Mapping the Study of Complexity to Human Factors: An Initial Model

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1 Executive Summary

What is the report about?

This work comprises part of a suite of reports that deal with Sociotechnical Theory and Network Enabled Capability (NEC) system design (HFI DTC Work Package 2.17). The current report describes some of the foundational work that has been used to design an actionable model of command and control in the form of an extended NATO SAS-050 approach space.

Background and reasoning behind the work:

The development of this model is founded on the study of complexity. An initial mapping has been performed between the physical sciences (wherein the formal study of complexity resides) and the human sciences (wherein the term is rarely or adequately defined). This report is about looking at complexity from a human factors point of view.

What was undertaken in the research?

The report distils complexity through three overlapping themes: 1) the attribute view, which leads to a multi-dimensional problem space through which the field of ergonomics appears to be travelling, 2) the complexity theory view, in which metrics and measures exist to complement established ergonomics methods and diagnose at least certain aspects of complexity, and 3) the complex systems research view. This is the domain of true complexity in the sense that it helps to explain not just the ‘what’ of complexity but also the ‘why’ and the ‘how’.

What was discovered?

As an ergonomic problem, command and control is redolent in complexity of the sort operationalised in this report. Key concepts such as emergence, sensitive dependence on initial conditions and dynamical system behaviour are illustrated with reference to ergonomic case studies in command and control.

Main conclusions and recommendations:

A major source of, and solution to, the challenges of complexity derives from the most adaptable component of all in complex systems: the human. Complex systems research provides a wealth of tools and concepts that map across to the study of ergonomics, and in doing so, are able to contribute meaningfully to the practice of HFI and the consequent improvement of NEC systems design.

Military relevance of the work:

The work has operational relevance because it helps to reduce complexity (through the use of models and concepts that help us to understand complex sociotechnical phenomenon), it meets a number of explicit NATO ‘key priorities’ for the SAS-050 model of command and control, and it contributes to an actionable understanding of

social/organizational structures and the ability to directly inform interventions against target networks.

This research has been exploited in the following ways:

- The extended NATO model of command and control has been applied to Operational Field Trial #3, a live example of NEC and part of the phased capability release for Bowman/ComBAT.
- Aspects of this work have also been presented to TTCP HUM TP11 and a forthcoming collaboration is currently under development.

2 Technical Summary

What is the report about?

The aim of this report is to put forward an initial model to show how the field of human factors can be put in touch with complex systems research.

Complexity research is routinely applied in Network Enabled Capability (NEC) yet the formal understanding of it in human factors has failed to gain real traction. The report takes a different perspective in order to try and address this. The question is not one of 'what is complexity' but 'what does complexity look like from a human factors point of view'. The aim of the work is to put forward a set of ideas and insights which have proximal concern to human factors and which have the potential to stimulate a two-way cross-disciplinary exchange of information. It is the authors' contention that human factors has much to learn from complex systems research and that it provides a potentially rich harvest of concepts, theories, tools and techniques through which the human component in NEC can be optimised.

This report is the final deliverable in a suite of reports that deal with Sociotechnical Theory and NEC system design (HFI DTC Work Package 2.17). This report describes the complexity concepts that can help us explain the effect of people in live NEC field trials adapting the system in unusual and unexpected ways (as evidenced in Operational Field Trial #3, HFI DTC report reference HFIDTC/IETH/3). It explains the rationale behind experimental studies which assume the human system interaction to be fundamentally unstable (delivered under HFI DTC Work Package 2.17.2). It also provides the rational behind our approach to extending the NATO SAS-050 model of command and control (as applied again to Operational Field Trial #3 and which offered the customer critical insights in the context of Bowman's phased delivery).

This report is about:

- Providing explicit definitions for the different ways that complexity is described in the human sciences, and tries to tighten up the often informal use of such terms;
- Examining the way in which human factors problems differ from each other and matching appropriate methods to them;
- Exploiting key concepts from complexity science, such as emergence, sensitive dependence on initial conditions, phase spaces and attractors, and using these insights to inform the science and practice of human factors;
- Confronting the difficulties associated with multidisciplinary research, attempting to overcome differences in vocabulary and bridging the gap between physical and human sciences.

This report is comprised of a technical summary, setting out the background and reasoning behind the work, what was undertaken, what was found and its relevance to MoD. The full report is contained in Appendix A and an example of the dialogue we hope to stimulate between human factors and complexity science is presented in Appendix B.

Background and reasoning behind the work:

Terms such as ‘complexity’ are used with increasing frequency in the field of human factors. The difficulty arises because they are often used in an exceedingly loose and ill defined manner. This report is a response to the overarching requirement to ensure that human factors meaningfully relates to NEC research, within which the term ‘complex’ has a specific and well defined meaning.

It is important to note from the outset that this report is written from a human factors perspective. It is an attempt to advance the current state of the art in this particular field. To do this it borrows from the formal study of complexity, and via a process of analogy, performs a number of initial mappings between these two disciplines. Because of this, the report necessarily focuses on breadth of coverage rather than depth, and sacrifices strict scientific rigour in favour of innovation. The report sets out to achieve no more than an initial attempt at a model to help stimulate the flow of information between the physical sciences (within which the formal concepts of complexity reside) and the human sciences (for which the effects of complexity are acutely felt).

What was undertaken in the research?

The research distils the complexity encountered in human factors through three overlapping views:

1. *The attribute view*: this is the first way in which complexity is represented in the literature, as an artefact or entity possessing a number of fairly distinct features. We use an established set of attributes drawn from within the field of human factors in which something labelled ‘complex’ possesses the following: multiplicity (i.e. many interacting parts), dynamism (i.e. change), uncertainty (i.e. incomplete knowledge), difficulty (i.e. as experienced subjectively) and importance. These attributes are explored from a human perspective by distilling the extant peer reviewed scientific literature through them.

2. *The complexity theory view*: this is the second way in which complexity is expressed in the literature, as a quantitative measure or a single number that quantifies the complexity of a system. This approach relies on constructing what complexity science refers to as a computational equivalent, a model which explains the system in question. Human factors abounds with such models, from Hierarchical Task Analysis to Social Network diagrams. These models can be subject to this form of analysis and various complexity metrics derived.

3. *The complex systems research view*: distinct from both the attribute and complexity theory views, here we refer to “emergent behaviour exhibited by interacting systems operating at the threshold of stability and chaos” (Roetzheim, 2007, p. 4), of “systems with a large number of interacting parts and a large throughput of energy, information, or material” (Hubler, 2007, p. 10; Hubler, 2006; Hubler, 2005) and systems which “don’t just passively respond to events

[…] they actively try to turn whatever happens to their advantage", which is to say they are 'adaptive' (Waldrop, 1992, p. 11). Research of this third type is concerned with the kinds of problems that 'emergent behaviours at the boundary of stability and chaos' create, which are often the problems that arise when humans and systems interact and for which solutions are sought within human factors. Particular emphasis is given to this third type of complexity and mapping across some concepts associated with it.

What was discovered?

The principle insights provided by this work are:

- To consider the way in which human factors problems are changing and to spin in from the military domain the idea of a 'problem space' within which human factors problems are located (and moving through).

- The appropriate methodological and theoretical approaches required to match the extant nature of these problems is then considered. Upon analysis, we discover that in the region of 65% of human factors methods are well suited to dealing with certain types of problems (and attributes of complexity) but not necessarily those that human factors seems to be moving towards in its problem space.

- We then move on to consider the organizational response to increasing complexity and the case of simple organizations like NEC (simple, that is, in structural terms) undertaking complex tasks, compared to complex organizations (like classic hierarchical command and control) undertaking highly coordinated and simplified tasks. Ashby's Law of Requisite Variety and the idea of complexity profiles are spun in to explore the ways in which command structures are, or can be, optimised for human capabilities.

- Emergence is variously defined as "the phenomenon wherein complex, interesting high level function is produced as a result of combining simple low-level mechanisms in simple ways" (Chalmers, 1990, p.2). Precisely this phenomenon occurred during a live NEC field trial which forms case study material in the report. The concept of Relative Predictive Efficiency is presented as a way of providing a firmer footing for deciding what human factors approach to adopt when faced with different types of emergence.

- Sensitive dependence on initial conditions, or the so-called butterfly effect, describes how very small changes can alter the evolution of an entire system over time. This reflects a common yet rarely acknowledged characteristic of human system interaction; that it is fundamentally unstable. This insight prompts us to consider the way in which construct and face validity can be upheld in experimental trials dealing with NEC. We present an example of a longitudinal study as a demonstration of this.

- Phase spaces and attractors are derived from the formal study of complexity and inspire the method by which we have extended the NATO SAS-050 model of command and control. This enables us to fix a live example of NEC into the space and understand how changes in doctrine, equipment, procedures etc. propagate through the system (i.e. sensitive dependence) and emerge to create the system that actually arises in practice.

Main conclusions and recommendations:

Complexity, as a field of scientific enquiry, is itself complex. It is not possible in this short report to be exhaustive, nor to pull through all the finer points associated with the myriad concepts involved. Having made a first attempt to meaningfully relate complexity to human factors what consistently emerges is a realisation that a major source of, and solution to, the challenges that complexity creates derives from the most adaptable component of all in NEC: the human.

Military relevance of the work:

This research has been exploited in the following ways:

- The extended NATO model of command and control has been applied to Operational Field Trial #3, a live example of NEC and part of the phased capability release for Bowman/ComBAT. The results from this were presented to senior frontline staff at the Sennelager training ground in Germany and key stakeholders at MoD Whitehall. The associated deliverable ‘exceeded expectations’.

- Aspects of this work have also been presented to TTCP HUM TP11 and a forthcoming collaboration is currently under development. Here, the extended NATO model will be used to represent large scale multi-national data derived from the ELICIT experimental platform.

The work has operational relevance in respect to:

- Reducing complexity (through the use of models and concepts that help us to understand complex sociotechnical phenomenon).

- Meeting a number of NATO ‘key priorities’ for the SAS-050 model of command and control.

- Permitting spin-in from non-military domains and encouraging an interconnected approach to science.

- Via the extended NATO model, providing a way of benchmarking successive iterations of live/operational NEC.

The work builds critical technical capability by:

- Beginning the process of enhancing Human Factors Integration (HFI) with complexity science by 1) understanding the way in which problems differ from each other, 2) ensuring that approaches and methods match the extant nature of these problems, 3) providing models that enable live examples of complex systems to be represented and visualised and 4) providing a set of concepts to understand the resultant behaviour of such systems.

- Extending MoD's analysis capability in regard to developing, via the extended NATO SAS-050 model of command and control, an actionable understanding of social/organizational structures and the ability to directly inform interventions against target networks.

- Representing a coherent and theoretically grounded approach for assessing solutions. In particular, this work speaks towards the goal of shifting risk from operations to science.

Scientific quality is evidenced because the work is:

- Based on established methodologies in complex systems research.

- Has been subject to favourable external peer review within the wider scientific literature (e.g. Walker, G. H., Stanton, N. A., Salmon, P. M. & Jenkins, D. P. (2008). A review of sociotechnical systems theory: A classic Concept for New Command and Control Paradigms. Theoretical Issues in Ergonomics Science, 9(6), 479-499 and Walker, G.H., Stanton, N.A., Salmon, P.M., Jenkins, D.P., (2009). An Evolutionary Approach to Network Enabled Capability, International Journal of Industrial Ergonomics. 39 (2) 303-312).

