Becking                    |

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1. INTRODUCTION

1.1 Background

The Maritime and Air Systems Section of the Defence Research and Development Canada’s (DRDC) Centre for Operational Research and Analysis (CORA), under DRDC Project 01AA, supports a force structure and concept development paradigm for the Royal Canadian Navy (RCN). One of the possible approaches to force structure planning in uncertain future is based on the Complex Adaptive System (CAS) approach. In order to ensure that the work reflects the state-of-the-art, a comprehensive literature review of related research was required.

CAS are understood as dynamic systems composed of mutually interacting subsystems with non-linear feedback; these interactions give rise to emergent behaviour that cannot be explained by decomposing the systems into smaller components. Such complex systems typically adapt to the changing environment. Through application of the CAS approach to the design of a future naval force structure, it is expected that a more adaptive fleet will be developed; a fleet that is better able to handle the variety of mission demands that arise over time.

1.2 Objective

The objective of this work was to conduct a search and review of literature describing a) the application of CAS within the naval domain, and b) the general application of CAS that can be applied to the naval domain.

1.3 Scope

The Technical Authority (TA) identified the following topics as out of scope for the current literature review:

a. Counter insurgency;
b. Mission assessment (strategic);
c. Fluid dynamics as it relates to the Land Forces;
d. Crowd control/crowd dynamics;
e. Mathematical proofs/theories (development); and
f. Tactical operations.

1.4 Document Overview

This report is organized into the following sections:

a. Section 1 – Introduction
   This section presents a brief background to the project, and the overall project objective and scope.

b. Section 2 - Complex Adaptive Systems
   This section presents a high-level overview of CAS.
c. Section 3 – Methodology
   This section presents the methodology used to conduct the literature search.

d. Section 4 – Results
   This section presents the literature that was gathered during the literature search, categorized according to relevance and relation to the Navy domain.

e. Section 5 – Discussion
   This section presents a discussion of the literature, which is categorized according to four main topic areas including: Future Operational Environment Analysis, Force Structure/Force Generation, Modelling and Simulation (M&S), and Command and Control (C2).

f. Section 6 – References
   This section provides a list of references reviewed during this work.
2. COMPLEX ADAPTIVE SYSTEMS

2.1 Overview

This report has reviewed a growing body of scholarship utilizing the study of complexity theory as a means of improving our understanding of warfare. This section summarises the origins and theory underpinning the CAS construct.

2.2 Background

Scientific research, until the middle of the twentieth-century, was dominated by the Newtonian paradigm which tried to explain and predict real-world phenomena; specifically the notion that physical laws dictated a correspondence between cause and effect. The belief of scientists during this era was that they could reduce even the most complex behavior to the interactions of a few simple laws and then calculate the exact behavior of any physical system into the future (Crandall, 2013). This conviction was based on the assumption that systems in the natural world displayed linear causality; that, loosely speaking, effects shown by a multicomponent system were proportional to the cause. Although there are instances in Newtonian physics in which a response to a linear force can be non-linear (e.g., linear ballooning instability in fluid dynamics), in general it was believed any system could be decomposed into simple sub-systems that could be analyzed separately, and that improvements to any component of the system should lead to an improvement of the overall system.

Towards the end of the twentieth-century, it became clear to scientists that systems often did not operate in the manner that Newtonian approach would predict; weather systems were still unpredictable, ecosystems and immune systems did not behave as expected, and quantum physics behaved according to a very different set of rules than simple cause and effect (Fryer, 2010).

Scientists gained a new appreciation for nature’s random properties and unpredicted responses, as evidenced by the recognition that very small changes in initial conditions could have a profound effect on the evolution of a system (Crandall, 2013). In other words, contrary to previous beliefs, such complex systems often did not actually show linearity. It must be stressed, however, that the inverse does not hold true – non-linearity itself does not make a system complex; rather it is the non-linearity of the feedback loop between stimulus and response that makes a system complex.

By the mid-twentieth century, these observations gave rise to an alternative perspective – chaos (popularised by Gleick in 1987 [Gleick, 2011]). Rather than suggesting a state of disorder, the term chaos was adopted by theorists to describe the notion that systems can be susceptible to apparently highly unpredictable behavior and extremely sensitive to initial conditions. Critically, the basic premise of chaos theory is that chaos is really “order masquerading as randomness” (Gleick, 2011). For example, chaotic systems can be fundamentally very simple, deterministic, and the chaotic behavior is only driven by the dependence on initial conditions (e.g., double pendulum or three-body motion).

As scientists of all disciplines explored these phenomena a new theory emerged – Complexity Theory – based on the notions of relationships, emergence, patterns and
iterations. The term *Complex Adaptive System* was coined to describe systems that exhibit complexity by constantly adapting to their environment. In contrast to chaotic systems, Complex Adaptive Systems have many mutually interacting parts and are typically impossible to describe by a small set of mathematical equations. They also tend to exhibit self-organised behaviour, such as the schooling of fish or the flocking of birds.

### 2.3 Complex Adaptive Systems

Given its recent recognition by the scientific community, there is no universally accepted definition of what constitutes a CAS (Crandall, 2013). Crandall, citing Holland (2006¹), states that CASs are:

> “Systems that have a large number of components, often called agents, which interact and adapt or learn.” (Holland, 2006).

These agents interact and connect with each other in unpredictable and unplanned ways. But from this mass of interactions regularities emerge and start to form a pattern which feeds back on the system and informs the interactions of the agents (Fryer, 2010; Figure 2-1²). For example, if a virus in an ecosystem starts to deplete one species this results in a greater or lesser food supply for others in the system which, in turn, affects their behaviour and their numbers. A period of flux occurs in all the populations in the system until a new balance is established.

![Figure 2-1: Complex Adaptive Systems (Fryer 2010)](image)

While Holland’s definition and Fryer’s example are somewhat helpful in broadly framing the discussion, Crandall (2013) argues that CASs are best understood by examining their properties. The properties of a CAS, as derived from the references cited at the beginning of this section, include: Complexity, Emergence, Adaptability, and

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² For clarity, in the diagram above the regularities, pattern and feedback are shown outside the system but in reality they are all intrinsic parts of the system.
Unpredictability; these properties are summarized in the following sections. It is important to note that all properties of the CAS are inter-related; indeed, this is the most distinctive feature of them.

2.3.1 Complexity

One of the most prominent features of CASs are their very complexity; a property of the fact that these systems are composed of numerous interconnected components, or agents, dynamically interacting with one another, as well as with other external systems (Crandall, 2013). Specifically, complexity is a function of:

a. **Diversity.** Diversity refers to the heterogeneity of the agents within the system. The greater the diversity of agents within the system the stronger it is. Fryer (2010) argues that ambiguity and paradox are intrinsic to CASs which uses these contradictions to create new possibilities to co-evolve with their environment. For example, the strength of democracy is derived from its assimilation of a broad variety of political perspectives.

b. **Connectivity.** The ways in which the agents in a system connect and relate to one another is critical to the survival of the system, because it is from these connections that the patterns are formed and the feedback disseminated. The relationships between the agents are generally more important than the agents themselves (Fryer, 2010).

c. **Nesting.** Nesting is a term used to describe the fact that the components of a complex system may themselves be complex systems. For example, a grocery store is itself a system with its staff, customers, suppliers, and neighbours. It also belongs to the food system and economy of that town and the country. Given that CASs are embedded within each other, changes to the subsystems (or even the agents within them) can significantly alter the entire system (Crandall, 2013).

2.3.2 Emergence

Another prominent feature of CASs is the notion of emergence. Rather than being centrally planned or controlled, the agents in the system interact in, what was perceived as, apparently random ways. From all these interactions patterns emerge, such as the flocking of birds or schooling of fish, which informs the behaviour of the agents within the system and the behaviour of the system itself. The notion of emergence has been described as the outcome of the collective interactions among agents performing something individually, or together, which creates some kind of pattern or behavior which the agents themselves cannot produce (Crandall, 2013). For example, a termite hill is a maze of interconnecting passages, large caverns, ventilation tunnels and much more. Yet there is no grand plan, the hill just emerges – seemingly unpredictable and unprecedented – as a result of the termites following a few simple local rules (Fryer, 2010). In other words, the shape of the termite hill cannot be easily predicted or deduced from behaviour any individual ant; its construction is, in essence, not governed by linear causality.

Scholars studying complex systems often distinguish between two categories of emergence: weak and strong (Murphy, 2014). Weak emergence “describes the difficult to understand micro-to-macro relationship between microscopic parts and their
interactions with each other, and their collective macroscopic behavior,” whereas strong emergence “describes properties that are unique to the collective [which] cannot be identified through any observations of the parts, and is counter to the conventional perspective that parts determine the behavior of the whole.” (Bar-Yam, 2004).

2.3.3 Adaptability

This notion of emergence leads to the third distinctive property of CASs – adaptability. As a result of their complexity, these systems, as well as the agents within them, are constantly changing in response to information they gather about themselves and their surroundings (Crandall, 2013). Specifically, adaptability is a function of:

a. Self-Organising. Self-organization is the process whereby a system transforms itself into states of higher order in an effort to create structure (Crandall, 2013). Critically, there is no hierarchy of C2 in a CAS to plan and manage; only a constant, feedback-driven re-organising of the system to find the best possible fit with its environment. For example, a countries economy responds to changing technological developments, changing lifestyles and preferences, immigration and the price of raw materials through a process of emergence and feedback.

b. Co-Evolving. All systems exist within their own environment and they are also part of that environment. Therefore, as their environment changes they need to change to ensure best fit. But because they are part of their environment, when they change, they change their environment, and as it has changed they need to change again, and so it goes on as a constant process (Fryer, 2010).

2.3.4 Unpredictability

Fryer (2012) argues that CASs exist on a spectrum ranging from equilibrium to chaos. As much as it is important for a system not to reach complete equilibrium (i.e., it no longer possess the internal dynamics to enable it to respond to its environment), it is also important for a system not to reach complete chaos and cease to function as a system. Fryer (2010) argues that the most productive state of a CAS is at the edge of chaos where there is maximum variety and creativity, leading to new patterns and structures.

These new patterns and structures, however, are virtually impossible to understand or predict with much accuracy. This has significant consequences for attempts to assess the impact of human intervention upon a CAS. Not only might small interactions produce monumental changes, they may also lead to drastic and deleterious unintended consequences (Crandall, 2013).

2.4 Complex Adaptive Systems and the Navy

The Royal Canadian Navy can be considered as a CAS insofar as it has a large number of components, which interact, adapt and learn in order to overcome an adversary. Specifically, the properties of a CAS align with the following characteristics of the RCN:

a. Complexity
   i. The navy comprises a wide range of platforms, personnel and systems;
whose capabilities are often complementary and mutually enabling;
ii. Combatants and command structure are inter-connected (e.g., voice, chat, datalink); and,
iii. The structure of the navy is highly nested; a fleet comprises numerous warships and auxiliary vessels, which in turn comprises thousands of personnel and systems performing a wide range of functions (i.e., it is a system of systems).

b. Emergence
i. Collective interactions among platforms and personnel within the navy create emergent patterns and behaviors which the individual platforms themselves cannot produce. For example, one cannot determine the emergent behaviour of the ship by observing a sub-set of the crew (e.g., engineers) in isolation.

In line with Moffat (2003), the RCN can be described as 'loosely coupled' in order to capture the notion of the local freedom available to the units to prosecute their mission within an awareness of the overall intent and constraints imposed by high-level command. Moffat also emphasises the looser correlation and nonsynchronous relationship between inputs to the system (e.g., sensor reports) and outputs from the system (e.g., orders). In this process, information is transformed into ‘shared awareness’, which is available to all. This leads to units linking up with other units, which are either physically co-located or connected through communications, to enable self-synchronisation. This in turn leads to emergent behaviour in the battlespace, as shown in Figure 2-2.

![Figure 2-2: Information Leading to Emergent Behavior (Moffat, 2003)](image-url)
3. METHODOLOGY

3.1 Phase 1

During Phase 1 of this work, a comprehensive search was conducted to identify potential relevant literature. The mediums used to conduct this search included:

a. Articles provided by the TA, including a review of literature provided in the articles’ reference lists;

b. General Google and Google Scholar searches; and

c. Literature sources identified by the TA, including:
   i. U.S. Naval Institute;
   ii. Centre of Naval Analyses;
   iii. Articles authored by Andrew Ilachinski;
   iv. Articles authored by Michael Lauren;
   v. Articles authored by James Moffatt;
   vi. New England Complex Systems Institute;
   vii. Santa Fe Institute;
   viii. Australia Defence Science and Technology Group; and

Once the literature search was complete, each paper was reviewed and evaluated against a) its relation to the naval domain (High/Medium/Low [H/M/L]) and b) its project relevance (H/M/L). Each paper was assigned a topic area, and a brief description of each paper was also provided.