- Is making a contribution to knowledge in this area through the publication of 'Digitizing Command and Control' and 'Sociotechnical Theory and NEC Systems Design' both of which are books to be published by Ashgate in their Human Factors in Defence series.

Take home message

What this mapping from complexity to human factors suggests, despite its analogous and tentative nature, is a fundamental re-think in the way that NEC should be perceived, designed and made ready for operational use. Instead of a techno-centric view of NEC (in which capability is viewed in terms of technological advancement) a human-centric view is required as a counter-balance. Most, if not all, failure of equipment to meet operational expectations can be laid firmly at the door of this techno-centric perspective and a concomitant failure to take the human-centric view into account. In this report, that human-centric view has been enhanced by the mapping across of concepts drawn from the physical sciences. As a conduit for knowledge to flow between disciplines the aspiration is for information to flow in *both* directions.

Appendix A Full Report

2.1 Background and context

In this Appendix we present the detailed work that sits behind the technical summary.

This Appendix describes in detail the theoretical background that has been developed in parallel to, and in support of, several pieces of work that have already been delivered. To that extent it comes out of sequence. Of particular note are the insights presented here in summary form concerning the NATO SAS-050 model of command and control. In previous reports these have been developed into actionable methods to assess live-NEC and applied as such in the context of the phased delivery of Bowman/ComBAT. In this Appendix we describe the complexity concepts which inspired it. Other examples relate to novel experimental studies into human adaptability. These too are inspired by complexity concepts. We look again at live NEC, this time from the point of view of unusual and unexpected behavioural adaptations that took place during it. The language and metaphors of complexity once again provide insight into perplexing issues such as these.

The work contained in this Appendix goes beyond these previous reports and puts forward a more detailed trans-disciplinary model. The aim is to facilitate discussion and debate so that knowledge can flow between the physical sciences and the human sciences. To do this we use a process of analogy to perform a number of mappings between these two disciplines.

It has not been possible to pull through every complexity related concept, so the Appendix necessarily focuses on breadth of coverage rather than depth. A further limitation is that the mapping between these two fields is at a tentative stage, thus it trades strict scientific rigour in favour of innovation and insight. What this Appendix does describe, however, is an initial attempt to understand complexity from a distinctly human factors point of view. Such a need arises because, in general terms, whilst complexity emerges as a phrase which describes certain human factors problems very well, it is not a term that human factors practitioners very often formally define.

This Appendix takes the form of a peer reviewed article to be submitted to the journal “Ergonomics”. The aim is to subject this tentative trans-disciplinary model to external peer scrutiny, to begin the process of discussion and debate within the wider human factors community and thereby offer MoD scientific quality in the form of a benchmark for future work. The written style of this Appendix reflects this peer-review exploitation route.

3 Ergonomic[1] Complexity

3.1 Introduction

A new buzzword has been making its way into the everyday lexicon of ergonomics: ‘complexity’. The word complex seems to have first justified a use in the title of a paper published in the mainstream ergonomics literature as far back as 1958 (e.g. Chiles, 1958) and since then over eighty journal articles have featured either the word ‘complex’ or ‘complexity’ in their titles too. Of considerably more relevance is the fact that nearly ninety percent of these articles have been published since 1990. Figure 1 shows that in the common vernacular (if nothing else) complexity is a term that ergonomists find increasingly relevant to the problem domains they now face[2]. The issue is that despite this, the ergonomics literature remains virtually silent on formal definitions, measures, and even awareness of complexity as a specific formal concept in its own right. To date, the precise meaning and implications of complexity have been left for the ergonomics practitioner to infer. Judging by Figure 1 the time has clearly come to try and address this gap in knowledge.

This report explores three distinct yet overlapping approaches that are taken to complexity in the human sciences:

- First is what can be termed the attribute view, which gives rise to a problem space through which the characteristics of ergonomics problems could be seen to be travelling.
- Second is the complexity theory view, in which metrics to objectively define certain aspects of complexity can be tentatively applied to established techniques in ergonomics, like Hierarchical Task Analysis for example.
- Third is the complex systems research view. This is arguably the domain of ‘true complexity’ and within which resides a set of approaches which represent a fundamental break with traditional ergonomic methods. As a number of case study examples will show, these methods provide a unique insight into the sorts of ergonomic problems stimulating the increasing use of terms like ‘complex’ in this field.

All of the above is viewed through the lens of ergonomics.

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[1] Ergonomics and human factors can be used interchangeably. The use of ergonomics reflects the peer-reviewed article to which this work is directed.

[2] The increase in the use of terms like complexity in the title of peer reviewed journal articles not only outstrips the upward growth in the number of articles published, but that growth in articles does not elbow upwards in the way seen for those that use ‘complexity’ in their titles.

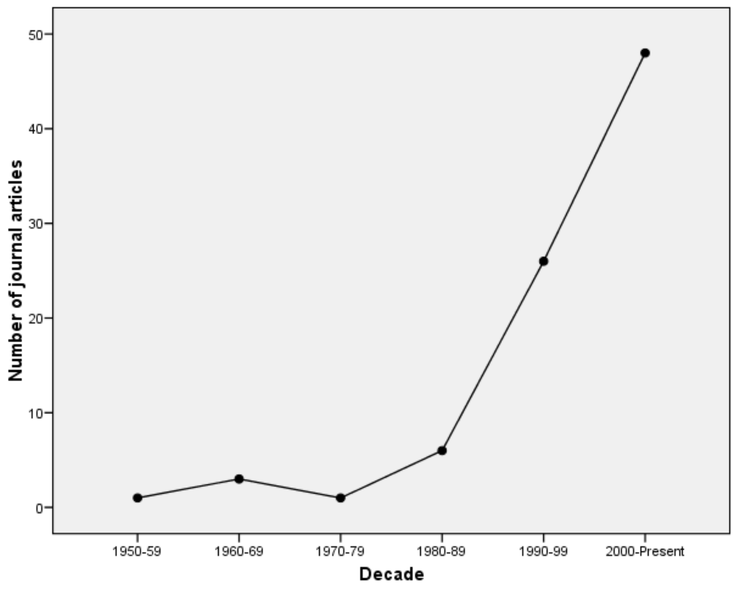

Figure 1 – Illustration of the number of articles in the mainstream, peer-reviewed ergonomics literature that have used either the word ‘complex’ or ‘complexity’ in their title (based on a search of Theoretical Issues in Ergonomics Science, Ergonomics, Applied Ergonomics, International Journal of Cognitive Ergonomics and Human Factors). This growth outstrips the wider growth in the total number of articles published.

4 The Attribute View

What do ergonomists typically mean when they invoke the term complexity? Quite often (e.g. Richardson, Jones & Torrance, 2004) it is little more than the dictionary definition of the term, that something consists of "several parts" and is "involved, intricate or difficult" (Allen, 1984, p. 145). But there is clearly more to complexity than this, and indeed, most articles that use the term seem to be trying to say something much more profound about a problem space which encompasses increasingly systemic and more naturalistic approaches to human-system interaction. David Woods' chapter 'Coping with complexity' (in Goodstein, Andersen & Olson, 1988) is one of the few that provides a self-conscious analysis of the way that ergonomics looks at complexity. The implication that it is as an entity or artefact which contains a number of distinct features (multiplicity, dynamism, uncertainty, difficulty and importance) is put to the test by distilling the extant literature, at least that which uses the word 'complex' in its title, through these five attributes.

4.1 Multiplicity

The first of these attributes can be labelled 'multiplicity', as in multiple potential causes for extant phenomena and multiple consequences, or in other words, "a great number of interrelated and therefore interacting factors" (Marmaras, Lioukas & Laios, 1992, p. 1224). In the wider ergonomics literature there are 'multiple people' and a class of paper headed 'complex team tasks' (e.g. Braarud, 2001). There are also 'complex multiple tasks' involving "the control of a large number of interdependent process variables" (Sauer, Hockey & Wastell, 2000, p. 2044) and there are 'complex distributed teams', another popular heading in which these two strands (multiple tasks that are dealt with by multiple people) are brought together, more often than not as a result of networked technology like the internet (e.g. Rogalski & Samurcay, 1993). As a dimension of ergonomics complexity, the notion of multiplicity also overlaps with that of a 'system' (Naikar, Moylan & Pearce, 2006), and certainly a large number of articles ally themselves to a systems perspective (and use the heading 'complex system' as a result; Gregoriades & Sutcliffe, 2006; O'Hare, 2000; Lo & Helander, 2007; Wei, 2007; Kaber et al., 2001; Hanisch, Kramer & Hulin, 1991; Swain, 1982 etc.). It is important to point out, however, that the term 'complex system' has a much more profound meaning than its current use as a descriptive label might at first suggest.

4.2 Dynamism

The second attribute is 'dynamism', that is, to what extent can the system change states without intervention from the user? To what extent can the nature of the problem change over time? To what extent can multiple on-going tasks have different time spans? (Woods, 1988). The role of time is captured in the numerous articles headed 'complex *dynamic* systems' (e.g. Elg, 2005; Howie & Vicente, 1998; Vicente, et al., 2004; Reinartz, 1993; Canas et al., 2005) in which the use of simulations, micro-worlds and/or other longitudinal methods are common to them all. This could be viewed as a tacit rejection of the non-dynamic representation of the human-system interaction embodied by the more ubiquitous psychology-esque cross-sectional study (Lee, 2001). It is certainly recognition of the entirely pragmatic fact of ergonomic life that problems rarely possess the clinical levels of control found in the lab, that there is often no 'one right way' to perform a task (Howie & Vicente, 1998) and that people will interpret their environment, "massage it and make such adjustments as they see fit and/or are able to undertake" (Clegg, 2000, p. 467). Ergonomic complexity, therefore, as well as being an attribute of systems is also associated with degrees of freedom and change over time.

4.3 Uncertainty

The third attribute is 'uncertainty'. Tacit in the literature is the idea that parts, interconnections and dynamism make it difficult to discern final states from initial conditions. Furthermore, these initial conditions seem sensitive to uncertainty in the form of inaccuracy, randomness, and vagueness (Hancock, Masalonis & Parasuraman, 2000). Of particular note is a growing class of paper that overtly recognises this attribute and terms it 'fuzziness'. As a result, there are numerous fuzzy models (e.g. Luczak & Ge, 1989; Karwowski & Ayoub, 1984), ranging from neuro-fuzzy models (Lee et al., 2003) to fuzzy linguistic models (McCauley-Bell & Crumpton, 1997), and perhaps as a final rebuke to the binary first order logic of category membership, there is the almost oxymoronic case of fuzzy signal detection theory (Masalonis & Parasuraman, 2003). If a trend can be discerned from this, then it is a recognition that artefacts of ergonomics problems do not always occupy neat categories and that it is not always possible to have complete knowledge of a problem or phenomena.