The literature was then highlighted according to its applicability: green (directly applicable); yellow (potential applicable) and red (not applicable).

3.2 Phase 2

During Phase 2, all literature that was categorized as directly (green) or potentially applicable (yellow) was reviewed in more detail. The detailed review of each paper may have changed its applicability status. Papers were grouped together according to content; once this was complete, a topic area that encapsulated each group of papers was identified. The topic areas include: a) Future Operational Environment Analysis, b) Force Structure/Force Generation, c) M&S, and d) C2. A more in-depth description was also provided for each paper.

3.3 Phase 3

This phase presented a thorough discussion of the relevant papers (i.e., papers marked green) identified in Phase 2.
4. RESULTS

4.1 Phase 1

The literature search resulted in 54 papers. From these papers, 18 were rated as directly applicable (green) and 13 were rated as potentially applicable (yellow). Annex A provides an overview of the literature gathered during Phase 1.

4.2 Phase 2

After a more thorough review of the literature, 15 papers were rated as directly applicable (green) and 12 were rated as potentially applicable (yellow) (Table 4-1). These papers were categorized according to four main topic areas: Future Operational Environment Analysis, Force Structure and Force Generation, M&S, and C2. Annex B provides an overview of the literature, including a brief summary of each paper.

Table 4-1: Phase 2 Final Results

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5. DISCUSSION

5.1 Future Operational Environment Analysis

The first topic of the literature review details the application of CAS to the analysis of future operational environments that the RCN is expected to operate within so that the necessary force structures can be developed. In order to better understand the motivation behind this, a brief explanation of what the future security environment is and the complexity of its influence upon the demand for capability within a force structure are provided below.

A security environment encompasses the whole of the geo-political situation, armament, science and technology, non-state actors, world economies, climatic and environmental conditions, social and commercial relationships, etc. (UK MOD, 2015). While it is inherently impossible to predict what the future security environment will look like, strategic analysts use a variety of approaches to identify key drivers, which are then used to develop a set of possible – or at least feasible – futures. These futures are typically represented through a set of strategic scenarios that are subsequently used for future force planning. The strategic scenarios are broken down further into operational and even tactical vignettes that are then subjected to table-top wargaming and other types of modeling and analysis to determine likely future capability requirements.

However, many futures are often non-complimentary; they can even be mutually exclusive. Consequently, it is likely going to be impractical (or even impossible) to optimize future force structure to suit all of these futures. Thus, there are two contradictory aspects of future planning process; the force structure analysis requires sufficient level of detail, while the detailed scenarios are likely to be incorrect. As a result, an approach is required that would encompass the uncertainty and yet provide sufficient level of detail to determine future force structure requirements. The CAS paradigm provides one such possible means of addressing this problem.


Albino et al. (2016) present a basis for the scientific analysis of the historical and contemporary conditions under which distinct types of military strategies will be successful and provides guidance to improved strategic thinking. Based on their work at the New England Complex Systems Institute and the Chief of Naval Operations Strategic Studies group, the authors attempt to broaden the discussion of military strategy by considering three distinct effects of inflicting stress on an opponent: (1) damage; (2) no effect; and (3) gaining strength. In addition, they discuss the notion of the adversary’s ability to anticipate (e.g., to avoid damage or exploit opportunities) in order to create a more complete characterisation of the system.

Using historical examples from the Punic Wars through to the recent Iraq conflict, the article offers a detailed characterisation of the effects of applying force on an adversary by broadening the discussion on what factors underlie strategic success over and above the traditional ‘manpower’ and ‘firepower’. These include effectiveness of action (sensitivity to relevant information, effective decision making based upon that information
and effective exercise of force), the degree to which the system is damaged by the application of force (robustness), and the ability to recover from damage (resilience). Furthermore, in addition to the impact on the adversary, an attack may have deleterious impacts on the attacker’s side by depleting military, economic, or political resources, or diverting resources from defense, creating vulnerabilities. It may also establish a persistent disadvantageous pattern of interaction with the adversary or with other groups.

In order to provide a theoretical underpinning to the range of outcomes that a conflict might generate (and in particular the importance of indirect effects), the article describes the ramifications of complexity for strategic military thinking – that learning and adaptation (properties of a complex system) can enable adversaries to become ‘antifragile’ \(^3\). The article gives preliminary indications of how strategists can apply these concepts to better assess risks posed by adaptable enemies and enable their own forces to take advantage of opportunities to reverse apparent setbacks. The authors argue that recognizing the potential limitations of applied force can improve both proactive solutions and countermeasures to an adversary’s action.

In summary:

a. **Confounding Forces in Strategic Theory.** There are a variety of reasons for a strategy to be confounded or non-optimal including:

   i. **Larger and other goals.** A successful strategy is one that recognizes not only the immediate objective, but also the existence of other goals that constrain methods or enable multiple goals to be achieved.

   ii. **Conflict and cooperation.** For example, an objective of national economic success may be alternatively framed in terms of conquest of land and other resources, or mutual advancement through economic cooperation and competition.

   iii. **Indirect effects as a disadvantage.** Awareness and evaluation of indirect effects are needed for effective strategic planning, including difficult to consider, longer term socio-economic impacts and psychological responses, as well as impacts on the environment and context in which a conflict occurs.

   iv. **Indirect effects as advantage.** A strategy often assumes a fixed set of conditions or constraints imposed by existing natural and social context. But, if one considers the conditions malleable, the indirect effects of changing the conditions may improve the set of options available.

   v. **Uncertainty and chaos in conflict.** Uncertainty arises from the absence of crucial information as well as the unpredictability of events as they unfold. Chaotic unpredictability is embodied in the adage ‘no plan survives first contact with the enemy.’ Effective strategies in such conditions focus on enabling responses to a set of possibilities rather than specific events.

b. **System Response to Attack.** An essential aspect of strategy is to understand the effect of actions on future capabilities of the adversary. The following alternatives must be considered (see Figure 5-1)

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i. **Fragility.** The deterioration under stress; the generally expected result of military attack, and the intent of strategy to degrade an enemy's forces to yield a desirable control.

ii. **Robustness.** The ability of an adversary to withstand the effects of force.

iii. **Resilience.** The recovery of capability following an initial degradation of an enemy’s forces.

iv. **Anti-Fragility.** Anti-fragile is used to mean the direct opposite of 'fragile'; a fragile system is one that deteriorates when stressed, an anti-fragile system grows stronger. Critically, resilience and robustness do not imply gains in strength; anti-fragility does.

c. **Sources of Anti-Fragility.** The foundations of antifragility as a basis for military strategy are as follows:

i. **Evolution.** Evolution is a repeated process of selection and reproduction with variation: varieties that outperform their predecessors become the basis for the next round of variation, competition and selection. Anti-fragility emerges in a system when its components are selected and replicated according to their contribution to system effectiveness.

ii. **Learning.** Learning occurs when exposure to stress provides information about the challenges faced. An adversary gains antifragility when it (a) has the opportunity to experiment with different responses and (b) makes use of accumulated knowledge about how to successfully respond to a stress.

iii. **Adaptation.** Adaptation allows for an increase in the effectiveness of a response to a particular stress after that stress has manifested itself.

![Figure 5-1: Characterization of the changes in system health when subject to external stresses (from Albino et al., 2016).](image)

The article concludes that strategy plays out in a context of complex interactions between actors with different objectives and capabilities. These objectives and capabilities and the environment in which they exist are rarely if ever static. An approach
to strategy that accounts for response capabilities, including fragility, robustness, resilience, antifragility, and anticipatory response can anticipate better the outcomes of planned action. This involves identifying relative strengthening or weakening of capabilities of actors as a result of their interactions over extended conflicts. An interaction that leads to a short term advantage assuming fragility may not lead to a long term advantage in the face of antifragility. An effective strategy should enhance its own force's ability to adapt in the face of setbacks to produce long term gains. Strategists should consider military conflict one process in an on-going relationship between groups, with the indirect effects on the political, social, and economic aspects of that relationship as, or more important than, the direct physical effects on the enemy forces.


Colvin’s monograph uses multidisciplinary analysis and synthesis to understand why and how the military environment is becoming more complex. He argues that this approach bridges the gap between, on one hand, the Joint Intelligence Preparation of the Operational Environment process which is limited to tools of analysis and organisation, and on the other hand, future-looking documents (e.g., Joint Operating Environment 2010) which describe possible futures in detail but do not outlines the way trends are determined.

Colvin acknowledges that the operational environment as a complex system of systems which requires a holistic view. With this in mind, the monograph attempts to meet three related goals. First, it seeks to outline the underlying principles of a systems approach. Second, it applies systems principles to synthesize various multi-disciplinary components of the operational environment. Third, it uses the multi-disciplinary tools to outline the major trends of the operational environment. These steps produce an iteration of analysis and synthesis, to address the question: “How does the future operational environment work”?

Overall, the monograph provides a broad-brush overview of many inter-related fields of research such individual psychology, group dynamics, general systems theory and CAS. Throughout this sometimes free-wheeling description of the literature, operational examples are described to illustrate how a multidisciplinary analysis and synthesis approach can be used to understand why and how the military environment is becoming more complex. The monograph comprises the following technical sections:

a. A Foundational Systems Model to Understand Trends in the Operational Environment. Provides a brief overview of General Systems Theory, work on cellular automaton (and the types of behaviour associated with these systems) and CAS (including the notions of simple components or agents relative to whole system, nonlinear interactions among components, no central control, emergent behaviors, hierarchical organization, information processing, dynamics, and evolution and learning).

b. Technological Growth: The Defining Catalyst of Change in the Future Operational Environment. From a CAS perspective, the growing prevalence of technological applications (e.g., internet, social media, and communications) causes the number of agent interactions to increase, pushing the operational environment system towards a chaotic environment. In addition, technology also
affects the immediacy of interactions in these systems, because it effectively compresses time (rapidity of communications) and space (virtual presence).

c. **Individual Behaviour: The Primary Component of System Dynamics.** This section of this monograph uses various theories to demonstrate how agents continue to employ differentiating/growth behaviors that push humanity to higher levels of development. In addition, it reviews how these natural propensities interact with technology’s integrating potential to accelerate human development. Using models such as Boyd’s Observe, Orient, Decide, Act (OODA) Loop⁴ and Maslow’s⁵ hierarchy of needs, Colvin argues that the choices of an individual agent, as influenced by their understanding of the environment, can become another influence of the path of system development.

d. **Group Dynamics: The Dancing Landscape Emerges.** The final technical section of the monologue is concerned with the majority of interactions in the operational environment that come through meetings with aggregates of individuals, or groups. Colvin describes how and why groups form, how they combine to influence group characteristics, and what the consequences are to the operational environment. By synthesizing various perspectives from social, information, and complexity sciences, distinct phenomenon emerge to affect the condition of the future operational environment. These include the continued individualized orientation of social groups, greater internal homogeneity that intensifies ideological identities, greater external heterogeneity, and power-law or long tailed behavior that leads to rapid change. He argues that understanding groups leads to understanding of the most visible observations encountered in the operational environment.

In summary, Colvin develops a CAS view to explain the underlying trends that drive changes in the operational environment, from the micro to the macro. Increasing growth of technological capability provides an incredible integrating capability that allows for individual and group development. The tempo and tendencies of this relationship result in an operational environment that is increasingly diverse, particularized, and subject to rapid change. As such, Colvin argues that this environment demands creative, flexible, and agile responses from the Joint force.

### 5.1.3 Summary

Using historical examples, both the articles reviewed strongly advocate the need to move beyond overly simplistic representations of the operational environment and integrate the key notions of CAS (e.g., evolution and adaptation and emergence) to better predict how future operational environments will shape military strategic thinking (and vice versa).

The articles argue that a multi-disciplinary approach to applying key concepts from CAS theory should lead to a better understanding of how an adversary might respond to force (Albino et al.) and how the relationship between technology and individual/group dynamics drives changes to the operational environment.

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5.2 Force Structure/Force Generation

The second topic of the literature review is concerned with the application of CAS to the definition and evaluation of future RCN force structures. Similar to the analysis of future operational environments, an understanding of the impact of force structure and generation options within those environments allows the RCN to plan more effectively for the future.


This article – a part of a series of deliverables for the Chief of Naval Operations Strategic Studies Group – discusses the relevance of Multiscale Complex Systems Analysis (MCSA) to a characterization of the differences between conventional and complex warfare challenges, with particular application to littoral warfare.

This article was a part of a larger effort to apply MCSA to military conflict; in it, Bar-Yam argues that MCSA provides a formal framework for understanding the interplay of scale and complexity in military forces, and their capabilities in the face of conflict. MCSA can also provide an understanding of appropriate measures of effectiveness for both conventional and information age military forces as well as guidance concerning what aspects of conventional military experience remain relevant and which should be changed in the context of more complex littoral conflicts.

After introducing the basic concept of complexity as it relates to functional capability, Bar-Yam discusses the notion of complexity profile which characterizes the dependence of complexity (amount of information necessary to describe a system) on scale (resolution / level of detail in the description). These concepts are then applied to littoral conflict and its implications for organizational structure. Bar-Yam argues that the main limiting factor on the complexity of hierarchical organizations implies that hierarchies are not effective at performing high complexity tasks. Indeed, the emphasis on network warfare concepts by current military planners reflects their recognition of the limitations of hierarchical control in this context.

Based on experience with complex warfare in Vietnam and Afghanistan, Bar-Yam argues that littoral warfare cannot be readily incorporated into naval operations without considering the specific organizational and technological requirements needed to perform effectively in this high complexity environment. For example, a conventional analysis of aggregate force size and firepower and incapacitation of the enemy via attrition provides little if any guidance for the conduct of complex warfare. Instead of scale alone (e.g. manpower or firepower), complexity (e.g. the variety of possible actions that can be taken) should be used as a measure of force capability in the context of complex military scenarios. In a high complexity environment, high complexity forces are more capable than low complexity ones. Thus, an effective analysis of warfighting capability must include both scale and complexity of the forces and the environment where the conflict occurs. Bar-Yam goes on to argue that scale and complexity are not, however, independently controllable – they are inter-related (a key characteristic of CAS) as discussed in Section 2 of this report.

Since complexity is a desirable characteristic of a military force, Bar-Yam suggests the
complexity of a force is directly linked to its ability to conduct multiple partially independent and coordinated actions of military units. It is thus related to command and control structures, its information sensing, processing, decision and communication capabilities as well as its socio-cultural background. Furthermore, a substantial improvement in the complexity of a military force requires profound redesign of force organization and related training and culture. Indeed, the basic paradigms and concepts of distributed control are often counterintuitive to commanders and planners whose training focuses on hierarchical systems designed for operation of large scale forces. When used to study specific examples, MCSA provides a way of understanding the functioning of distributed control systems. MCSA, therefore, can be used for both the analysis of the capabilities of an existing force and for military planning to increase the capability of the force.

In summary, Bar-Yam argues that MCSA provides a more formal approach to understanding warfare in complex environments (e.g., littoral warfare) by replacing conventional attrition analysis of force capability based on collective firepower to an approach that can directly consider the organization of enemy and friendly forces and the conditions of conflict between them.


Murphy’s (2014) Master's thesis is a recent, detailed, and award-winning (Drew Papers) review of the CAS literature relevant to military development of force structures (albeit Air Force oriented). Murphy argues that force-structure analysis (i.e., the mathematical and scientific discipline of assessing the utility of various material force structures) is critical to the process of planning, programming, and acquiring the military means to provide for national security and to shape the strategic environment. For this analysis to provide appropriate recommendations regarding force structure, however, he argues that it is vital that the prevailing analytic paradigm be consistent with the true nature of force structure, the environment, and their relationship to one another. As such, he argues that CAS is an appropriate analytical paradigm to conceptualise and analyse force structure.

The thesis comprises the following chapters:

a. Complex Adaptive Systems: A Primer. This section provides an excellent overview of the CAS in which their main characteristics are described (including mathematical equations and real-world examples. Specifically:

i. Diversity. Diversity is described in terms of both within a population (variation) and across types of populations (entropy, distance and attributes).

ii. Interdependence. The elements of a complex adaptive system are said to be interdependent in that the fitness of the elements is mutually defined (e.g., predator-prey relationship).

iii. Adaptation. A change their behavior to improve their chances of survival or success through learning or evolutionary processes.

iv. Nonlinearity. Nonlinear systems or processes are simply those that are not linear – the behavior of the system is not fully described as the sum of its parts.
v. **Emergence.** Collective behaviors that are in some sense difficult to infer from the properties of the parts and their laws of interaction.

vi. **Co-evolution.** A change in one ‘fitness’ of one adaptation strategy has the potential to affect the evaluation of fitness for the other adaptation strategies (e.g., co-evolution within predator-prey relationships).

vii. **Path dependence.** Positive feedback and increasing returns may cause the (decision) path selected to become locked in and difficult to escape.

b. **Is a Force Structure a Complex Adaptive System?** This section determines the degree to which force structure is a CAS by comparing it against the characteristics described above. Specifically:

i. Diversity and the different types of platforms within the US Air Force.

ii. Interdependence and the relationship between the platforms (e.g., command and control, air superiority, strike and aerial refuelling).

iii. Adaptation and the evolution of strike and bomber aircraft in response to changing operational needs and environments.

iv. Nonlinearity and different aircrafts’ performance parameters.

v. Emergence and the behaviour of autonomous and semiautonomous unmanned aerial vehicle ‘swarms’.

vi. Co-evolution and the rise of terrorist and insurgent adversaries.

vii. Path dependence and the development of stealth technologies.

c. **Complexity and Force Structure Analysis.** This section presents a discussion of complexity and force structure analysis, including a brief history of applied complex systems and military theory (including Boyd’s OODA loop\(^6\) as a model for interaction in a complex adaptive system; see Figure 5-2).

![Interacting OODA Loops](image-url)  

*Figure 5-2: Interacting OODA Loops (Boyd, 1996 as cited by Murphy 2014) used as model of interaction in a Complex Adaptive System.*

Murphy also cites the work of Ilachinski (1994; see Section 5.3.1) who developed a series of nine open ended questions designed to establish a research agenda for complexity and the military. The goal was use CAS as a shaping mechanism for policy and strategy, and a mechanism for assessing the models for conventional conflict. Specifically:

- Are there measures of combat complexity?

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- Can patterns of observed chaotic data be exploited?
- What is the appropriate phase space description for combat?
- Can the chaos of combat be controlled or tamed?
- What are the optimal strategies for adaptation on the battlefield?
- What role does the psychology of the individual combatant play in shaping the combat process?
- How complex must a combat system be in order for it to be amenable to the tools of complex systems theory?
- How can one quantify the true value and nature of information on a battlefield?
- Does the presence of fractals in combat point to something fundamental?

Finally, Murphy discusses the analytical gap between theories of complexity and the prevailing view in the US Air Force that force structure should be treated as a simple system. Indeed, the explicit or implicit treatment of the complex adaptive system of physical force structure as a system in (dynamic) equilibrium or stasis is problematic because it cannot anticipate the possibility of rapid, unforeseen changes in the relative capabilities of opposed force structures due to “Black Swan” type changes in technology (e.g., smart phones and social media). Murphy warns of the dangers of conducting force planning using a limited number of carefully prescribed, threat-based scenarios. The resulting lack of diversity induced by the narrowly predictive nature of the scenarios used for analysis creates a class of unexamined risk and increases the potential for surprise (see also Bowden et al., 20157).

d. **Recommendations and Conclusions.** This section presents the recommendations and conclusions from this study, relating to measures (i.e., robustness, diversity and redundancy), models (including a larger range of scenarios) and manpower (paradigm shift towards complexity by the force structure analysis community).

In summary, this Master’s thesis presents the theory of CAS and demonstrates that force structures are examples of such systems. The argument is then made that the prevailing paradigm of the force-structure-analysis community in the United States Air Force is inconsistent with this reality. A collection of recommendations identifies low-cost opportunities with the potential for significant long-term effects in aligning the force-structure-analysis paradigm with the fact that force structures are complex adaptive systems.

**5.2.3 Ryan, A. (2007). A multi-disciplinary approach to complex systems design.**

Ryan’s (2007) PhD thesis is concerned with the application of CAS to defence and security applications. It includes a detailed and comprehensive review of CAS theory and its application to defence and security (specifically, asymmetric warfare and capability development).

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The aim of the thesis was to advance a ‘conceptual analysis’ approach to complex systems design that exploits deep insights from the mathematics of complex systems, without building explicit models of the underlying system. Ryan argues that this approach is advantageous because it can extend the domain of applicability of the discipline of complex systems into (military) situations where quantitative data are unavailable, and human and social factors are significant. The thesis attempted to answer the following questions:

1. How do models represent the underlying system of interest?
2. What is a systems approach?
3. What sorts of insights are unique to a complex systems approach?
4. How are the concepts of complex systems interrelated?
5. What is emergence?
6. Are there alternatives to model-based applications of a complex systems approach?

The thesis comprises three parts:

a. Philosophy. The first part of the thesis discusses the philosophy underlying complex systems; including key philosophical insights. Ryan explores the topic of representation and presents a theory of the representational relationship between entities, models and agents; providing clear definitions of key terminology. The history of systems theory is introduced, as is his own definition of ‘system’ (i.e., “a representation of an entity as a complex whole open to feedback from its environment”). Finally, following an alternative to model-based applications of a complex systems approach, broad guidance for conceptual analysis and important considerations are presented.

b. Theory. The second part of the thesis develops the theory of complex systems further by describing (and defining) the central concepts (including mathematical equations):

   i. Complexity. Defined as the amount of information needed to describe a process, system or object.
   ii. Edge of chaos. Defined as the region where system behaviour shifts from ordered regimes towards chaotic regimes (effectively approaching random dynamics).
   iii. Self-organisation. Defined as the spontaneous arising of dynamics implicit in progressing in time the system from a not (or less) organised to an organised state.
   iv. Emergence. Defined as the process whereby the assembly, breakdown or restructuring of a system results in one or more novel emergent properties (i.e., a property present in a macro-state, but not present in a micro-state).
   v. Adaptation and Evolution. Defined as the process where behaviour of the system changes such that there is an increase in fit, and therefore mutual information, between the system and a potentially complex and non-static environment.
   vi. Self-referentiality. Defined as an interaction between levels in which the top loop reaches back down towards the bottom level and influences it, while at the same time being itself determined by the bottom level.
Ryan concentrates on the theme of emergence for the remainder of this section; a new framework in terms of scope, resolution and state is presented. In addition, emergent properties and emergence are formalised within a new framework to provide precise and testable definitions. This section of the thesis marks the most valuable contribution of the thesis to the study of CAS.

c. **Application.** The third and final part of the thesis applies conceptual analysis to two problems in the defence and security domain. The first example applies the theory of multi-scale complexity to the operational requirement to counter asymmetric warfare; structural impediments and potential solutions are also discussed. The second example is a critical look at the capability development process which transforms security needs into capability purchasing requirements. Ryan argues that this problem is the most challenging application of CAS due to its scale, complexity and socio-technical nature. He continues to argue that such an approach can yield deeper insights and practical improvements compared to traditional quantitative methods.

In summary, this thesis argues that multi-disciplinary research is important by demonstrating how the synthesis of philosophy, theory and application can offer deeper and more valuable insights into military strategic issues (i.e., asymmetric warfare and capability development) over and above individual research disciplines.

5.2.4 **Summary**

Similar to the research articles reviewed under auspices of Future Operational Environment Analysis, all three articles stress the utility of CAS theory to the analysis of the environmental complexity, the force structure, and the command and control of the force structure in view of specific mission objectives. For example, Murphy makes the explicit the direct link between CAS and force structures by advocating that force structures are examples of a CAS. Ryan, in line with the Albino and Colvin articles reviewed in the previous section, argues for the importance of multi-disciplinary research for providing deeper and more valuable insights into military strategic issues; in particular, capability development. Bar-Yam (2004) makes a similar claim regarding the application of CAS to Navy planning associated with littoral conflict. Finally, all three articles provide several recommendations for applying CAS theory to the issue of force structure/generation and capability development.