4.4 Difficulty

The fourth attribute of complexity is 'difficulty', with the ergonomics world reflecting back a prominent component of the dictionary definition. An ergonomic axiom is that complex tasks take longer to learn and are often more demanding to perform (Sauer et al., 2006) with around a third of articles that feature complexity in their title doing so in relation to what they term 'task complexity'. Although complexity can be expressed objectively as a form of 'intrinsic complexity', different levels of which form independent variables in studies (e.g. Sauer et al, 2006), it is much more common within the literature for complexity to reside in the eye of the beholder in the form of 'supposed complexity' (Leplat, 1988) or "complexity seen from the perspective of the person describing the task" (Cronshaw & Alfieri, 2003, p. 1108; Bar-Yam, 2004b). Interestingly, several articles use the NASA TLX, and by implication workload, as a surrogate for supposed complexity (e.g. Gregoriades & Sutcliffe, 2006; Braarud, 2001). The higher the workload the more difficult, and more complex the task is held to be. O'Brian & O'Hare (2007) point out that a major source of this difficulty are modern systems that "increasingly challenge the operator's perceptual and cognitive, rather than physical, abilities" (O'Brian & O'Hare, 2007, p. 1064), attached to which is an unfortunate trend that addresses shortfalls in system capability with more, not less complexity (e.g. Hollnagel & Wood's 'self reinforcing complexity cycle'; 2005). This too is a prominent facet of the literature gathered under the umbrella of 'complex decision making tasks' (Quesada, Kintsch & Gomez, 2005; Canas et al., 2005; Reinartz, 1993; Marmaras, Lioukas & Laios, 1992; Coury & Drury, 1986 etc.).

4.5 Importance

The fifth and final attribute of ergonomic complexity is ‘importance’. Woods (1991) equates complexity with what is at stake, so for an entity or artefact to be complex in an ergonomics sense it has to be meaningful. However, with reference to Figure 1 and the apparent growth of complexity, it seems rather improbable to suggest that the domains of anaesthesiologists, air traffic controllers, aircraft pilots, military personnel, car drivers and nuclear power plant operators have become any more or less important than they were in the 1950’s (O’Brian & O’Hare, 2007). Perhaps it is more correct to say that the term complexity is not generally used in connection with things like children’s games, mowing a lawn or buying groceries (although even here there is multiplicity of parts and degrees of interrelation, dynamism, uncertainty and difficulty). The point seems to be that, “Something is complex if it contains a great deal of information that has a high utility, while something that contains a lot of useless or meaningless information is simply complicated” (Grand, 2000, p. 140).

4.6 Problem Spaces

Multiplicity, dynamism, uncertainty, difficulty, importance; these five factors represent one of two ways that the term complexity is used in the literature. In this case it is “as a quality whose attributes […] characterize all complex systems” (Bar-Yam, 2004a, p. 3). This attribute view of complexity, therefore, describes a five dimensional ‘problem space’, with the curve in Figure 1 showing perhaps the trajectory of ergonomics through it. Of course, five dimensional problem spaces are not easy to visualise whereas three dimensional spaces are. It is possible to draw from the world of military command and control (e.g. NATO, 2006) in order to illustrate just such an attempt (Figure 2). The attempt to apply it to the field of ergonomics is purely conjectural at this stage, but it is useful for starting to think about the way ergonomics problems differ from each other at some fundamental level.

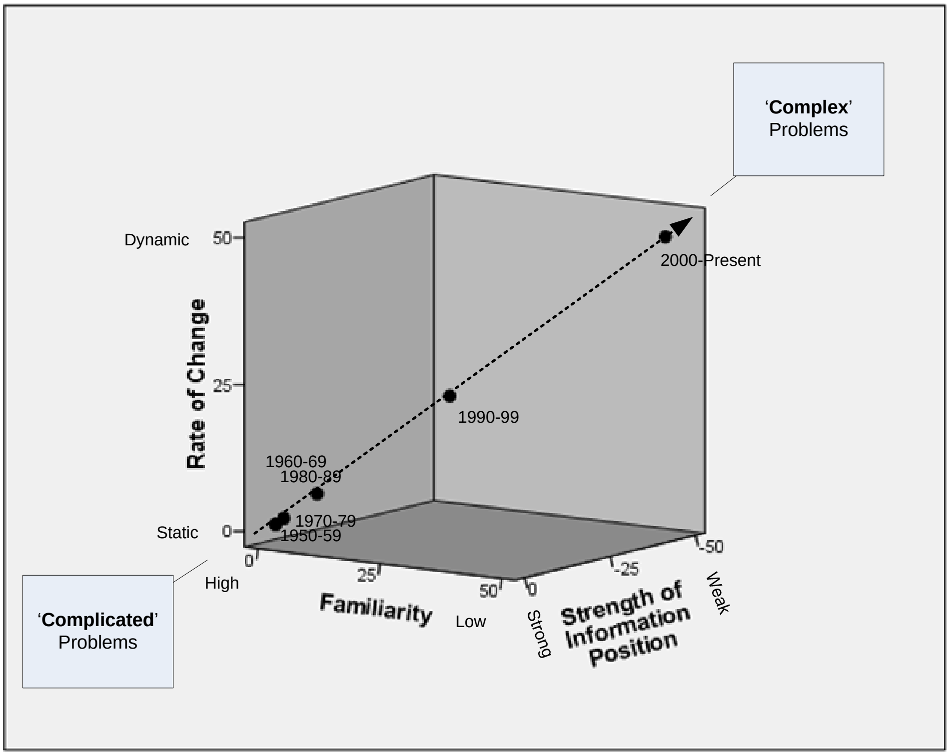

Figure 2 – Alberts & Hayes (2006) problem space provides a 3D approximation of the attribute view of complexity. The number of papers using 'complex' in their titles serves as a crude metric for the overarching nature of ergonomics problems and this is projected identically onto the x, y and z axes. A fit line is drawn through the coordinate points in order to provide an illustration of the general trajectory of ergonomics through this problem space.

The overlap between this model and the five attributes described above is largely coincidental, but nonetheless readily apparent. The x-axis is labelled familiarity, and is the extent to which facets of the problem space are well-known. The proximal attribute is of course 'uncertainty', but 'multiplicity' and 'difficulty' clearly serve as distal causes. The y-axis is labelled rate of change, and of course this finds a ready link with 'dynamism'. The z-axis, labelled 'strength of information position' is defined as follows: "Regardless of the degree of dynamism (though very possibly influenced by that factor) and the degree of knowledge available about it (though, again, very possibly influenced by it) the strength of the information position has an important impact on the applicability of [particular approaches to coping with complexity]" (Alberts & Hayes, 2006). In a sense this relates to 'importance', that some types of information about complex artefacts and entities are more important than others. Obviously, this collapsed three dimensional version of the five dimensional attribute view of complexity is not necessarily "orthogonal or totally independent" (Alberts & Hayes, 2006, p. 76), neither are the five attributes just described regarded as final. Furthermore, the problem space undeniably reflects a bias towards command and control issues. But, it still conveys a powerful point about the way ergonomic problems differ from each other, specifically, problems that are merely 'complicated' can be characterized by high familiarity (often bestowed by the adoption of a reductionist, atomic approach that decomposes phenomenon into small understandable units), non-dynamic rates of change (in which the human-system interaction can be regarded as stable) and a strong information position (familiarity being 'very possibly' implicated in a strong information position). Complicated problems, therefore, find themselves in the bottom left hand corner of the problem space (as shown in Figure 2).

Complex problems, on the other hand, can be characterised by unfamiliarity (due to the interactions between components), varying rates of change (due to the human-system interaction being potentially unstable as humans adapt themselves to their context) and a weak information position (as familiarity and quantity of information are no longer assured). These problems occupy a position in the opposite corner of the problem space, the area into which the complexity curve seems to be pointing and which can be grounded in the set of key trends identified by Boehm (2006) in Table 1. These help to illustrate the kinds of 'real-world' challenges that ergonomists are facing and why 'complex' arises as such an appropriate term.

Table 1 – Wider trends associated with opposite corners of the ergonomics problem space (Boehm, 2006).

From complicated…	…to complex
A focus on specialization.	An increasing integration of disciplines, specialisms and expertise.
A focus on what a system 'is' (i.e. requirements and functionality).	An increased emphasis on what a system 'does' (i.e. end value, effects and capabilities).
An increasing level of criticality and dependability required of complicated systems.	An increasing level of criticality and dependability required of complex systems.
A focus on constraining dynamism and imposing stable behaviour.	An increasing level of dynamism and rates of change.
A focus on stand-alone systems.	An increased emphasis on interoperability.
An emphasis on controlling complexity.	An increasing emphasis on ever more complex systems and systems of systems.
A focus on end-products often based on new technology which replaces obsolete equipment.	An increasing trend towards through life capability, integration of legacy systems and reuse.
An increase in computational power and the ability of entities and artefacts to exhibit complicated behaviour.	An increase in computational power and the ability of entities and artefacts to exhibit complex behaviour.

5 The Complexity Theory View

The second way that complexity is expressed in the HF literature, aside from a set of non-orthogonal attributes, is to ascribe a quantitative measure to it. Variations on this approach are referred to generically under the heading of 'Complexity Theory'[3]. In this case complexity is equated to the amount of information needed to describe the phenomenon under analysis.

5.1 Information Entropy

Under the rubric of information theory (e.g. Shannon, 1948) the amount of information needed to describe a system is based on the uncertainty inherent in that system. The greater the uncertainty the more difficult it becomes to predict future system states from current system states. Information entropy in these cases is said to be high because past system states do not communicate full information about future system states. Each new state has to have more new information ascribed to it, thus the information content of its numerical description becomes longer, and it this that ultimately communicates something about the complexity of that system.

In cases where information entropy is low, when future states *can* be predicted from past states, then there is less need to encode each new state with more information (this information would be redundant). As a result, the information content of the system's description can be shorter for the same predictive efficiency. This too communicates something about the complexity of the system.

Closed systems tend to be associated with low information entropy: new states do not contribute much additional information that can be used to describe the system numerically. Open systems (of various sorts) tend to be associated with high information entropy: each new system state delivers new information to the system's description of itself. This entropic behaviour is reflected in various complexity metrics.

Implied in much of the extant NEC literature is high information entropy and Moffat (2003) uses this approach to explore the issue much more thoroughly. From a human sciences point of view the notion of problem spaces is suggestive of parallelism, with NEC potentially able to exhibit the characteristics of open and dissipative systems in conjunction with more closed system states. It is likely that NEC's information entropy, and the subsequent behaviour of its complexity metrics, varies across time and function.

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[3] Note that 'complexity theory' is sometimes used in a more general sense to encapsulate a much wider range of approaches than this. See Moffat (2003).

5.2 Kolmogorov Complexity

The theme of information entropy leads into the derivation of more specific complexity metrics, a notable core example being Kolmogorov complexity (Solomonoff, 1960). Underlying this is the principle of Computational Equivalence. Traditionally applied to algorithmic analysis of information content (in the signal processing sense of the term) it has found wider application with more sophisticated models of more sophisticated entities and artefacts. The rationale is that if the computational model were to be 'run', it would generate and/or fully explain the entity or artefact in question. Kolmogorov complexity, in generic form, is about subjecting such models to analysis to indirectly diagnose the complexity of the entity or artefact that generated the model in the first place.