5.3 **Modelling and Simulation**

The third topic of the literature review is concerned with the application of modelling and simulation to analyse CAS. This section describes models that have been used to model and analyse land combat as a CAS (i.e., dynamic, changing environment). An understanding of these models may allow the RCN to identify similar analysis toolboxes that could evaluate future naval operations.

This paper presents two agent-based models, ISAAC (Irreducible Semi-Autonomous Adaptive Combat) and EINSTein (Enhanced ISAAC Neural Simulation Toolkit) to illustrate “how certain aspects of land combat can be viewed as emergent phenomena resulting from the collective, nonlinear, decentralized interactions among notional combatants” (Ilachinski, 1994). Agent-based models are being used to assess modern warfighting concepts, examining how militaries may change together during combat; specifically these models illustrate how the interactions of the individual agents, as well as their subsequent feedback create impact the ‘rules’ underlying agent behaviour.

ISAAC and EINSTein are considered interactive toolboxes that were designed to answer the question “To what extent is land combat a self-organized CAS?” ISAAC uses a bottom-up synthesis approach to modelling combat, using mobile cellular automata (CA) rules. ISAAC agents incorporate four underlying characteristics including:

a. Doctrine: Default local-rule set dictating how to act in a generic environment;
b. Mission: Goal directing behavior;
c. Situational Awareness: Sensors generating an internal map of the environment; and

d. Adaptability: An internal mechanism to alter behavior and/or rules (Ilachinski, 1994).

Agents belong to either a ‘blue’ or ‘red’ force; each agent can exist in one of three states, Alive, Injured or Killed. Components of the ISAAC model include:

a. Personalities: Each agent can respond to one of four pieces of information presented, including: number of alive friendly, number of alive enemy, number of injured friendly, number of injured enemy. Agents are also able to respond based on their distance from its own flag or enemy flag;
b. Move Selection: Each possible move is ranked according to a penalty function, which measures the distance that the agent will be from other agents, its own or enemy flags;
c. Meta-Rules: Meta-rules are able to modify a default personality in response to environmental conditions and contexts; and

d. Combat: This allows an agent to ‘fire’ at all enemy agents within a specified fire range. Firing at an ‘alive’ agent will cause that agent to become ‘injured’. Firing at an ‘injured’ agent will cause that agent to become ‘dead’. The combat function is influenced through: Defense (an agent’s status is controlled by the number of ‘hits’ the agent can withstand), Reconstitution (injured agents can retort back to the alive state, and Fratricide (allows ‘friendly fire’).

A sample of the behaviors embedded into ISAAC include Forward Advance, Frontal

Attack, Local Clustering, Penetration, Retreat, Attack Posturing, Containment, Flanking Maneuvers and ‘Guerrilla-like’ assaults. In the present paper, Ilachinski (1994) illustrates six samples of behaviors using ISAAC.

ISAAC, in contrast to traditional Lanchester models\textsuperscript{10}, allows the analysis of patterns that may become apparent when the system is out of equilibrium (Ilachinski, 1994).

EINStein was developed as an enhanced version of ISAAC, which facilitates an analysis of combat as CAS. According to Ilachinski (1994), EINStein allows users to run ‘what if’ scenarios, and experiment with the dynamics of war. EINStein was also being used to study a) Command and Control topology, and b) Relevance of Battlefield Information.


Lauren (2001a) presents a new equation-based method to model combat, developed to estimate losses in non-conventional environments, such as dispersed land warfare operations. The New Zealand Defence Technology Agency developed cellular automata-based simulation model of conflict – MANA (Map Aware Non-uniform Automata); this paper reports on the results of testing the equations using MANA. The MANA model was used to “illustrate a theoretical framework for describing complex and non-linear battlefields using fractal methods by exploring the spatial and temporal correlations within the population of entities, which arise as the result of multiple interactions of the personalities of the combatants” (Lauren, 2001a). MANA is based on the concepts of complexity and emergence.

MANA was developed using the ISAAC model as its foundation; ISAAC was developed for the U.S. Marine Corps by Ilachinski (1994). MANA facilitates global interactions, which differs from traditional cellular automaton models.

The scenario used for this work was based on a generic dispersed ‘battlefield’, where a “small but powerful Blue force must maneuver its way through a much larger but dispersed and (in most cases) individually less powerful Red force” (Lauren, 2001a). A set of weightings rules each automaton; these weightings control each automaton’s tendency to move toward or away from friends or enemies and goals and waypoints (Lauren, 2001).

Lauren (2001) conducted an analysis of the MANA model by expressing the equation through varying scenarios using a large, fixed number of runs (600). The analysis indicates that the equation presented in Lauren (2001a) is suitable for describing attrition, and illustrating a theoretical framework for understanding the results of a dispersed battlefield, involving correlations between entities in terms of space and time.

5.3.3 Lauren, M.K. (2001b). Describing rates of interaction between multiple autonomous entities: An example using combat modelling.

Lauren, 2001b uses an example of combat analysis to illustrate how a fractal-based approach can describe rates of interaction in complex systems. The scenario used by Lauren is one that is mimics the modern battlefield – a battlefield that is dispersed and involves spatial and temporal correlations of deployments. The scenario used has been previously described in Lauren (2001a). Lauren indicates that this scenario represented a previous but recent event at the time; specifically the scenario resembles the Battle of Mogadishu (Somalia) in 1993. The MANA model is used to analyse this scenario.

Lauren (2001) states that cellular automata models produce power-law or ‘fractal’ distributions as compared to conventional combat models, which is of importance since power laws have shown to exit in real combat data (Moffat and Passman, 2001; Robers and Turcott, 1998; Richardson, 1941, 1960, as cited in Lauren, 2001b).

This paper presents an equation based on fractal distributions for describing attrition in dispersed battlefields; however, the Lauren (2001) indicates that this research may have general applicability to describing interactions in other complex systems. This equation facilitates an analysis of a dispersed battlefield with spatial and temporal correlations between agents; this analysis would not be possible using the traditional Lanchester equations (1914).


This objective of this work is to illustrate the ability of the Fractal Attrition Equation (FAE) to be used as a Metamodel for the MANA cellular automaton combat model, to better explain the rate of attrition between two opposing forces. Specifically, the underlying motivation for this work is to develop improved attrition algorithms which facilitate the inclusion of enhanced command and control and network enabled capabilities (Lauren et al., 2005).

As previously mentioned, the Lanchester equations (1914) do not consider the spatial distribution of forces on the battlefield. The intent of this paper is to use ‘fractal dimension’, through the use of the FAE to incorporate a spatial element to the algorithm. The FAE is viewed as modelling combat as a self-organising system, i.e., combat fronts will become distorted during combat but the combat system will adapt without losing order (Lauren et al., 2005). This distortion can be described by a fractal, and the degree of distortion is a fractal dimension.

As a result, Lauren et al., (2005) state that the FAE can be used to illustrate the attrition rate when the Blue and Red opposing forces are able to self-organization when they are within close-range of each other.

Models discussed in previous sections such as the MANA and ISAAC cellular automata models, have illustrated that Blue and Red forces have self-organized according to
fractal-type patterns; the attrition rate has been shown to behave as a power-law function during these conditions.

Lauren et al., (2005) seek to quantitatively predict combat behaviour by comparing the Loss Exchange Ratio derived from the FAE to the results of using simple cellular automaton combat models. To explore this comparison, a variety of test scenarios were used; a common theme across these scenarios was that the agents were allocated low kill probabilities to facilitate self-organisation before one force (Blue or Red) was eliminated.

The results illustrate that the FAE can potentially be used when at least one force involves spatial distribution on the battlefield. It can also be employed to illustrate combat as a self-organizing system. Lauren et al., (2005) suggest that it can assist in understanding the potential implications of new military concepts at this time, such as Network Centric Warfare (NCW). The results also validated their hypothesis, such that the power spectrum of the time series of casualties is governed by a power law.


Multi-agent systems (MAS)\textsuperscript{11} are now recognized as a tool for modelling combat as a CAS. Agent-based distillations (ABD)\textsuperscript{12}, originally developed by the US Marine Corp are considered a type of MAS that are able to analyse combat as a CAS. These models include ISAAC, EINStein, MANA, CROCADILE and BactoWars; the former three models have been described in previous sections (Ilachinski, 1994; Lauren, 2001). These models however, now face challenges in modelling networked forces.

The objective of this dissertation was to present a Network Centric Multi-Agent Architecture (NCMAA), which is founded on the network theory and CAS. All agents are modelled as nodes, and relationships and interactions between agents are modelled as a network. The NCMAA is advantageous over other ABDs such that:

\begin{itemize}
  \item a. Interactions and relationships are able to be analysed;
  \item b. Interactions or influences between networks can be described; and
  \item c. Provides a real-time reasoning framework.
\end{itemize}

The Warfare Intelligent System for Dynamic Optimization of Missions (WISDOM), a land-combat system, is presented. WISDOM-I is founded on the same principles as other

\textsuperscript{11} Multi-Agent System is a distributed collaborative environment which allows a number of agents to cooperate and interact with other agents (including both people and software) that have possibly conflicting aims, in a complex environment.

\textsuperscript{12} Agent Based Distillations are low resolution abstract models, which can be used to explore questions associated with land combat operations in a short period of time. Being agent based means that only simple behavioural rules need to be assigned. This is generally achieved by ‘assigning’ personalities to the agents by way of relative weightings to various elements on the battlefield and a linear penalty function to determine the entity’s next move (Gill & Grieger, 2003). An agent-based model was originally understood as an abstract ‘distillation’ of a system, being implicitly a static construct; it is a conceptualization, not a dynamical reproduction (Ilachinski, 2004). However, at the present, the terms agent-based model and agent-based distillation are often used interchangeably.
ABDs; WISDOM-II is founded on the NCMAA. Yang (2006) illustrates that WISDOM-II provides distinctive characteristics such as:

- Provides a real-time network analysis toolbox, which is able to gather information/patterns while agent interactions evolve;
- Incorporates flexible Command, Control and Communication models;
- Facilitates the link between strategic planning and tactical decisions;
- Provides a recovery model; and
- Provides real-time visualization of information, allowing the user to provide real-time input into the simulations.

As part of the dissertation, WISDOM-II is employed with and without strategic planning in different urban terrains. Yang (2006) also tested communication in urban terrains.

This dissertation provides the groundwork for future work conducted using the NCMAA and WISDOM-II (Yang et al., 2006, 2008)


Agent-based models were initially used to model warfare as a CAS (Ilachinski (1994), Lauren (2001). However, these models have demonstrated limitations in terms of their application to NCW. As a result, Yang et al., (2006) have proposed WISDOM-II, which is founded on the NCMAA. WISDOM-II was developed to facilitate the analysis of warfare dynamics, specifically for NCW.

The NCMAA is based on network theory. The architecture is based on the concept of networks, where each operational entity in the system is either a network or a part of a network; the simulation engine is also based on the concept of networks (Yang et al., 2006). NCMAA is a two layer architecture; the top layer describes the relationship types, and the influence of one relationship on another. The bottom layer consists of agents, which interact based on those relationship types.

WISDOM-II was developed incorporating the primary concepts in CAS. There are 5 components to WISDOM-II including:

- C3 Component: Command and Control and Communication; each has a separate computer model;
- Sensor Component: retrieves information from the environment;
- Engagement Component: firing and movement activities;
- Visualisation Component: information presentation (i.e., graphs); and
- Reasoning Component: results interpretation in natural language.

WISDOM-II contains 5 concept networks that form the top layer of the NCMAA – the influence network – including:

- The C2 Network is the command and control hierarchy within one force. Each
force is comprised of a commander and a control structure; each force may involve individual teams, which is then broken into groups. Groups are comprised of agents, identifiable by their individual characteristics.

b. The Vision Network illustrates the visual link between two agents.

c. The Communication Network provides the communications links within a force (there is no communication between forces). Communication consists of only situation information and commands. WISDOM-II facilitates Point to Point directly (P2Pdirect), Point to Point indirectly (P2Pindirect) and Broadcast (BC).

d. The Information Fusion Network presents information about ‘friends’ and ‘enemies’ through vision and communication.

e. The Engagement Network illustrates the agents being fired at.

WISDOM-II includes 4 types of agents, including the combatant agent, group leader, team leader and general commander. Team leaders and general commanders are virtual agents at force headquarters that are only capable of communication. Combatant agents and group leaders incorporate 8 possible attributes, including:

a. Health – An agent can either be healthy, wounded, immobile, or dead. An agent’s initial health is established by the user.

b. Skill – An agent’s skill level describes an agent’s hit probability (i.e., probability of the enemy being hit). An agent’s initial skill level is established by the user.

c. Probability to Obey – This defines the probability to obey a command given by an agent’s leader.

d. Invisibility – An agent’s detection probability by another agent, controlled by an agent’s sensor. An agent’s invisibility level is established by the user.

e. Vision – Detection defines what kind of agents can be detected by using a sensor. For example, if the detection of agent A is equal to or larger than the invisibility of agent B, and agent B is within agent A’s vision range, then agent A may detect agent B.

f. Communication – This is facilitated through the communication network (i.e., communication occurs between combatant agents and other agents that are linked to each other). Communication is facilitated through a communication channel which is modelled by noise level, reliability, latency, and communication range.

g. Movement – This is controlled by an agent’s speed (still, low, medium, and high) and personality.

h. Engagement – This is determined by the type of weapon that the agent used, which is defined by weapon power, fire range and damage radius.

WISDOM-II uses the personalities of agents to influence whether they move closer or far from each other; agent personality is a vector quantity specified by magnitude and direction. WISDOM-II also incorporated tactical or strategic decision making. Tactical decision making assists an agent’s movement, based on current knowledge and personalities. General Commanders use strategic decision making to identify the way point for each group, based on the group’s mission type and the firepower of each force (Yang et al., 2006). Real-time reasoning at the network level is also possible during the simulation through establishing causal relationships and establishing the degree of
influence.

The design of WISDOM-II also involves a model of a hospital, which is available to each team. The model is defined by the number of doctors and the recovery rate, which is used to identify the recovery capability of a team.

WISDOM-II is able to provide visualisations that are not available with other agent based systems. Visualisations can either present information regarding the following:

- Agents in the battlefield – agent status, including number of deceased agents and wounded agents, number of agents in the hospital, number of agents in each force and damage to each force; and
- Interactions between agents – C2 structure, information flow chain, vision, knowledge and engagement.

WISDOM-II supports interactive simulation, which allows a user to send a command to any group based on their own personal knowledge of the military domain. This allows either predefined scenarios, or a scenario that is guided by the users in real-time.

Yang et al., (2006) present an example scenario in this paper using WISDOM-II. The scenario is based on a ‘red’ force, which is a traditional force with a large number of soldiers and traditional weapons and a ‘blue’ force which is a networked force, with a small number of soldiers but advanced weapons.

The scenario analysis illustrates that WISDOM-II overcomes some of the shortcomings that exist with other agent based systems. The authors have shown that real-time reasoning at the network level is possible, which illustrates the interactions between networks. Yang et al., (2006) indicate that the theory of NCW can be easily modelled, analysed and verified using WISDOM-II. Further, strategic decisions are based on a rule based algorithm, which facilitates a ‘semi-reactive’ agent’s decision making.


Agent based modelling has been used to model and simulate complex adaptive systems since they are able to analyse nonlinear interactions. Although agent based modelling is more suitable for CAS, there are still several shortcomings when using these models. As a result, Yang et al., (2008) developed the NCMAA, which is able to provide reasoning in real-time, based on network theory and causal models.

MASs are able to study CAS since agents are able to adapt, evolve and co-evolve within their environment (Yang, et al., 2008). As indicated in Yang et al., most agent based models\(^\text{13}\) (ABM) can be categorized as Cognitive Agent Architectures, Reactive Agent Architectures, or as a Hybrid (layer) Agent Architecture. Each of these model types incorporate critical components which are essential for modelling CAS. However, these models also have limitations. Table 5-1 provides a comparison between these models.

\(^{13}\) Agent Based Models simulate the actions and interactions between individuals or groups of agents to provide useful insight into the effects of the agents on a system, as well as how their interactions give rise to emergent properties.
and NCMAA for modelling CAS and describes their ability to incorporate critical components.

### Table 5-1: Comparison between NCMAA and other agent Architectures (Yang et al., 2008)

<table>
<thead>
<tr>
<th>Essential characteristics</th>
<th>Cognitive</th>
<th>Reactive</th>
<th>Hybrid</th>
<th>NCMAA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalability</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Heterogeneity</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Explicit model of interaction</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Reasoning on emergent behaviors</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Reasoning on agent level</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Rationality</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Adaptivity</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Sociality</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

NCMAA is based on network theory, which implies that each agent in the system is a network or is a component of a network. A system developed on NCMAA requires the:

- Development of a causal network among concepts: causal network is a directed graph of concepts defining the interdependency of concepts in the concept space; and
- Design of the finite state machine which will control the simulation oracle: finite state machine is a collection of states, each representing the state of a network in the system (Yang et al., 2008).

Figure 5-3 presents the two-layer architecture of NCMAA. Yang et al., (2008) indicate that the top is a conceptual layer, whereby agent relationships, as well as how these relationships influence one another are defined by the causal network. The bottom layer – the implementation layer – defines the instances of each concept.
Causal models can be used to predict future events, interpret present events, and achieve objectives through actions (Yang et al., 2008). The NCMAA builds a causal structure (network) based on domain knowledge about the causal status of relationships, which determines the direction of the ‘causal arrow’ within the models; covariation information is collected to estimate the strength of each causal relation (Yang et al., 2008). The NCMAA illustrates the causal structure through agent interactions. The type of interaction is represented by a node, and a link between nodes represents how the interaction is influenced by another type of interaction. A statistical analysis can be conducted on the top layer of the NCMAA to formulate covariation information from the bottom layer to estimate the strength of each relationship (Yang et al., 2008).

The reasoning engine embedded in NCMAA uses time series analysis to understand how ‘organization and behavior emerges from local interactions and then to plan or manipulate the behaviors emerging from the networks’ (Yang et al., 2008).

In this paper, Yang et al., (2008) propose a four phase, 12 step approach for developing an application based on the NCMAA, as illustrated in Figure 5-4. Each step is described in more detail in the paper.
Yang et al., 2008 further demonstrate the advantages of the NCMAA by executing a scenario in WISDOM-II, a multi agent combat system. WISDOM-II was designed and developed using the NCMAA as the model. The scenario analysis illustrates that the NCMAA is a valuable architecture to study warfare simulations.


Moffatt et al., in collaboration with Dr. Michael Lauren, have used the TTCP to progress theoretical developments regarding the MANA model, specifically providing “an analytical approach to the linkage between local clustering assumptions concerning the forces and the resultant emergent behaviour seen in the battlespace”. This approach is relevant to Information Age Forces and Network Centric Warfare, such that:

- “The approach is relevant to dispersed, dynamically evolving information age scenarios, involving local force clustering and re-clustering (a form of local self-organisation; and
- The linkage between such local self-organisational and global emergent behaviour also lies at the core of ideas such as network centric warfare” (Moffat et al., 2006).
This paper reports on a series of investigations which provide experimental evidence from an agent-based model of conflict (MANA) which supports the authors' theoretical analysis.

Modified MANA scenarios were used as the basis of the investigations. These scenarios involve a type of force that is stable, and moves in a wave, swarming behaviour, and a Lanchester-style battle (Moffat et al., 2006). In each of these scenarios, there was a comparison between the casualties suffered by the forces and the theoretical metamodel prediction of a power law relationship (Moffat et al., 2006). The initial investigation verifies for all three scenarios, the power law relationship between casualties and unit firepower effectiveness (Moffat et al., 2006).

The secondary investigation focussed on the second term of the metamodel, testing the power spectrum for casualties. Contact data was used since insufficient information could be gathered from casualty data to calculate the power spectrum; there is an expectation that as contact increases, casualties will increase. The MANA scenarios used were those used in the initial analysis (Meet, Swarm, Lanchester) as well a Western Front used in World War Two. Moffat et al., illustrate that a power law explains 88% to 96% of the data in the experiments. The MANA scenarios were replicated 200 times, increasing the value to 97%.

The current work confirms that the predictions of a previous theory of casualty generation developed by Moffat et al., are consistent with the experimental results of executing scenarios through the MANA agent-based simulation model of conflict (Moffat et al.).

5.3.9 Summary

One of the key aspects of modeling warfare in order to assess effectiveness of technologies or operational concepts is the representation of attrition. The Lanchester Equations (LEs) were developed in 1914 (Lanchester, 1914), providing the initial models of attrition for ‘modern warfare’. Through time, these models have provided the foundation for modern theories of combat attrition, and often have been incorporated in the more complex combat models to analyze or validate force structure analysis. However, as combat warfare evolves, the employment of LEs have shown limitations; specifically, the most significant limitation that makes LEs currently unusable is the assumption of a homogeneous and evenly distributed battlefield, which is no longer relevant in present day’s modern warfare. These equations have now become too simplistic and irrelevant to model modern warfighting concepts.

As mentioned in Section 2.2, a significant amount of recent scientific research has focussed on defining and describing CAS; the premise of CAS is the interaction and connection between agents in an unpredictable and unplanned way. But from this mass of interactions regularities emerge and start to form a pattern which feeds back on the system and informs the interactions of the agents (Fryer, 2010). Military research has focussed on describing military conflict as a CAS. According to Ilachinski (1994) military conflicts exhibit similar characteristics as of CASs including:

a. Battlefields are spatially dispersed and not homogeneous, and are composed of nonlinear interacting components;
b. Organized according to a command and control hierarchy;
c. Self-organizing;
d. Forces continually adapt to a changing military environment to survive; and
e. Combat is composed of decentralized control, i.e., there is no ‘master voice’ that
controls every agent on the battlefield.

To begin to characterize military conflict as a CAS, new models have been developed to
replace the outdated LEs. The first of these models are Agent Based Models, such as
ISAAC and EINSTein (Ilachinski, 1994) and MANA (Lauren, 2001; 2005). ISAAC and
EINSTein were the first two systems that modelled warfare as a CAS. ISAAC and
EINSTein are considered interactive toolboxes that were designed to answer the
question “To what extent is land combat a self-organized CAS?”

MANA (Lauren, 2001) was developed using the ISAAC model as its foundation; MANA
facilitates global interactions, which differs from traditional cellular automaton models.
MANA differed from ISAAC such that it introduced way-points, internal situational
awareness (SA) map, and event driven personality changes (Yang et al., 2008). The

Although agent based systems such as ISAAC, EINSTein and MANA improved
modelling warfare from the original LEs, these models now have several limitations
modeling Network Centric Warfare, including:

a. Difficult to validate and verify;
b. Lack of reasoning during the simulation;
c. No connection between tactic and strategy (models are either developed based
   solely on tactic or strategy);
d. Difficult to identify the interactions between agents during a simulation; and
e. Modelled based on conventional tactics as opposed to a high level systems view
   (e.g., NCW) (Yang et al., 2008).

Multi-agent systems facilitate the study of CAS. MASs are effective in modelling CAS if
they contain the following CAS properties:

a. High scalability: allows a significant number of agents to interact with one
   another;
b. Heterogeneity: CAS is composed of a number of heterogeneous components;
c. Model of interaction: facilitates the role of each type of interaction;
d. Reasoning on emergent behaviors: to study the why and how emergency
   behaviors occur;
e. Rationality: agent acts rationally to achieve goals; and
f. Adaptation: system should improve its performance over time (Yang et al., 2008).

To address the limitations of ISAAC, EINSTein and MANA, and to achieve the
characteristics of an effective MAS, Yang et al., (2008) introduced the NCMAAA, which is
based on network theory. NCMAAA is based on the concept of networks, where each
operational entity in the system is either a network or a part of a network; the simulation
engine is also based on the concept of networks (Yang et al., 2006).

Yang et al., 2006, 2008 introduced WISDOM-II, which is based on the NCMAAA.
WISDOM-II was designed based on the fundamental concepts of CAS. Work completed
by Yang et al. illustrates that the NCMAA is a valuable architecture to study warfare simulations as a CAS. The authors have also shown that real-time reasoning at the network level is possible. WISDOM-II also incorporates flexible Command, Control and Communication models, facilitates the link between strategic planning and tactical decisions, provides a recovery model, and provides real-time visualization of information, allowing the user to provide real-time input into the simulations.