Traditionally, such analyses are undertaken with computer programs serving as computational equivalents, but in ergonomics something like Hierarchical Task Analysis (HTA; Annett et al, 1971; Annett, 2005; Stanton, 2006) appears to serve an identical purpose. HTA is a description of, and a computational equivalent for, its top-level goal. In other words, 'running the HTA', performing all the operations, sub-goals and plans, should generate the top level goal, and because of this, it has computational equivalence to the actual entities or artefacts which 'in real life' produce it. Subjecting HTA to analysis using metrics from complexity theory could potentially reveal important aspects of the real-system's complexity.

5.3 Complexity Metrics

Some examples of metrics derived from complexity theory, that is to say the quantitative measures, the single numbers that can characterises a system, are applied to HTA and detailed in Table 2. At this point it is relevant to note that HTA is not the only computational equivalent available to ergonomists. The authors have applied several of these metrics successfully to social networks (e.g. Walker et al., 2008b), and there is good reason to suspect that they can provide a measure of complexity for all manner of other representations, from process diagrams to fault trees. For the time being, though, Table 2 focuses on HTA.

Table 2 – Examples of complexity theory metrics (from Hornby, 2007) explained using Hierarchical Task Analysis as the 'Computational Equivalent' for an entity or artefact.

Name	Description
Number of Build Symbols	The number of goals/sub-goals that produce the overall goal.
Algorithmic Complexity/Algorithmic Information Content/Kolmogorov metric	The number of goals and plans that produce the overall goal.
Logical Depth	The *minimum* number of sub-goals and plans that will produce the overall goal.
Sophistication	The total number of logical operators (e.g. IF, THEN, AND, OR) that are used in the plans in order to generate the overall goal.
Grammar Size	The number of new and distinct logical operators used to generate the overall goal.
Connectivity	The maximum number of edges that can be removed before the task analysis splits into two.
Height	The maximum number of links between sub-goals from the bottom to the top of the analysis.

Interestingly, the complex theoretic approach does have a minor legacy in ergonomics, albeit a very small one limited to the realm of axiomatic design (e.g. Suh, 2007). This quantitative approach to ergonomics lends itself well to similarly quantitative measures of complexity. Unfortunately, metrics are employed that are so specific to this approach (for example, complexity is seen "as a measure of uncertainty in achieving the specified [Functional Requirements]; Suh, 2007, p. 111) that its lack of wider usage is understandable.

Axiomatic design reveals a further, somewhat wider limitation. By relying once again on a certain degree of analogy we can argue, in these cases, that an equilibrium state is represented by a physical design that has arisen from mathematical axioms, or an overall goal that has been generated from an HTA. We can argue further that in both cases this state has been predicated on strongly rational assumptions which focus on stable behaviour, well understood dynamics and a form of 'IF THEN' logic (Burke, Fournier & Prasad, 2006). These are a set of pre-requisites that are firmly located in the 'complicated' octant of the problem space shown above in Figure 2). A common criticism of the complex theoretic approach, therefore, is that mathematical proofs like this are able to describe rational (and by implication simple, or at least merely ‘complicated’) systems, but only certain aspects of truly complex ones (Boguta, 2005, p. 18). For ‘non-equilibrium’ systems, systems that embody various degrees of change, uncertainty and throughput, as is the case for most sociotechnical systems, we need to go beyond both the attribute view and the complex theoretic view to a further approach, one that is encapsulated under the heading ‘complex systems research’. This forms the backdrop to the remainder of the report.

6 The Complex Systems Research View

Components of the ‘attribute’ and ‘complex theory’ views are highly useful, yet they still do not, on their own, completely get to the heart of what it means for the real-world problem spaces increasingly occupied by ergonomists. Here we are talking about “emergent behaviour exhibited by interacting systems operating at the threshold of stability and chaos” (Roetzheim, 2007, p. 4), of “systems with a large number of interacting parts and a large throughput of energy, information, or material” (Hubler, 2007, p. 10; Hubler, 2006; Hubler, 2005) and systems which “don’t just passively respond to events […] they actively try to turn whatever happens to their advantage”, which is to say they are ‘adaptive’ (Waldrop, 1992, p. 11).

The field variously called ‘Complex Systems’, ‘Complex Adaptive Systems’ and/or ‘Complex Systems Research’ would recognise this as the essence of what true complexity, as a distinct phenomenon, is all about. At this point we run into a problem of terminology. Complexity is such a new and turbulent field that all of these terms are still surprisingly fluid. To illustrate the problem it can be noted that some authors (e.g. Moffat, 2003) use what we have called ‘Complexity Theory’ (above) to describe what we have just attempted to label ‘Complex Systems’. They (and we) are both correct. From a human factors point of view we use Complex Systems in the same way that Moffat uses Complexity Theory, “as a shorthand term to cover a number of areas, each with its own distinct heritage” (Moffat, 2003). If the attribute view of complexity is our first view, the complexity theory view, that of numerical metrics, is our second view. The complex systems research view is our third.

Regardless of the label given to it, complexity research of this third type is concerned with the kinds of problems that ‘emergent behaviours at the boundary of stability and chaos’ create. Appropriately termed ‘wicked problems’ by systems engineers, these are less amenable to the ‘complex theory’ approach as they are often not fully understood, have fuzzy boundaries, lots of stakeholders and lots of constraints with no clear solution (Rittel & Webber, 1973). They are also not completely explained by the ‘attribute’ view of complexity, which is better at answering the ‘what’ of complexity rather than the underlying ‘how’ and ‘why’. Truly complex problems “are the problems that persist – the problems that bounce back and continue to haunt us” (Bar-Yam, 2004, p. 14). They also tend to be the very problems that prompt the intervention of last resort: the ergonomist.

Of course, problems of a *non* wicked nature are often what the stated regime is designed to yield. At a superficial level systems are usually procured such that for a given set of inputs a requisite set of outputs are anticipated. To the extent that, despite this, wicked problems still appear is what makes complex systems research highly relevant to ergonomics. One author notes of complex problems that they “may appear to be scattered examples from the corner of [disparate scientific] fields. But in fact they are just the borders to a vast world that science has assiduously evolved to avoid” (Boguta, 2005 p. 16).

6.1 Atomic Methods for an Atomic Age

6.1.1 Reductionism

The reason that scientific endeavours like ergonomics might appear to have assiduously avoided this third type of complexity is due in large part to the methods employed. Complex systems research advocates an inversion to what it sees as the reductionist, decompositional, Newtonian logic of 'traditional science' (e.g. Waldrup, 1992; Bar-Yam, 2004a). Instead of a top down approach to investigating problems, complex systems research "studies how relationships between parts give rise to the collective behaviours of a system and how the system forms relationships with its environment" (Bar-Yam, 2004a, p. 24). In numerous fields where this approach has been tried, which include extremely large scale examples of collective behaviour (such as global weather patterns and social systems the size of nations), they are all understood as phenomena that are not adequately explained by understanding their constituent parts. Instead, what is required is a focus on the 'relationships' between those parts, relationships that are normally fractured and discarded by the reductionist agenda In ergonomics, concepts and methods in human error and cognitive systems engineering, for example, Reason's layered systems 'Swiss cheese' model (1990), Perrow's 'normal accidents' (1999), Hollnagel and Woods' 'joint cognitive systems' (2005) and Vicente's Cognitive Work Analysis (1999), seem to come closest to not just dealing with complexity, but specifically *this t*ype of complexity, although rarely is it defined in this way explicitly. Complex systems research presents a much more forceful agenda than either of these ergonomics specialisms in terms of challenging the ubiquity of the reductionist approach.

6.1.2 Physics Envy

A very crude characterisation of the so called 'traditional approach' to science is that in order to understand how something works and behaves it has to be taken apart. This has been the basis of scientific endeavour and progress since the renaissance and Carl Linnaeus, the acknowledged father of taxonomy, who produced such a thing in 1735 for plant and animal species and called it the 'Systema Naturae'. The rationale behind taking things apart and reducing them down to their fundamental properties is that it makes them less complex and easier to understand. When all parts have been understood, they can be reassembled back into the 'whole' from whence they came using the hierarchical map of decomposition that was used to take the system apart in the first place. The whole, therefore, is assumed to be no more and no less than the sum of its parts. It is precisely by these means that true complexity, in the complex systems research sense of the term, can be assiduously avoided (as the author above notes). None of this is to suggest an active conspiracy, yet despite all the attention given to this paradox within classic organisational and sociotechnical literature over the decades, it still persists.

Emblematic of the progress and success of this approach is physics. Taxonomy and reductionism might have a longer history in the field of biology, but physics can lay claim to the finest level of decomposition (in the form of particles smaller than atoms) and the most erudite set of fundamental laws and theories stretching forward in time from Newton to Einstein. No wonder, then, that "scientists in disciplines outside physics wished their own subjects could boast the intellectual profundity, the mathematical agility and the foundational rigour that was evident in physics” (Ball, 2004, p. 256). This phenomenon is light-heartedly termed ‘physics envy’ and lest there be any doubt that ergonomics is not afflicted with this condition then consider for a moment Venda’s paper (1995) in which first, second and third laws of so-called ‘ergodynamics’ are expounded. Yet despite wearing the clothes of mathematics, ergonomics cannot hope to attain anything approaching the same level of precision (Ball, 2004) and falls foul of the same problems that complex theoretic approaches do: they only deal with certain aspects of complexity, and not those described by the complex systems research perspective. Nevertheless, the influence of ‘physics envy’ (to persist with the colloquialism) is much more implicit and pervasive than the highly specialist nature of ‘theories of ergonomics’ and ‘axiomatic design’ papers might otherwise suggest. In the science and practice of ergonomics, the simple reductionist expedients of decomposition and hierarchy are alive and well.

Consider for a moment what could be regarded as a fundamental unit of ergonomic analysis. Physics has the atom, ergonomics has ‘the task’; “something that needs to be done, an act that one must accomplish” (Reber, 1995, p. 784). To judge by its long legacy and enduring popularity among practitioners, one of the central analysis methodologies in ergonomics is undoubtedly Task Analysis, which generally speaking involves identifying tasks, collecting task data, analysing the data so that tasks are understood, and then producing a documented representation of the analysed tasks (Annett et al., 1971). Armed with this data on tasks, ergonomists can then begin to answer useful questions related to them: what is the workload associated with this task? Who should perform that task? What are the situational awareness requirements? What are the error probabilities? And so on. As Table 3 shows, all of the half dozen task analysis methods in widespread use today rely to some extent on taking tasks apart (i.e. decomposition), drawing a map of what, and how the task has been dismantled (i.e. by creating a hierarchy) and analysing the pieces in fine detail (i.e. exhaustive description and re-description).

Table 3 – Task analysis methods all rely on the analysis of parts in order to understand the whole (data drawn from Stanton et al., 2005).

Name/Acronym	'Whole' Under Analysis	Brief Description
Hierarchical Task Analysis (HTA)	Goals	Describes "activity under analysis in terms of a **hierarchy** of goals, sub-goals, operations and plans" (p. 46)
Goals, Operators, Methods and Selection rules (GOMS)	Human computer interaction	"GOMS attempts to define user goals, **decompose** those goals into sub-goals and demonstrate how the goals are achieved through user interaction" (p. 54)
Verbal Protocol Analysis (VPA)	Processes, cognitive and physical, used to perform a task	"It is recommended that a HTA [**Hierarchical** Task Analysis] is used to describe the task under analysis" (p. 58)
Task Decomposition	Task or scenario	"…using specific task-related information to **decompose** the task in terms of specific statements" (p. 62)
Sub-Goal Template method (SGT)	Information requirements for tasks	"…involves **re-describing** a HTA for the task(s) under analysis" (p. 68)
Tabular Task Analysis (TTA)	Task or scenario	"…**takes each bottom level task step** from a HTA and analyses specific aspects" (p. 72)

Out of a total of 91 ergonomics methods that are widely available, readily applicable, original, and in widespread use (Stanton et al., 2005), 65% of them either rely explicitly on these task analysis methods or else some other form of decomposition, hierarchy and/or exhaustive re-description. Not all methods and approaches are like this but clearly, taking things apart in order to understand them is an undeniable hallmark of a significant tranche of ergonomics practice, and of course, significant progress has been made using it. But as a strategy for understanding complex phenomena, not just those that are comprised of lots of parts and difficulty, or those that can have numerical values ascribed to them, but phenomena at the edge of stability and chaos; the limitations of this reductionist approach are starting to become apparent. In physics, understanding nature's laws on these terms leaves "unanswered the question of how to apply those laws to any but the simplest of systems" (Gleick, 1987). In ergonomics, Lisanne Bainbridge writes of complex tasks and that "classic ergonomics does not offer many of the concepts and techniques needed" (1993, p. 1399). De Greene (1980) looks at 'major conceptual problems in the systems management of ergonomics research' and notes the difficulties that stem from "future uncertainty, the use of static models, the relationships between models and data" and so on (p. 3). These traditional methods find themselves increasingly criticised because they seem to "under estimate (if they capture them at all) the context-dependent aspects of human performance", i.e. the complex ones (McLeod, Walker & Moray, 2005, p. 673). The question here is not one of a strict systems versus classical dichotomy, in which each is completely if mutually orthogonal. The very notion of a problem 'space' (however conjectural) highlights instead the idea of transitive complexity, with global systems comprised of interacting sub-systems (which are variously complex themselves; Ardis, 2008). In other words, problems can exhibit a high degree of parallelism and overlap, exhibiting traits that are amenable to classical, bottom-up, reductionist approaches simultaneous with traits that require a systemic, top down approach.

7 Command and Control

One problem domain that has played a prominent role in accelerating the use of terms like ‘complex’ and ‘complexity’ in the titles of papers published in the ergonomics literature is command and control. “The relationship between complexity and ‘information-based’ warfare is […] less deterministic and more emergent; less focussed on the physical, and more behavioural; less focussed on things, and more on relationships.” (Moffat, 2003, p. 3). The “post-9/11 world suggests a different set of mechanics for competition and conflict, a new model of conflict, and different operational and tactical problems from those upon which we have grown to focus” (Smith, 2006, p. 5). Command and control is undeniably complex and this is not the first time it has been examined through this lens. Whilst it is not possible to be comprehensive what we have set out to achieve in this section is a further harvest of complexity concepts. The aim is to start using them as a way of providing insight into perplexing human factors phenomena.

7.1 Traditional Hierarchical Command and Control

If hierarchies are a generic approach to science then they are certainly a generic approach to organisational design (Davis, 1977). In general terms command and control (given the notation C2) describes the management infrastructure for many large, complex, dynamic resource systems, but of course, not all such management infrastructures are the same (Harris & White, 1987; Bar-Yam, 2004a). Traditional military command and control, for example, possesses the following three organisational attributes (Alberts & Hayes, 2006):

- Unitary decision rights (in which optimum means to ends are specified at the top of, or at higher levels of a vertical hierarchy);
- Tightly constrained patterns of interaction (due to rules, standard operating procedures and other means by which the organisation embodies its past experience and specifies optimum means to ends) and;
- Tight control (in which the distribution of information occurs via intermediate echelons of management).

Decision rights, patterns of interaction and distribution of information form intersecting x, y and z axes and a so-called ‘approach space’ (Alberts & Hayes, 2006; NATO, 2006) which, despite lacking any overt cross-referencing, is somewhat reminiscent of the classic Aston University organisation studies of the sixties (see Pugh & Hickson, 1976). With these characteristics in mind, traditional command and control can be plotted into the space as shown in Figure 3.

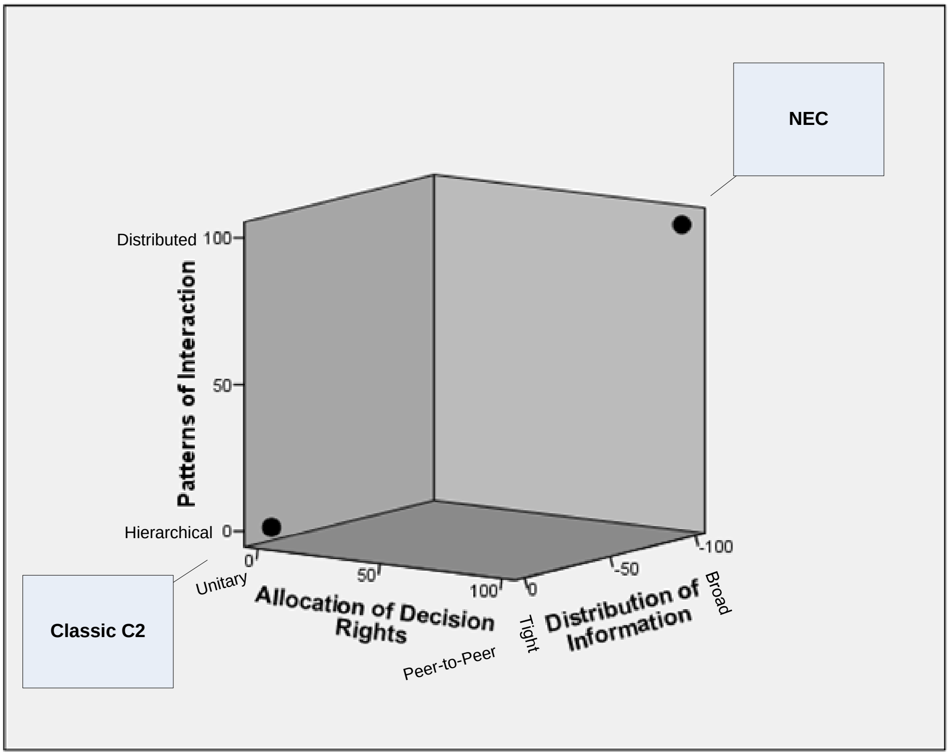

Figure 3 – Patterns of interaction, decision rights and dissemination of information create a three dimensional approach space and an established model of command and control (Alberts & Hayes, 2006; NATO, 2006).

If a highly caricatured version of traditional hierarchical command and control is deployed, which can be labelled ‘classic C2’, then it can be seen through the lens of classic organisational theory (i.e. in the sense of Weberian Rationality) as an overt attempt to maximize the following four aspects of performance:

- Efficiency: hierarchical command and control excels at amplifying the effect of whoever resides at the top of the structure. It is seen as “…the most efficient structure for handling large numbers of tasks…no other structure could handle the massive quantity of work as efficiently” (Ritzer, 1993, p.20).

- Predictability: hierarchical command and control excels at performing coordinated, coherent action so that the “Outsiders who receive the services [which command and control] dispenses know with a high degree of confidence what they will receive and when they will receive it” (Ritzer, 1993, p. 21).

- Quantification: “The performance of the incumbents of positions within [the management infrastructure] is reduced to a series of quantifiable tasks…handling less than that number is unsatisfactory; handling more is viewed as excellence” (Ritzer, 1993, p. 21). Through the lens of Formal Rationality, hierarchical command and control represent a form of organisational reductionism that tends to focus on the performance of repeated, simplified tasks.

- Control: hierarchical command and control can "…be seen as one huge nonhuman technology. Its nearly automatic functioning may be seen as an effort to replace human judgement with the dictates of rules, regulations and structures" (Ritzer, 1993, p. 21). Hierarchical command and control, therefore, embodies the linear cause and effect logic of inputs being proportional to outputs and of sums being equal to their parts.

It is possible at this point to say a number of useful things about classic C2 from a complex systems research point of view. The first of these relates to the idea of 'scale', a concept developed by researchers at the New England Complex Systems Institute (e.g. Bar-Yam 2004a, b). They state that there is a trade off between scale of observation (defined as the "level of detail visible to an observer of a system"; Bar-Yam, 2002, p. 1), and the sorts of behaviours occurring at different levels (more specifically the number of 'distinct' behaviours). Depending on how an organisation is designed, behaviour changes in quite specific ways depending upon the scale of observation. This relationship is termed a complexity profile and defined as "the amount of information necessary to describe a system as a function of the level of detail provided" (Bar-Yam, 2002, p.1). In the case of classic C2 its primary behaviours are generally visible at large scales because the entities and actors are behaving in highly coordinated ways, or to use Perrow's terminology, there is a 'tight coupling' (1999). This is due to the hierarchical nature of the management infrastructure of which they are a part. As we zoom in on this stereotypical organisation, decreasing our scale of observation, that high level of coordination gives rise to a distinctive property. Although the effects of hierarchical command and control can be viewed from a large scale of observation its fine scale behaviour is not always especially complex. In other words, it is an example of a complex organisation (in terms of its control structures, rules, myriad procedures and patterns of vertical communication), which nonetheless only really permits people to undertake simple tasks (e.g. Sitter, Hertog & Dankbaar, 1997). Complex organisations with simplified tasks finds an analogy in the 'thin agent models' characterized by the "Santa Fe Approach" (e.g. Guerin & Kunkle, 2004). The behaviour of such organizations (and models) reflects a fundamental principle of complex (and not so complex) systems: when parts of a system are acting together, the fine scale complexity is small (Bar Yam, 2004b).

The second point about hierarchies is that the large scale behaviours they are capable of cannot be more complex than the person(s) at the top of the structure, which is complex but ultimately limited (Bar-Yam, 2004b). Hierarchies are large scale but also low variety. Variety refers to the total number of states that a system can adopt, or the number of behaviours it can emit, or its degrees of freedom (Ashby, 1956). In discussions of scale, it is variety that is often being used as shorthand for complexity. Less complex is equated with only limited numbers of behaviours (low variety), and vice versa for more complex.

Ashby's Law of Requisite Variety is a cybernetic principle founded on a raft of concepts too numerous to present here (the reader is referred to Ashby, 1956, for a classic introduction to the topic). The Law of Requisite Variety states, quite simply, that the degrees of freedom of which system is capable, must match the degrees of freedom that the environment within which the system resides is capable. Or to put it another way:

"in active regulation only variety can destroy variety. It leads to the somewhat counterintuitive observation that the regulator must have a sufficiently large variety of actions in order to ensure a sufficiently small variety of outcomes in the essential variables [..]. This principle has important implications for practical situations: since the variety of perturbations a system can potentially be confronted with is unlimited, we should always try to maximize its internal variety (or diversity), so as to be optimally prepared for any foreseeable or unforeseeable contingency." (Heylighen & Joslyn, 2001).