5.4 Command and Control

The fourth topic of the literature review is concerned with the application of CAS to the definition and evaluation of command and control within the naval domain. This section will assist in understanding new approaches to supporting tactical decision makers by improving the Commander’s environment, to effectively command, control, and coordinate naval operations.


This article – part of a series of the deliverables for the Chief of Naval Operations Strategic Studies Group – discusses the relevance of MCSA to a characterisation of the differences between conventional and complex warfare challenges; particularly littoral warfare. The author argues that MCSA, and in particular the interplay between scale and complexity in complex systems, is relevant to the selection of appropriate technology and to identifying military objectives in littoral warfare.

The notion of a networked force does not specify, in and of itself, how distributed information is to be shared between networked parts. However, in various suggested strategies for implementation of network concepts it is assumed that information can be gathered and coherently presented by a single system. Although there are many competing visions, they all share the main characteristics of the Common Relevant Operational Picture (CROP) concept. The CROP concept suggests that all the militarily relevant information about a battlespace can be collected in a single repository and displayed in a single presentation architecture that is available for and can be tuned to the preferences and scope of authority of individual commanders at all levels as well as individual soldiers, airmen, marines and sailors.

Since the purpose of the CROP is to collect sensory information and describe the military environment, whether or not it will successfully fulfill its promise is less a question of engineering design than it is a matter of system description. For most Information Age military contexts, the systems that must be described are complex systems. For the purpose of this discussion, a complex system is a system of interacting components whose collective behavior cannot be easily inferred from the behavior of the parts in isolation. Therefore, a scientific understanding of descriptions of complex systems is fundamental to successful development of concepts such as the CROP. Central to this scientific understanding is the notion of multiscale representations. Multiscale representations provide an analysis tool for the linkage of information and action. Multiscale representations treat information as an enabler of effective function and avoid the generic, universal information representation that does not work in complex contexts.
The author cites three tasks that were undertaken to support this project:

a. **Initial Investigation.** The objective of this task was to investigate the principal system concepts including scale-based information valuation and process dynamics. The foundation for the use of multiscale representations involves specific development of methods for analysis of system capabilities. Among the essential concepts developed are:

   - There is a finite complexity of any entity at a particular scale;
   - This finite complexity implies a limitation in the diversity of contexts that can be dealt with by the system. It also implies a limitation in the information flow that can be responded to by the system.
   - Of particular relevance to systems involving human beings, including military ones, is the finite complexity of a human being at the scale of interaction between human beings.

b. **Concept Definition.** The objective of this task was to provide a thorough analysis of the scale-based dynamics of information in the context of military operations; particularly, recognizing the role of information in action and response to environmental demands and challenges associated with specific tasks. The author found that the CROP concept as articulated violates a basic principle of information distribution in complex systems. The central task of a sensor system is to provide relevant information. Increasing the availability of potentially relevant information must be carefully weighed against the damage due to distraction by irrelevant information.

c. **Evaluation Framework.** The objective of this task was to develop a general framework for evaluating the CROP concept, to include the constraints of limited resources (humans, machines, bandwidth, collectors, knowledge, and time) suitable for defining, in the abstract, solutions to the information dynamics problem. This framework will be used in further efforts (including Fleet Battle Experiments) to evaluate the CROP and similar concepts.

In conclusion, the framework of multiscale representations provides a mechanism for evaluating CROP concepts through the comparison of the system (human and machine) capability in aggregation of information, and commander capability in responding to this information. Bar-Yam argues that the importance of this subject extends beyond the analysis of CROP, to the analysis of the environmental complexity, the force structure, and the command and control of the force structure in view of specific mission objectives. Furthermore, a more systematic evaluation of multiscale representations in the context of military applications should support the effectiveness of military command and control structures in the context of 21st century complex military operations.

Note: The results of further investigations into these concepts were described in oral reports to the Chief of Naval Operations Strategic Studies Group and the Newport Center for Information Age Warfare Studies.

This heavily-cited book is concerned with the application of Complexity Theory to NCW. Moffat views warfare as a complex system that is linked and interacts (in a co-evolving way) with the surrounding socio-economic and political context. The goal of the book, therefore, is to attempt to analyse and structure the nature of warfare in order to help understand it in this larger context.

For the purposes of the current review we will not attempt to summarise the contents of the book in their entirety; rather we will summarise the content of each chapter.

Chapter 1 describes complexity in natural and economic systems. Moffat reviews in depth the complex behaviour of natural biological and physical systems. From this analysis of these open and dissipative systems, he describes and defines mathematically a number of key properties of complexity that are important to the consideration of the nature of future warfare:

- Non-linear interaction;
- Decentralised control;
- Self-organisation;
- Non-equilibrium order;
- Adaptation; and
- Collectivist dynamics.

Chapter 2 applies concepts from complexity theory to warfare. In particular, Moffat describes the similarities between NCW and CAS. NCW is an emerging theory of war based on the concepts of nonlinearity, complexity, and chaos. It is less deterministic and more emergent; it has less focus on the physical than the behavioural, and it has less focus on things than on relationships. Moffat argues that Complexity Theory is the essence of these ideas.

Chapter 3 summarises the evidence for complex emergent behaviour (a property of complex systems) using historical data (and statistical analysis) from land force engagements during World War II. Given its emphasis on land forces, this chapter has limited applicability to the current review.

Chapter 4 describes the mathematical modeling of complexity and how it can be applied to conflict. In this chapter Moffatt describes several ‘mathematical meta-modeling’ approaches that can be applied to understanding complexity in military conflicts. In the modelling of natural systems (such as fluid dynamics, or heat flow), the principal variables in these models can often be separated out from the rest of the model to produce a mathematical meta-model that is aimed at relating the outputs of the model to these driving inputs in a more transparent and explicit way. If this can be achieved, Moffat argues, it will improve our understanding of the system and its likely emergent behaviour, as well as complementing the use of detailed simulation.

Finally, Chapter 5 provides an example of complexity theory applied to a model of land-based warfare. Once again, given its emphasis on land forces, this chapter has limited applicability to the current review.

This article was presented at the CCRTS conference in 2006 by personnel from the Office of the Chief Engineer Space and Naval Warfare Systems Command (USA). The objective of the research described in the article was to assess whether or not emergent and self-organizing capabilities will really improve command and control; specifically the complexity theory characteristics of emergent behaviour/capabilities and self-organisation.

This article evaluates the practical usefulness of the CAS characteristics of self-organization and emergence with respect to warfighting command and control. In particular, research on self-organization seeks general rules about the growth and evolution of systemic structure, the forms it might take, and finally methods that predict the future organization that will result from changes made to the underlying components. Research on emergence, on the other hand, anticipates the appearance of capabilities or properties not presently available.

The article reviews and summarises many definitions of emergence (and predictability) and self-organisation from complexity theory and focuses on what process mechanisms attract the actors to different entities with which to self-organize and what happens to the entities themselves. Most notable is a tabular detailed description of Fromm’s work concerning types of emergence and their attributes. This table is extremely useful in simplifying yet bounding the discussion of emergence. Emergence, as viewed by Fromm, varies from Type I emergence (i.e., nominal, planned, or intentional, no feedback, feed forward only) on one hand, and Type V emergence on the other hand (i.e., strong emergence and supervenience\(^\text{14}\)). Strong emergence can be defined as the appearance of emergent structures on higher levels of organization and complexity, macroscopic level is independent from microscopic level) on the other. Finally, Lenahan defines the broad types of knowledge required by self-organising entities, culminating in a discussion of the ‘knowledge modeling gap’.

For the remainder of the article, Lenahan is concerned with a number of facets of complexity theory; knowing when something is about to self-organize or emerge, and its relationship with command and control. Lenahan proposed the following hypothetical command and control model utilising self-organisation:

1. Clearly define a simple process set, attractor set and environment in which the agents must select the appropriate attractor to be drawn to.
2. Develop the ‘attractor rules’ which will force a particular agent instantiation to be drawn to it.
3. Develop a set of attractor formation rules (controls for the attractors).
4. Develop minimum agent attributes and capabilities, which are independent of any particular process.
5. The agents must be able to seek out attractors or seek a particular state space (attractor basin) based upon some rule set.
6. The agents will respond to a process input type known as an ‘agent stimulus’. The agent stimulus will cause the agents to begin early self-organizational

\(^{14}\) An ontological relation that is used to describe cases where, broadly speaking, the upper-level properties of a system are determined by its lower-level properties.
phases and to possibly go into ‘learn mode’ by seeking knowledge.

7. After stimulus reactions and learning, the agents will complete self-organization within a process context after receipt of a valid input type.

8. The newly self-organized process will begin executing the process steps and transform the input into the correct output sets or states.

9. The agents and the process will be able to recognize ‘completion states’ and top transformation of the inputs, returning to an idle condition awaiting the next stimulus.

10. The process verification agents will analyze the success or failure of the process transformation of input to output created by the self-organized entities.

Lenahan goes on to describe multi-agent systems and the relationship to command and control with concrete examples (i.e., ‘organisation creation agents’ and ‘C2 planning agents’). Figure 5-5 depicts the self-organising process through the following capabilities required of the command and control agents:

- **Sense** its local environment and construct an internal representation - a perception - of the external world;
- **Plan** its own behaviour, based on the current perception of the external world; and,
- **Exchange** information with other agents.

![Figure 5-5: ‘Process Creation’ and ‘Mission Planning’ Agents (Lenahan and Charles, 2006)](image)

Lenahan and Charles conclude the article by stating that the goals of C2 process and NCW capability design in terms of the usability of these concepts must include the following:

1. Predictable, stable and reliable emergence and self-organization.
2. Self-organization and emergence must apply to processes, organization, systems, software, and individual agent capabilities.
3. It is imperative that self-organizational theory and emergence theory co-evolve
with NCW and C2 process assessment theory in order to achieve any meaningful improvement in the state of the art or state of the practice of self-organizational C2 or emergent C2 behaviors.

4. Assessment methodologies and processes must focus on positive emergence and self-organizing capabilities as well as negative self-organization, and negative emergence.

5. A "Process Instrumentation and Metrics Theory" must be a key component of any assessment theory expected to be capable of successful prediction of useful emergent capabilities or self-organizing capabilities.

6. The processes and resources expected to exhibit self-organizational and emergent phenomena must have access to the knowledge which will enable such behaviors within the actors. The knowledge must be of the proper types as described in the sections above concerning the relationships between knowledge types and categories of self-organization and emergence.

7. Reliability and predictability seem to evolve as key requirements for any potential use of self-organization and emergent capabilities. The military must be able to have reliable capabilities before entering combat situations with such entities.

5.4.4 Summary

The articles reviewed in this section attempt to apply theoretical concepts from CAS to command and control aspects of modern warfare; specifically, littoral (Bar-Yam), NCW (Moffat), and planning (Lenahan). Moffat views warfare as a complex system that is linked and interacts (in a co-evolving way) with the surrounding socio-economic and political context. He argues that it is important to attempt to analyse and structure the nature of warfare, using the theoretical concepts underpinning CAS (nonlinearity, complexity, and chaos), in order to help understand it in this larger context. Similarly, Bar-Yam argues that the interplay between scale and complexity is also pertinent to the selection of appropriate technology and identification of military objectives. Finally, Lenahan argues that research must be undertaken to evaluate the practical usefulness of the CAS characteristics of self-organization and emergence with respect to command and control. Furthermore, he questions whether or not emergent and self-organizing capabilities will really improve command and control; specifically emergent behaviour/capabilities and self-organisation. The goal will be to possess the ability to predict the future organization that will result from changes made to the underlying components.
REFERENCES


## ACRONYMS

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<thead>
<tr>
<th>ABD</th>
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</tr>
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<td>ABM</td>
<td>Agent Based Model</td>
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<td>Broadcast</td>
</tr>
<tr>
<td>C2</td>
<td>Command and Control</td>
</tr>
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<td>CA</td>
<td>Cellular Automata</td>
</tr>
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<td>CAS</td>
<td>Complex Adaptive Systems</td>
</tr>
<tr>
<td>CORA</td>
<td>Centre of Operational Research and Analysis</td>
</tr>
<tr>
<td>CROP</td>
<td>Common Relevant Operating Picture</td>
</tr>
<tr>
<td>DRDC</td>
<td>Defence Research and Development Canada</td>
</tr>
<tr>
<td>EINSTein</td>
<td>Enhanced ISAAC Neural Simulation Toolkit</td>
</tr>
<tr>
<td>FAE</td>
<td>Fractal Attrition Equation</td>
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<td>ISAAC</td>
<td>Irreducible Semi-Autonomous Adaptive Combat</td>
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<td>Network Centric Multi-Agent Architecture</td>
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<td>NCW</td>
<td>Network Centric Warfare</td>
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<tr>
<td>OODA</td>
<td>Observe, Orient, Decide and Act</td>
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<td>P2PDirect</td>
<td>Point to Point Directly</td>
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<td>Multi-scale Complex Systems Analysis</td>
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<td>Technical Authority</td>
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<tr>
<td>TTCP</td>
<td>The Technical Cooperation Program</td>
</tr>
<tr>
<td>WISDOM</td>
<td>Warfare Intelligent System for Dynamic Optimization of Missions</td>
</tr>
</tbody>
</table>
ANNEX A. PHASE 1 RESULTS

After a review of the literature, papers were rated as directly applicable (green), potentially applicable (yellow), or not applicable (red). This was based on a subjective ranking (Low/Medium/High) of the combination of the relationship between the CAS methodology in the selected paper and its potential applicability to the navy, as well as the relevance of the topic and application to future force structure planning.