As Ashby states, if "the system is continuous, we can ask whether it is stable against all disturbances within a certain range of values" (1956, p. 85). However, the idea of 'stable' is problematic and the Law of Requisite Variety brings some of these issues into relief. Ashby saw stability as a property which in most useful cases could only be specified over a brief time envelope and only then under certain conditions:

"As shorthand, when the phenomena are suitably simple, words such as equilibrium and stability are of great value [but] phenomena will not always have the simplicity that these words presuppose" (Ashby, 1956, p. 85).

Whilst Ashby recognized certain aspects of systems were invariant, he also recognised evolution, which is something that Requisite Variety connotes quite strongly in some cases. In possessing Requisite Variety a system doesn't just possess the means to move itself from one state to another, but in some cases to use those states to inform future states and thereby alter the variant aspects of the system itself.

Referring back to the problem space (Figure 2) that was derived from the 'attribute view' of complexity, clearly, the area of the space bounded by high familiarity, constant rates of change and a strong information position connotes low variety. In this situation: "Control or regulation is most fundamentally formulated as a reduction of variety: perturbations with high variety affect the system's internal state, which should be kept as close as possible to the goal state, and therefore exhibit a low variety. So in a sense control prevents the transmission of variety from environment to system" (Heylighen & Joslyn, 2001). Such an organization would be something akin to classic C2.

But what happens when the area of the problem space being occupied by classic C2 shifts, as is evidently the case, towards the high variety that arises from a weak information position, unfamiliarity and dynamism? Whilst "…the hierarchy is good at amplifying, increasing the scale of behaviour of an individual", and by doing so meeting the comparatively low-variety requirements of one octant of the problem space, it is "not able to provide a system with larger complexity than that of its parts". As a result, variety does indeed start to destroy variety and the organization starts to become afflicted with the performance sapping pathologies characteristic of all bureaucratic organisations (Ritzer, 1993).

7.2 Network Enabled Capability

The reality of traditional military command and control is that today it finds itself increasingly challenged by a host of modern problems, namely; environmental complexity, dynamism, new technology and distinctly small scale competition that is able to exploit the weaknesses of a paradigm that has been dominant since before the industrial revolution (this latter point is appropriately termed ‘asymmetric warfare’). The conceptual response to these challenges is a new type of command and control called Network Enabled Capability (NEC). This is an organisational paradigm, facilitated by network technologies (hence the ‘Network’ in NEC), that can exhibit greater variety by being based on a non-hierarchical structure, one that emphasises smaller semi-autonomous groups and minimum critical specification. In sociotechnical systems parlance this can also be seen, organisationally, as a network, although this version is not normally what is meant within the acronym NEC. As shown in Figure 3 above, NEC can be characterised by distributed patterns of interaction, peer-to-peer decision rights and broad dissemination of information. This means that it occupies the diagonally opposite region in the command and control approach space. Once again, there is also a more fundamental level at which this type of command and control can be seen as an attempt to maximise a different set of performance characteristics, these being:

- Instead of efficiency and amplifying the effect of the few individuals who reside at the top of a hierarchy, emphasis is given to self-synchronisation, or “…forces that can work together to adapt to a changing environment”.

- Instead of predictability and coordinated, coherent action, there is emphasis on shared awareness in order “to develop a shared view of how best to employ force and effect to defeat the enemy”.

- Instead of quantification and organisational reductionism, there is a shift from ‘doing things better’ to ‘doing better things’ entirely.

- Finally, instead of control and nearly automatic functioning bounded by rules and structures, NEC “removes traditional command hierarchies and empowers individual units to interpret the broad command intent and evolve a flexible execution strategy with their peers” (Ferbrache, 2005, p. 104).

If the difference between these two instances of command and control can be summarised, then it can be done so by stating that classic C2 is an organisation that is ‘programmed’, whilst NEC is one ‘that can learn’.

As before, two points about scale and variety can be made. In terms of scale, the reverse situation to hierarchical command and control pertains to NEC. Its behaviour is not as visible at coarse scales of observation; however, as the scale of observation is decreased complexity (or variety) increases. The reason for this is that finer scales reveal not echelons of actors and entities performing simplified, repeated tasks, but self-synchronising teams who have much greater freedom of action. This also is a fundamental principle of scale and complexity: “When parts are acting independently, the fine scale behaviour is more complex” (Bar-Yam, 2004a, p. 58). The complexity profile that this scale dependent level of variety traces is thus completely different to the comparable profile traced by classic C2 as Figure 4 shows.

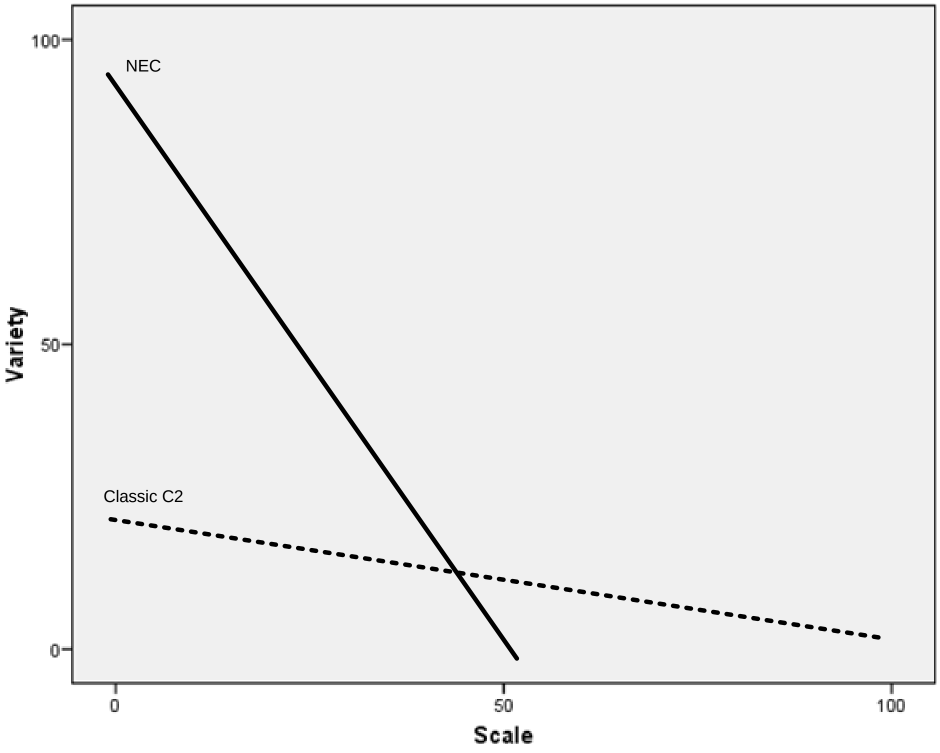

Figure 4 – Complexity profiles for NEC and traditional hierarchical command and control (classic C2). The profiles arise from considering the number of distinct behaviours (i.e. variety) available to the organisation at different levels of observation (scale).

The second point to make is that unlike hierarchical command and control, NEC's behaviour can be more complex than the person(s) at the top of the structure. The focus on self-synchronising teams, effects based operations, shared awareness and so forth, creates the conditions for greater freedom of action, that is to say more variety. If it is only variety that can destroy variety, then NEC should be more robust when partnered to areas of the problem space bounded by un-familiarity, dynamism and a weak information position.

A certain degree of caricaturing and stereotyping has been necessary to draw out these key differences between NEC and classic C2, so in order to temper any over-enthusiasm for one approach or another it is important, firstly, to state that scale versus complexity is a trade-off. There are situations that require sheer scale, and others that require high organisational variety. As mentioned above, the very notion of a problem and approach 'space' highlights the fact that important aspects of complexity (and the response to it) vary as a function of time and of behaviour, they are not orthogonal. That being the case, it behoves of organisations to try and match their 'approach' to the extant 'problem', as Table 4 shows in highly simplified form. When a wicked 'problem' meets a C2 'approach', the mismatch in variety (or lack thereof) results in irrational system behaviour or something approximating to chaos. When an NEC approach meets a stable problem, there is also a mismatch. The increased variety is redundant, and the relative lack of coordination means that the ultimate scale of action will be limited. On the other hand, when a C2 approach meets a stable problem there is a match and rational behaviour can arise. Likewise, when an NEC approach meets a wicked problem there is also a match, the organisation has equal variety to the context in which it is operating and complex behaviour can ‘emerge’.

Table 4 – Matrix of ‘Approach’ versus ‘Problem’ and a simple taxonomy of resultant system behaviours.

		Problem	
		Deterministic	Wicked
Approach	C2	Rational	Chaotic
	NEC	Redundant	Complex

The discussion surrounding Table 4 serves as a powerful metaphor for ergonomics. No one is denying the achievements that have been made using existing approaches (reductionist or otherwise) or that can continue to be made by using them. It is also fair to say that a putative ergonomics problem possesses a high degree of parallelism, simultaneously occupying a part of the problem space for which deterministic, reductionist approaches are entirely appropriate. The question to ask, however, is where the complexity curve is pointing? As in the case of command and control, it behoves of ergonomics to also attempt to match its approaches to parts of the problem space being occupied by an extant ergonomics problem. It is not a question of it being one thing or another, reductionism versus complexity, but a complementary approach which recognises the limitations inherent in both. It is to this debate that the final section of the report turns. Rather than complexity representing an expansive array of obtuse concepts, it has real world applicability, as the following case studies will hopefully demonstrate.

8 Ergonomic Case Studies in Complexity

In the varied literature on the complexity of military command and control one factor comes across quite clearly. "…underlying the theory of Complexity and Networks is not mathematics, science, and technology, but people […]" (Atkinson & Moffat, 2005). This acknowledgement of the role of people within NEC is where human factors can begin to make a contribution. Whilst it is not possible to be exhaustive, and while we have to readily acknowledge a considerable amount of scientific legacy attached to the various concepts pulled through from the field of complexity, an opportunity nonetheless arises to consider a selection of ostensibly human factors findings from this new perspective.

8.1 Emergence

Attention now turns to the effects of complexity; not how it can be defined and caused, but what complex systems behaviour actually is and how it can be detected and analysed. The first and most prominent aspect of this is the concept of emergence. In some senses, complexity is the science of emergence (Waldrop, 1992), furthermore, Moffat (2003) has already provided a set of initial insights and motifs from the formal study of complexity and has applied them to warfare. In this section we take a different perspective and look upon the results derived from a human factors study of live NEC and examine the extent to which they describe human behaviour which could also be considered emergent.

Emergence describes behaviour that is not deducible from its low level properties. At one end of the spectrum are emergent properties that appear as mysterious and deeply perplexing, at the other are the vast array of mundane phenomena that can also be seen as emergent. In the former case, with increasing difficulty in diagnosing systemic behaviour lies the region of 'strong emergence'. In the latter case, diagnosis can remain difficult and far from readily apparent, indeed, it requires knowledge of initial conditions and an approach based on modelling and simulation, but herein lies the more tractable region of 'weak emergence'. Table 5 presents a more comprehensive definition of the various types of emergence, but to sum up, negotiating a route between the two extremes of 'strong' versus 'weak' is a workable definition of the concept that relates well to ergonomics problems: "Emergence is the phenomenon wherein *complex, interesting high-level function* is produced as a result of combining *simple low-level mechanisms in simple ways*" (Chalmers, 1990, p.2). Note that the definition of 'interesting' is, to varying extents, a subjective one, as is the definition of 'level'.

Table 5 – Types of emergence, the information needed in order to make a diagnosis of the phenomenon, and the associated relative level of difficulty in doing so (definitions from Bar-Yam, 2004c).

Emergence	Type	Information needed in order to make a diagnosis of collective system behaviour	Difficulty in diagnosing collective system behaviour
None	Deterministic	Knowledge of individual system components sufficient to fully explain global system behaviour.	(Relatively) Easy…
Weak	Type 0*		
	Type 1	As for Type 0 but with additional knowledge about the positions and dynamics of individual entities in a system, this being sufficient to describe the "microscopic as well as macroscopic properties of the system" (Bar-Yam, 2004c, p. 17).	…more difficult…
Strong	Type 2	As for Type 1 but with additional knowledge of possible states and configurations the system can adopt. "the state of one part may determine (or be coupled to) the state of other parts" (Bar-Yam, 2004c, p. 17).	…extremely difficult
	Type 3	As for Type 2 but with additional knowledge of the environment that the system resides in. "This is not contained in the conventional discussion of properties of a system as determined by the system itself" (Bar-Yam, 2004c, p. 17).	

* This form of emergence carries with it a variety of epistemological issues which are beyond the scope of this article. Suffice to say that at least some forms of emergence can be understood from knowledge of parts alone.

Table 5 shows that: "As systems become more complex […], self-organization appears at more than one level […]. Such systems have multiple, hierarchical levels of self-organization, and calculation of system level emergent properties from the component level rapidly becomes intractable" (Halley & Winkler, 2008, p. 3). In other words, it can become easier to describe and to predict the behaviour of a complex system by looking at the emergent behaviour itself rather than its detailed component level antecedents. The question, then, is how one is able to decide on what perspective to adopt? One approach is based on the concept of Relative Predictive Efficiency (RPE; Crutchfield, 1994) which can be expressed as follows:

$$RPE = E/C$$

E is 'excess entropy', or for practical ergonomic purposes, the extent to which a system can be adequately modelled. In fields that deal with physical systems the extent to which (typically mathematical) models are able to predict a given behaviour is easy to quantify, unfortunately it is rather less so in the human sciences. However, it is not too difficult to imagine a way forward. Even at the crude and overly simplistic level, there is a comparison to be made between the system behaviours predicted by a model (say, HTA) compared to those behaviours actually observed. Any disparity between 'expected' and 'observed' could represent some measure of 'excess entropy', or 'E' in the formula. C, on the other hand, is 'statistical complexity' and is considerably easier to quantify. It is a measure of the size and/or complexity of the system's model at any given scale of observation. In this respect the metrics presented earlier under complexity theory are ideally suited.

Providing suitable metrics for E and C can be derived and/or approximated, RPE enables the analyst to decide what approach to take: reductionism (and a focus on component antecedents of system behaviour) or systemic (and a focus on the system's behaviour itself). Put simply, emergence exists, and therefore systemic methods become more appropriate, "if the higher level description of the system has a higher predictive efficiency than the lower level" (Halley & Winkler, 2008, p. 13).

This concept links back to the discussion above which was about complexity and scale (e.g. Bar-Yam, 2004a). Once again we see an interplay between the scale of observation and the scale of behaviour. In this case RPE provides insight into the type of analysis suited to a particular complex system, and in this respect could lead to considerable savings in analysis time and effort for a corresponding increase in predictive efficiency.

RPE is within the purview of future work, but an interesting ergonomic example in which the behaviours expected differed considerably from those actually observed was very evident during a large scale NEC field trial. The NEC system itself took the form of a pervasive secure radio infrastructure to which various radio and computer systems were attached. Of particular interest, from an ergonomic perspective, was the bespoke software that ran on the computer terminals and upon which staff undertook tasks that were previously analogue in nature (e.g. using paper maps and transparencies). The software was of a highly prescriptive nature. An attempt had clearly been made to pre-empt every conceivable interaction that the users would partake of, with an appropriate function, template or pro-forma provided at every stage. However, when users began to engage with the system, they discovered for themselves the functionality within the system that was useful to them, in particular, a highly simplistic messaging function that allowed users to circumvent the prescriptive functions entirely. This function can be called 'free text', and to judge by the level of functionality provided by the system it was clearly not something that the designers anticipated being used very heavily. However, when its usage was analysed, it significantly exceeded every other individual form of 'constrained communication' provided by the system by a considerable margin, as Table 6 and Table 7 show:

Table 6 – Free versus 'constrained' communications (transmitted).

Transmit				
Observed N		Observed Proportions		
Constrained Comms	Free Text	Constrained Comms	Free Text	Exact Sig (2-Tailed)
4	39	0.09	0.91	p<0.0001
3		0.07	0.93	p<0.0001
2		0.05	0.95	p<0.0001
2		0.05	0.95	p<0.0001
4		0.09	0.91	p<0.0001
11		0.22	0.78	p<0.0001
1		0.03	0.98	p<0.0001
1		0.03	0.98	p<0.0001

Table 7 – Free versus 'constrained' communications (received).

Receive				
Observed N		Observed Proportions		
Constrained Comms	Free Text	Constrained Comms	Free Text	Exact Sig (2-Tailed)
4	65	0.06	0.94	p<0.0001
3		0.05	0.95	p<0.0001
2		0.03	0.97	p<0.0001

In RPE terms, the system clearly possessed a lot of 'excess entropy'; likewise, the 'designer's model of the system' (in the Donald Norman sense; 1998), undoubtedly had high levels of ‘statistical complexity’ (to judge by the almost extreme level of functionality and prescription provided). The relationship between the two is unbalanced: the low level model of the system (i.e. the way it was designed to behave) did not predict all of its high level behaviours (i.e. how it ‘actually’ behaved). The design approach therefore had ‘low predictive efficiency’. From this all too common finding flows an alternative definition of emergence, one particularly relevant to this situation and to ergonomics more generally: it is “the phenomenon wherein a system is designed according to certain principles, but interesting properties arise that are not included in the goals of the designer” (Chalmers, 1990, p. 3).

There is nothing particularly new in this observation (e.g. Lee, 2001; Roth et al., 2006). As mentioned earlier it reflects an important sociotechnical principle of design, that the human-system interaction is not stable, on the contrary, people using a new system should be expected to “interpret it, amend it, massage it and make such adjustments as they see fit and/or are able to undertake” (Clegg, 2000, p. 467). Taking a complex systems research perspective, what individuals are doing is increasing the system’s variety at finer scales and thus increasing the system’s ability to cope with complexity. The motivation for doing so, at this individual level, is presumably because the system cannot cope adequately with complexity as experienced by those facing it directly. This could be defined as an instance of Type 3 strong emergence: in order to go about diagnosing ‘why’, one would have to know about the parts of the system, their dynamics, their interconnections, and those of the environment. Perhaps in this case it is sufficient merely to be receptive to the fact that these phenomena frequently occur and to capture them when they do. The ergonomic function that emergence serves in this case is as an indication of the type of interaction that users are trying to design for themselves: faced with complexity it is a simple type of interaction that enables them to do complex things (Sitter, Hertog & Dankbaar, 1997; Rothrock et al., 2002; Walker et al., 2008a). An approach to design and analysis which acts in sympathy with this phenomenon is likely to be model-able at higher, more aggregated levels of abstraction. Paradoxically, then, it becomes a case of simpler models with greater predictive efficiency, as opposed to complex models with less.

One final point is the extent to which these ‘interesting properties not included in the goals of the designer’ are constrained by what Atay and Jost (2004) term ‘the interior environment of the organisation’. This is another phrase that refers to the three principle axes of the NATO approach space (e.g. Figure 3). The key point here is that emergent behaviours rely on these constraints just as much as they do on complexity. This is why the phrase ‘boundary of stability and chaos’ is used. Emergent behaviour “depends on the coordination of the activities of the participating agents [i.e. a certain degree of stability], which are complex themselves [i.e. embody a certain degree of chaos]. As long as these operate in an uncoordinated manner, no higher scale is available for the encompassing system [i.e. too much chaos]”(Atay & Jost, 2004, p. 21). So if emergence cannot ‘emerge’ without some form of constraint, then how do complex systems behave under different constraints?

8.2 Sensitive Dependence on Initial Conditions

Another prominent artefact of complex systems is 'sensitive dependence on initial conditions'. Attached to this concept are a host of other concepts (e.g. sensitivity, convergence, entropy etc.) each of which have very specific meanings. In order to be consistent with the aims of this report the level of analogy and mapping is maintained at a high level but the reader is nonetheless alerted to the presence of a considerable underlying body of knowledge.

The alternative name given to sensitive dependence on initial conditions is 'the butterfly effect', in recognition of a paper by mathematician and meteorologist Edward Lorenz. The title of the paper was 'Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?" (see Hilborn, 2004). Lorenz argued that, at least in theory, it could. This supposition was based on the now legendary story of how a primitive computerised simulation of the weather gave birth to the then entirely new scientific discipline of Chaos Theory. The story goes that mid way through a simulation some interesting phenomenon had emerged and the simulation was paused in order to look more closely. To avoid re-starting the simulation from scratch, the state of the simulation at that moment, which was represented by a single number expressed to six decimal places (.506127) was re-entered, except to only three decimal places (.506) in order to save time. The assumption was that any effects of such a small difference would be damped out by the larger and presumably more powerful global phenomena. This assumption, however, proved to be incorrect. .506127 represented the initial conditions of the simulation and it was highly sensitive to change. This one part in a thousand (and smaller) difference led the simulation, over a fairly short time envelope, to evolve to a completely different state. So why the butterfly? It is because a flap of a butterfly's wings may represent a one part in a thousandth, millionth, billionth or even less of a total weather system, but given enough time, it is conceivable (if not especially probable) that its presence and absence could conceivably be the difference between a tornado in Texas. The locations of the butterfly and the ensuing tornado have varied over the years, but the fundamental attribute of 'sensitive dependence on initial conditions' has remained.

Like emergence, sensitive dependence on initial conditions is also a feature of ergonomics problems and can be illustrated with the following case study (full details in Walker et al., 2008c). A classic C2 organisation was instantiated within a simulated environment and pitted against an NEC organisation on an identical task. Both organisations contained live actors and they performed a C2 task within a complex, adaptive environment. The traditional approach to examining the relative performance of these two command and control organisations might be to garner a sample of teams, subject them to one or even a few practice trials, then expose them once to the experimental condition. Inferential statistics would then be applied and these findings would be inferred to the population from which the sample was drawn.

The presence of the butterfly effect and the organisational properties of NEC, however, create different experimental requirements, indeed, somewhat different experimental questions, questions that require such a study to go beyond traditional human centred techniques and not rely on static representations of the human-system interaction (Lee, 2001; Woods & Dekker, 2000). The focus shifts to how the incumbents of the different organisations adapt themselves and their context to suit their needs and preferences, and how the initial conditions instantiated by the two organisational types (NEC and C2) affect this process over time. As a result, the situation shifts from running an ‘experiment’ to something more akin to running a ‘model’, albeit with human participants. The benefits of this so-called micro-world approach are that it allows human adaptability to flourish within whatever boundaries are set, as well as allowing novice participants to become highly expert in a task (which is an often criticised component of traditional cross sectional studies which invariably rely on a non-expert sample). This type of modelling approach is touched upon in Moffat (2003) and Atkinson and Moffat (2005). In the present case, multiple regression was pressed into service as a means of time series analysis. The goal becomes one of being able to detect, statistically, the underlying theory behind the data. If the constraints of C2 and NEC represent initial conditions, then what system results from sensitive dependence on them?