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<tr>
<td>Beech, M. (2004). Observing al Qaeda through the lens of complexity theory - Recommendations for the national strategy to defeat terrorism. U.S. Army War College, Carlisle Barracks.</td>
<td>Counter Terrorism Strategy</td>
<td>L</td>
<td>L</td>
<td>Using the fundamental characteristics of Complexity theory, paper analyzes al Qaeda's behaviors, and proposes that al Qaeda is a highly complex and adaptive network, which leads to its resilience to the current US counter terrorism strategy.</td>
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<tr>
<td>Young, B. (2013). Complex Systems Engineering Applications for Future Battle Management and Command and Control. Presented at the 18th International Command &amp; Control Research &amp; Technology Symposium (ICCRTS), Alexandria, VA.</td>
<td>Battle Management and C2</td>
<td>H</td>
<td>L</td>
<td>This paper explores future tactical battle management and command and control (BMC2) as a complex system of systems.</td>
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<td>Dodd, L., Moffat, J. &amp; Smith, J. (n.d.). Discontinuity in decision-making when objectives conflict: a military command decision case study.</td>
<td>C2 and Decision Making</td>
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<td>This paper describes the application of non-liner multi-attribute utility theory in conflict scenarios in order to extend the representation of the Rapid Planning process to account for a wider set of subjective attributes of the decision-maker.</td>
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<td>De Oliveira, M. (2007). C2 at the edge of chaos: the real transformation to enable network warfare. Air University, Air War College.</td>
<td>Network Warfare</td>
<td>L</td>
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<td>Focus on recommendation that people will make up the social networks that are key to network warfare; focus on US Army</td>
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ANNEX B. PHASE 2 RESULTS

After a review of the literature, papers were rated as directly applicable (green), potentially applicable (yellow), or not applicable (red). This was based on a subjective ranking (Low/Medium/High) of the combination of the relationship between the CAS methodology in the selected paper and its potential applicability to the navy, as well as the relevance of the topic and application to future force structure planning.

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<tr>
<td>Bar-Yam, Y., Cares, J. R., Dickmann, J. Q., &amp; Glenney IV, W. G. (2001). Multiscale representation phase I. Final Report to Chief of Naval Operations Strategic Studies Group.</td>
<td>Command &amp; Control</td>
<td>H</td>
<td>M</td>
<td>This 14 page project summary briefly describes the concept of a Common Relevant Operational Picture (CROP); whereby all militarily relevant information about a battlespace can be collected in a single repository and displayed in a single presentation architecture that is available for, and can be tuned to, the preferences and scope of authority of individual commanders at all levels as well as individual soldiers, airmen, marines and sailors. The article has three main sections: (1) An investigation of the principal system concepts including scale-based information valuation and process dynamics; (2) An analysis of the scale-based dynamics of information in the context of military operations; and, (3) A general framework for evaluating the CROP concept, to include the constraints of limited resources (humans, machines, bandwidth, collectors, knowledge, time) suitable for defining, in the abstract, solutions to the information dynamics problem. The article states that this framework will be used in future work (including Fleet Battle Experiments) to evaluate the CROP and similar concepts. The review did not identify more recent articles from the author reporting the results of these future studies.</td>
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<td>Moffat, J. (2003). Complexity theory and network centric warfare. Office of the Assistant Secretary of Defense Washington DC Command and Control Research Program (CCRP).</td>
<td>Command &amp; Control</td>
<td>M</td>
<td>H</td>
<td>This heavily-cited, 177 page book is concerned with the application of Complexity Theory to Network Centric Warfare. Moffat views warfare as a complex system that is linked and interacts (in a coevolving way) with the surrounding socioeconomic and political context. The goal of the book, therefore, is to attempt to analyse and structure the nature of warfare in order to help understand it in this larger context. Chapter 1 describes complexity in natural and economic systems. Chapter 2 applies concepts from complexity theory to warfare. Chapter 3 summarises the evidence for complex emergent behaviour (a property of complex systems) using historical data. Chapter 4 describes the mathematical modeling of complexity and how it can be applied to conflict. Finally, Chapter 6 provides an example of complexity theory applied to a model of land-based warfare.</td>
</tr>
<tr>
<td>Lenahan, J. &amp; Charles, P. (2006). Assessing self-organization and emergence in C2 processes. Space and Naval Warfare Systems.</td>
<td>Command &amp; Control</td>
<td>M</td>
<td>H</td>
<td>This article was presented at the CCRTS conference in 2006 by personnel from the Office of the Chief Engineer Space and Naval Warfare Systems Command (USA). The objective of the research described in the article was to assess whether or not emergent and self-organizing capabilities will really improve command and control; specifically the complexity theory characteristics of emergent behaviour/capabilities and self-organisation. The article summarises succinctly the definitions of emergence (and predictability) and self-organisation from complexity theory, and goes on to describe multi-agent systems and the relationship to command and control with concrete examples (i.e., &quot;organisation creation agents&quot; and &quot;C2 planning agents&quot;).</td>
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<td>Mocanu, M. (2014). Intelligence and Complexity Theory. The International Annual Scientific Session Strategies XXI, 1, 46.</td>
<td>Command &amp; Control</td>
<td>M</td>
<td>M</td>
<td>This 17 page article suggests that improving intelligence in risk management and operational planning can be achieved through an understanding the concepts underlying complexity theory; specifically the notion of surprise. Following a discussion of the intelligence system as an 'open' system (i.e. affected by the external environment), the article provides a high level review of the relevant concepts from complexity theory and how they can apply to the intelligence system to improve risk management and operational planning.</td>
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<td>Dodd, L., Moffat, J. &amp; Smith, J. (n.d.). Discontinuity in decision-making when objectives conflict: a military command decision case study.</td>
<td>Command &amp; Control</td>
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<td>This 23 page article by personnel from DSTL and QinetiQ (United Kingdom) describes the application of non-linear multi-attribute utility theory in conflict scenarios in order to extend the representation of the Rapid Planning process to account for a wider set of subjective attributes of the decision-maker. The Rapid Planning process relates to the processing of information for situation assessment to support a course of action decision (i.e. tactical decision making). The article introduces non-linear theory, and its application to command (tactical) decision making, and a theory of human decision making (recognition primed decision making). Following this, the article describes an evaluation of the model using 24 military commanders and two land force (tactical) scenarios.</td>
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<tr>
<td>Liu, L., Russell, D., Looker, N., Webster, D. &amp; Xu, J. (2008). Evolutionary Service-Oriented Architecture for Network Enabled Capability. International Workshop on Verification and Evaluation of Computer and Communication Systems (VECoS).</td>
<td>Command &amp; Control</td>
<td>L</td>
<td>M</td>
<td>This 11 page article was presented at the International Workshop on Verification and Evaluation of Computer and Communication Systems in 2008 by personnel from the University of Leeds and BAE Systems (United Kingdom). Paper concludes that Service Orientated Architecture should be able to provide the agility to handle the change and dynamic evolution in Network Enabled Capability. Based on a second review, the relevance of this article was downgraded to Medium.</td>
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<td>Bar-Yam, Y. (2004). Multiscale Representations Phase II. New England Complex Systems Institute</td>
<td>Force Structure / Force Generation</td>
<td>H</td>
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<td>This 78 page final technical report for the Air Force Research Laboratory focuses on assessment of military capabilities and military technology and the process of military modernization. Specifically, the final report comprises the results of three projects (two of which are covered elsewhere in this review - #5 and #7): (1) the application of multiscale concepts to assess the Combined Relevant Operational Picture (CROP) design concept [see Reference #5]; (2) the process of military modernization through evolutionary engineering that applies beyond the complexity limit of planning and decomposition; and (3) the application of multiscale analysis to functional capabilities of military force organization with specific application to littoral warfare [see reference #7].</td>
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<tr>
<td>Murphy, E.M. (2014). Complex adaptive systems and the development of force structures for the United States Air Force. Air Force Research Institute. Air University Press.</td>
<td>Force Structure / Force Generation</td>
<td>M</td>
<td>H</td>
<td>This 125 page Master's thesis is a recent, detailed, and award-winning review of the Complex Adaptive Systems (CAS) literature relevant to military development of force structures (albeit Air Force oriented). The thesis has the following chapters: (1) a primer on complex adaptive systems in which the main characteristics of CAS are described (diversity, interdependence, adaptation, nonlinearity, emergence, co-evolution and path dependence); (2) determining the degree to which force structure is a CAS by comparing it against its characteristics described above; (3) a discussion of complexity and force structure analysis, including a brief history of applied complex systems and military theory; and (4) the recommendations and conclusions from this study, relating to measures, models and manpower.</td>
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<td>Ryan, A. (2007). A multi-disciplinary approach to complex systems design. Doctor of Philosophy Thesis, University of Adelaide, Australia.</td>
<td>Force Structure / Force Generation</td>
<td>M</td>
<td>H</td>
<td>This 222 page PhD thesis is concerned with the application complex systems to defence and security applications; including a detailed review of Complex Adaptive Systems theory and its application to defence and security (specifically, asymmetric warfare and capability development). The PhD was supervised by personnel from the Land Operations Division of DSTO (Australia). The aim of the thesis is to advance a 'conceptual analysis' approach to complex systems design that exploits deep insights from the mathematics of complex systems, without building explicit models of the underlying system. The author argues that this approach is advantageous because it can extend the domain of applicability of the discipline of complex systems into (military) situations where quantitative data are unavailable, and human and social factors are significant. The thesis comprises three parts: (1) a review of the philosophy and assumptions behind the research; (2) a detailed review of the information theory of complex systems (including their characteristics); and, (3) the application of this theory to asymmetric warfare and capability development.</td>
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<tr>
<td>Ryan, A. J. (2011). Applications of complex systems to operational design. Booz Allen Hamilton.</td>
<td>Force Structure / Force Generation</td>
<td>M</td>
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<td>This 15 page, high-level article describes how complexity theory can be applied to operational design for the US Army. The article cites examples from military operations to illustrate complex systems applications to operational design. The author shows how an appreciation of complex systems has been captured in US Army doctrine on design (particularly to support the adaptation and emergence), and identifies further opportunities to build on this success within the Army.</td>
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<td>Albino, D., Friedman, K., Bar-Yam, Y. &amp; Glenney, W. (n.d.).</td>
<td>Future Operational Environment Analysis</td>
<td>M</td>
<td>H</td>
<td>This 22 page article by personnel from the New England Complex Systems Institute and the Chief of Naval Operations Strategic Studies group provides a basis for scientific analysis of the historical and contemporary conditions under which distinct types of strategies will be successful and provides guidance to improved strategic thinking. Specifically this article attempts to broaden the discussion of military strategy by considering three distinct effects of inflicting stress on an opponent: (1) damage; (2) no effect; and (3) gaining strength. This article discusses the scientific analysis of historical and contemporary conditions under which distinct types of strategy will be successful (i.e., cause damage to an opponent) and provides guidance to improved strategic thinking. Based on a second review, the relatedness of this article to the navy was upgraded to Medium.</td>
</tr>
<tr>
<td>Colvin, N. M. (2014). A Complex Adaptive Systems Approach to the Future</td>
<td>Future Operational Environment Analysis</td>
<td>M</td>
<td>M</td>
<td>In US Army, the operations process is founded on understanding, visualization, description, direction, leading, and assessing. The operational environment provides the foundation that enables commanders to anticipate and prepare for operation, providing a framework for decision-making processes. Current doctrine highlights that the operational environment is linear and is indicative of complexity. This 89 page report focusses on answering the question &quot;how does the future environment work?&quot; through a new synthesis of existing theories in order to increase the margin for operational success.</td>
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<td>Operational Environment. Army Command and General Staff College Fort</td>
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<td>Leavenworth School of Advanced Military Studies.</td>
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<td>Bowden, F., Pincombe, B., and Williams, P.B. (2015). Feasible Scenario</td>
<td>Future Operational Environment Analysis</td>
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<td>This 7 page conference proceeding introduces the notion of Feasible Scenario Space (FSS) to enable a broader assessment of future Australian defence capability options. Scenario development method for future force generation (army). Based on a second review, the relevance of this article has been downgraded to Low.</td>
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<td>Spaces: a new way of measuring capability impacts. 21st International</td>
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<td>Congress on Modelling and Simulation, Gold Coast, Australia.</td>
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<td>Green, K.L. (2011). Complex Adaptive Systems in Military Analysis. Institute of Defense Analysis. IDA Document D-4313.</td>
<td>Future Operational Environment Analysis</td>
<td>M</td>
<td>L</td>
<td>This 18 page report provides a synopsis of information presented from a series of informal lectures on complex adaptive systems, funded by IDA's Central Research Program. These lectures were given typical by an expert in Academia, government, or industry. This synopsis describes complex adaptive systems, explains how they can be of value to commanders and military analysts, and provides examples of applications that demonstrate how the emerging field of complexity can contribute to military analysis.</td>
</tr>
<tr>
<td>Norman, J. &amp; Bar-Yam, Y. (2016). Special operations forces: a global immune system. New England Complex Systems Institute.</td>
<td>Future Operational Environment Analysis</td>
<td>L</td>
<td>M</td>
<td>This 10 page report provides a conceptual framework to clarify and differentiate the role of Special Operations Forces within the larger military system to aid decision-makers in identifying when it is necessary and appropriate to utilize SOF and when conventional forces are better suited. This framework is based on the association between the role SOF may serve and that of the immune system in complex organisms. The association between the potential role of SOF and the immune system in organisms is described in terms of the multiscale control systems theory and a complexity profile analysis.</td>
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<td>Crandall, C. (2013). If You Can't Beat Them, Kill Them: Complex Adaptive Systems Theory and the Rise in Targeted Killing. Seton Hall L. Rev., 43, 595.</td>
<td>Future Operational Environment Analysis</td>
<td>L</td>
<td>M</td>
<td>This 45 page chapter provides a comprehensive review of Complex Adaptive Systems. In the latter half of the chapter, a discussion is provided focussing on the relationship between the government’s detention and targeted killing programs using CAS theory. This article argues that legal policies regulating the war on terror actually implicate two systems—that of both warfare and law. Because these two systems “interact complexly with each other, as well as with all . . . other complex social and physical systems with which they are interconnected,” introducing even small changes into either of these complex adaptive systems can generate dramatic effects that are unforeseeable when the intervention initially is introduced. The article then discusses that the government’s expanded use of drones is representative of an unexpected and unintended consequence that can arise as a result of human intervention into complex adaptive systems.</td>
</tr>
<tr>
<td>Bar-Yam, Y. (2003). Complexity of military conflict: Multiscale complex systems analysis of littoral warfare. Report to Chief of Naval Operations Strategic Studies Group.</td>
<td>Modeling &amp; Simulation</td>
<td>H</td>
<td>H</td>
<td>This 30 page article was part of a series of the deliverables for the Chief of Naval Operations Strategic Studies Group (see also references #5 and #28). The article, based on a presentation to the Strategic Studies Group, discusses the relevance of Multiscale Complex Systems Analysis (MCSA) to a characterisation of the differences between conventional and complex warfare challenges; particularly littoral warfare. The author argues that MCSA, and in particular the interplay between scale and complexity in complex systems, is relevant to the selection of appropriate technology and to identifying military objectives in littoral warfare.</td>
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<td>Ilachinski, A. (1999). Towards a science of experimental complexity: An artificial-life approach to modeling warfare. Alexandria, VA: Center for Naval Analyses, undated.</td>
<td>Modeling &amp; Simulation</td>
<td>M</td>
<td>H</td>
<td>This 14 page article from the Center of Naval Analyses (USA) describes the use of agent-based models and evolutionary learning algorithms (also known as 'artificial life techniques') to understand some of the fundamental processes of combat. Two simple 'toy models' of land combat were designed to illustrate how land combat can be viewed as a Complex Adaptive System (i.e., as emergent behaviour resulting from collective, nonlinear, decentralised interactions between the combatants). The intent is to support the longer-term development of a complex systems theoretic analyst's toolbox for identifying, exploring and exploiting these behaviours on the battlefield.</td>
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<tr>
<td>Yang, A., Curtis, N., Abbass, H., &amp; Sarker, R. (2008). NCMAA: a Network Centric Multi-Agent Architecture for Modelling Complex Adaptive Systems.</td>
<td>Modeling &amp; Simulation</td>
<td>M</td>
<td>H</td>
<td>This 29 page article by personnel from the Defence and Security Applications Research Centre (Australia) and the Land Operation Division, DSTO (Australia) describes a novel agent-based modeling approach to Complex Adaptive Systems (CAS) - Network Centric Multi-Agent Architecture (NCMAA). The article discusses the requirements for modeling CAS, followed by a review of three agent architectures in terms of their applicability to Multi-Agent Systems (MAS). Finally, the NCMAA is described in detail, together with an embedded real-time reasoning agent, followed by its implementation to study warfare [see also references #33 and #53].</td>
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<tr>
<td>Yang, A. (2006). A networked multi-agent combat model: Emergence explained (Doctoral dissertation, Australian Defence Force Academy).</td>
<td>Modeling &amp; Simulation</td>
<td>M</td>
<td>H</td>
<td>This 305 page PhD thesis is the basis of the other publications by the author identified as part of this work. Similar to the author's other publications, the underlying premise of the thesis is the use of Multi Agent Systems (MAS) to study Complex Adaptive Systems (CAS) in the context of warfare. Similar to references #31 and #53, a Network Centric Multi-Agent Architecture (NCMAA) approach is proposed, based on CAS and network theory. Two models based on this approach are described in detail and implemented to conduct analyses of military operations in urban terrain.</td>
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<td>Lauren, M. K. (2001). A new framework for combat risk assessment using the MANA model. In ORSNZ Conference.</td>
<td>Modeling &amp; Simulation</td>
<td>M</td>
<td>H</td>
<td>This short, 10 page article introduces a new equation-based method for estimating and determining losses in land conflict based on the New Zealand Defence Technology Agency's (Map Aware Non-uniform Automata) MANA model to describe complex and non-linear battlefields using fractal methods. The article focusses specifically on dispersed land combat (i.e. a small but powerful blue force moving through a much larger but more dispersed red force). [see references #49, #51 and #54].</td>
</tr>
<tr>
<td>Moffat, J., Smith, J., &amp; Witty, S. (2006). Emergent behaviour: theory and experimentation using the MANA model. Advances in Decision Sciences, 2006.</td>
<td>Modeling &amp; Simulation</td>
<td>M</td>
<td>H</td>
<td>This 14 page journal article uses the New Zealand Defence Technology Agency's (Map Aware Non-uniform Automata) MANA model to evaluate emergent properties resulting from local unit interactions. Previous research by the authors [references #35, #51 and #54] had developed a theory of casualty generation which replaced the “industrial age” Lanchester equations with the fractal attrition relationship. They argue that this is more appropriate to the more self-organising types of conflict likely to occur in the “information age” (i.e., network centric warfare). In this article, they show that the predictions of this theory are consistent, in general terms, with the results of a number of scenarios investigated experimentally using the MANA agent-based simulation model of conflict.</td>
</tr>
<tr>
<td>Lauren, M. K. (2001). Describing rates of interaction between multiple autonomous entities: An example using combat modelling.</td>
<td>Modeling &amp; Simulation</td>
<td>M</td>
<td>H</td>
<td>This 21 page article shows how methods such as cellular automaton models and fractal equations can replace differential equations as methods for addressing real world problems. The origin of this work is in the area of military analysis, specifically, estimating combat losses. This work is highly related to (if not partially duplicated in) references #35, #49, and #54.</td>
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<td>Yang, A., Curtis, N., Abbass, H. A., Sarker, R., &amp; Barlow, M. (2006). WISDOM-II: A network centric model for warfare. Complex Science for a Complex World: Exploring Human Ecosystems with Agents, 149-173.</td>
<td>Modeling &amp; Simulation</td>
<td>M</td>
<td>H</td>
<td>This 26 page book chapter, the authors propose a Network Centric Multi-Agent Architecture (NCMAA) modeling approach (based on complex adaptive systems theory) to understand and analyse the dynamics of both platform centric and network centric warfare. In this article, the authors critique the modeling approach of Lauren and Moffat (Mana) and list a number of shortcomings which NCMAA is able to overcome. The authors provide a detailed description of the WISDOM-II model (based on the NCMAA approach) and a small validation study on its effectiveness [see also references #31 and #33].</td>
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<tr>
<td>Lauren, M. K., Smith, J. M., Moffat, J., &amp; Perry, N. D. (2006). Using the fractal attrition equation to construct a metamodel of the MANA cellular automaton combat model. arXiv preprint nlin/0607051.</td>
<td>Modeling &amp; Simulation</td>
<td>M</td>
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<td>This 35 page report documents the collaboration between New Zealand (Lauren) and United Kingdom (Moffat) as part of the TTCP Joint Systems and Analysis Group. New Zealand and the UK have been collaborating closely on the development of a new attrition equation for warfare. This equation is different from the standard approach developed by Lanchester because it incorporates spatial patterns into the analysis. This in turn may allow for the better representation of the value of command and control and networked forces in attrition algorithms. It is envisaged that this work may lead to the replacement of many ideas in existing aggregated combat models. In this article, the authors examine the possibility of using the Fractal Attrition Equation as a metamodel to describe outcomes of cellular automaton combat models. [references #35, #49 and #51].</td>
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<td>Ryan, A., &amp; Grisogono, A. M. (2004). Hybrid complex adaptive engineered systems: a case study in defence. In Proceedings of the International Conference on Complex Systems.</td>
<td>Modeling &amp; Simulation</td>
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<td>This 8 page paper explores the interactions between centrally imposed controls and the underlying complex adaptive system. Issues of predictability and unintended consequences are discussed with reference to historical studies of warfare. A contemporary terrorist scenario is developed as an Agent Based Model (ABM) to explore the effect of constraining local interaction rules through centralised control. Two alternative control mechanisms are contrasted in terms of the emergent system behaviour they produce.</td>
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<td>Mason, C. &amp; Moffat, J. (2001). An agent architecture for implementing command and control in military situations. Proceedings of the 2001 Winter Simulation Conference.</td>
<td>Modeling &amp; Simulation</td>
<td>L</td>
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<td>The author's research is concerned with representing the effects of military Command and Control, and determining how these effects can be incorporated successfully into constructive simulations of conflict. Including the C2 process in such models of military operations is essential if the simulation is to provide a realistic model of a military force’s behaviour and effectiveness. This 9 page article provides a representation of military C2 based on a decentralised system of interacting intelligent “command agents”. One objective of the research was to identify sets of simple rules and entity interactions that will give rise to emergent collective behaviour that resembles realistic military behaviour. A re-usable software framework that implements command agents is described. Architecture and its software implementation can produce agents that can simulate C2 at any level in the military command hierarchy and in the operations across the warfare spectrum - from high intensity combat to Operations Other Than War (OOTW).</td>
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<td>Niazi, M. (2011).</td>
<td>Modeling &amp; Simulation</td>
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<td>In this 292 page PhD thesis, a unified framework for facilitating the development, comparison, communication and validation of CAS models is proposed. The framework is founded using a combination of agent-based and complex network-based modeling approaches and guidelines formulated in the form of a set of four levels of usage. This facilitates researchers to choose a suitable framework level based the following criteria inherent in their research: data type, research objectives and expected outcomes.</td>
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