Very briefly, the two teams (C2 and NEC) were set to work within a quasi-simulated Military Operations in Urban Terrain (MOUT) game called ‘Safe houses’. The primary task of the commander was to manage two live fire agents (Alpha and Bravo) as they negotiated an urban environment en-route to a ‘safe house’. The fire team had to correctly locate and deal with a number of Target Areas of Interest (TAIs) along the way (i.e. correctly co-locating themselves with the TAI, correctly identifying it, and using a handheld computing device to place an appropriate icon on the digital map display according to simple pre-set rules). The onus in the primary task is thus on speed and accuracy, reaching the safe house in the shortest time whilst correctly dealing with all en-route TAIs. Critically, unlike a cross sectional study, the two teams separately undertook the task over no less than thirty iterations.

Something analogous to sensitive dependence on initial conditions can be clearly seen in the results for task completion time. The maximum amount of time that was allowed to be spent on the task was 15 minutes (900 seconds). As one would expect due to practice and learning, over the course of the thirty iterations both teams sped up considerably and continued to do so for every trial (as Figure 5 clearly demonstrates). This we can consider as a linear first order effect which we can analyse using linear regression as a simplified method of time series analysis. In this case a strong association between the first order effect of task time and trial was obtained for both conditions (NEC $r = -0.84$ and C2 $r = -0.85$), both of which were significant to beyond the 1% level. The regression ANOVA supports the hypothesis which states that this first order effect is linear in nature: $F(1,28) = 64.74$; $p < 0.01$ for the NEC condition and $F(1,28) = 73.53$; $p < 0.01$ for the C2 condition.

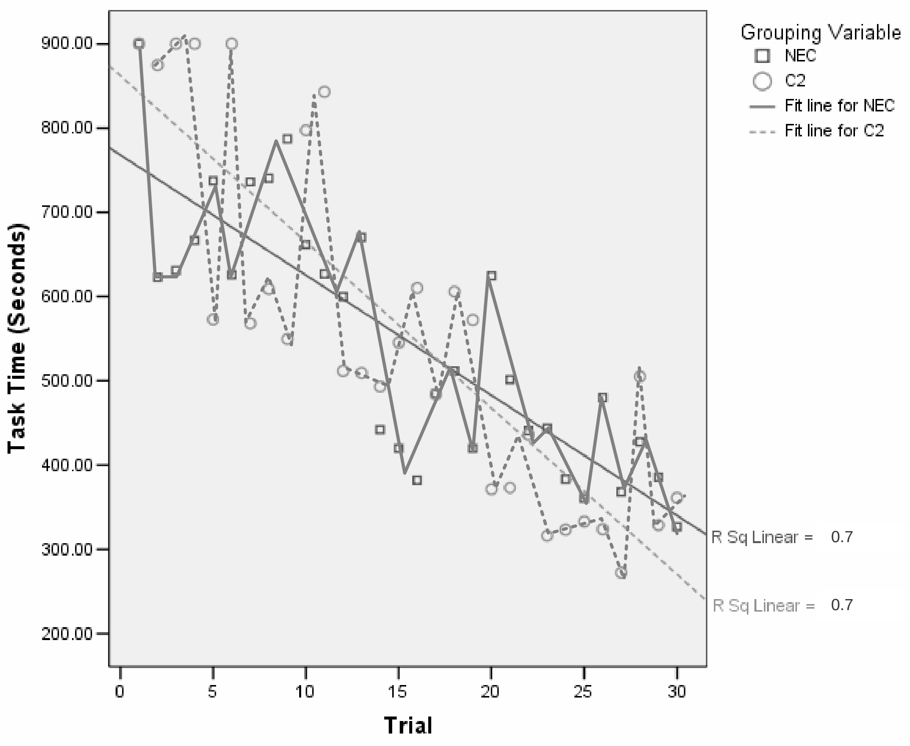

Figure 5 - Scatterplot showing the regression lines for both NEC and C2 conditions in relation to task time.

The linear regression model fitted to the data is represented by the diagonal fit lines in Figure 5. In the case of the NEC condition the fit line/regression model accounted for 69% of the variance in the NEC condition (Adjusted $R^2 = 0.69$) and 71% of the variance in the C2 condition (Adjusted $R^2 = 0.71$). Both of these values represent a large effect size and both regression models were statistically significant to beyond the 1% level. In summary, then, the statistics lend support to linear first order relationship between time and trial number, with the time series model accounting for a meaningful amount of the variance in the data.

With this in mind, the effect of sensitive dependence on initial conditions can be seen in the different slopes described by the regression lines. The intercept for the C2 condition was at $b_0 = 862$ seconds, somewhat nearer the maximum value of 900 seconds permissible for the task than the NEC condition, whose intercept was at $b_0 = 762$ seconds. However, the regression line for the C2 condition has a slightly more precipitous slope than that for the NEC condition, $b_1 = -14.26$ compared to $b_1 = -19.73$. Thus, despite the higher intercept, the regression lines actually cross at trial 17. This means that by trial 30 the time series model predicts the task being completed in 270 seconds for the C2 condition compared to 334 seconds for the NEC condition (approximately a minute faster). The findings are an example of emergence in the sense that they do not match the aspirations of NEC (which emphasises, amongst other things, tempo). But they also fundamentally demonstrate that despite identical team composition, matched participants and an identical task, the initial conditions represented by the C2 and NEC conditions lead to markedly different system performance.

Of course, this is not the only theory that might lie behind the data shown in Figure 5, merely the simplest one that enables us to postulate the existence of processes analogous to sensitive dependence on initial conditions. The lines which join the discrete data points (also shown in Figure 5) are suggestive of more complex higher order effects of adaptation. Visual inspection alone would seem to suggest that alternative fit lines for C2 and NEC could be sinusoidal in nature, with the classic C2 condition seeming to oscillate quite widely initially and, apart from the spike near the end, homing in on faster task completion times. The NEC condition seems to show wider oscillations throughout, perhaps suggestive of greater agility and/or adaptability and/or self-synchronization?

Whether first or higher order effects, the question becomes one of what is optimum performance? If the maximisation of one factor such as task time is the sole criterion for success, and in some cases this may be entirely appropriate, then the C2 organisation is superior in this instance. If, however, value is placed upon resolving conflicting goals and optimising more than one factor, and again, there are many cases where this is also entirely appropriate, then NEC is the corresponding organisation.

8.3 Phase Space and Strange Attractors

In the example above, just one attribute of a complex system's behaviour (task completion time) is plotted as a simple time series. Complex systems, according to the attribute of multiplicity, are specified by more than one variable, so at the other extreme from a simple time series is a fully multidimensional space (i.e. a matrix) effectively containing an axis for every parameter of a system. The space created by the intersection of the axes would, in theory, allow every possible state that a complex system could adopt to be plotted.

Taken to this extreme, multi-dimensional phase spaces are only tractable using significant computing resources. Therefore, in most practical studies of complexity, the fundamental laws and equations that govern the behaviour of a system tend to be simplified, indeed, some of the most powerful examples of these spaces for physical systems possess just three dimensions, x, y and z. These intersect to create a coordinate space that obeys a simple and intuitive Cartesian geometry so that values of x, y and z adopted by a dynamical system can be fixed. Such spaces are termed phase spaces. Many of the variables of interest within ergonomics are not easily or usefully reduced to a set of fundamental equations (although presumably the complex theoretic approach could help) so in most cases an alternative method is required in order to construct something analogues to a phase space within the human sciences.

To a large extent the NATO approach space has done this already. It is very similar in essence to an approach in complexity science called Functional Holography (Baruchi, Towle & Ben-Jacob, 2005). The NATO approach space maps onto this by taking an underlying reference model containing over 300 dimensions and subjecting the relationships between them to an analysis via systems engineering tools in order to detect clusters (NATO, 2006). The three clusters that described the maximum amount of information about command and control organisations form the primary axes in the model (x = decision rights, y = patterns of interaction and z = distribution of information). The notion of phase spaces and the Functional Holographic technique used to derive something analogous goes on to provide inspiration for innovating ways of projecting live data into the model. To that end, the NATO model can be advanced from being merely an ‘approach space’ to something much closer to an actual ‘phase space’. The means by which this is achieved is to derive quantitative measures for decision rights, patterns of interaction and distribution of information and this is achieved through the use of social network theory.

Social network analysis is a popular approach in the analysis of NEC. From a human factors perspective it particularly excels in capturing the interaction between socio and technical (see Monge & Contractor, 2003 for an overview). Briefly, a social network is “a set of entities and actors […] who have some type of relationship with one another.” (Driskell & Mullen, 2005, p. 58-1). A social network is created by plotting who is communicating with whom on a grid-like matrix. This matrix then forms the basis of a social network diagram, a graphical representation of the entities and actors who are linked together. The matrix can then be subject to mathematical analysis using techniques from graph theory in order to diagnose important properties about the network which are not necessarily apparent from visual inspection alone. Put simply, the question becomes one of mapping appropriate social network metrics across to the NATO model, selecting metrics that provide a quantitative measure of decision rights, patterns of interaction and distribution of information. This mapping has been undertaken and is outlined in Table 8:

Table 8 – Mapping of social network metrics to the NATO approach space’s primary axes.

Dimension	Metric	Notes
Patterns of interaction	Diameter	This is about how many nodes have to be crossed to go from one side of the network to the other. The bigger the diameter, the more nodes there are on that line of communication. A fully peer-to-peer network facilitates more direct communication (and thus has a smaller diameter) than a hierarchical network, with more intermediate layers (and a larger diameter).
Distribution of information	Density	This is about the number of nodes in a network and the number of interconnections between them. A peer-to-peer network is denser than a hierarchical one, and as a result will generally facilitate broader dissemination of information because there are fewer intervening nodes between sender and receiver.
Decision rights	Sociometric status	This is about the status of a particular node (or nodes) in the network based on their level of interconnectivity. Unitary networks like hierarchies will have just one (or a few) key nodes or person(s) ‘in charge’. At the other end of the network spectrum, all, or considerably more nodes will be high status in a peer-to-peer network (high status is defined as the number of agents whose status is greater than one standard deviation above the mean).

Diameter, density and status now provide quantitative measures of decision rights, patterns of interaction and distribution of information. By these means, the communications data gathered from the live case study (described above under the heading emergence, in Section 8.1) can be plotted into the phase space as shown in Figure 6. What is represented, therefore, is the behaviour of a large scale military command post exercise involving over 70 personnel, two levels of headquarter, live assets mobile in the field and in excess of 2800 communication events, all of which took place over a 4 hour 20 minute time period. Data collection was split into 34 time intervals and 34 separate social networks were created in order to provide a series of dynamic snapshots under the rubric of 'dynamic social network analysis'. By these means, not only can a considerable amount of data be compressed into the space but a similarly large amount of data can be extracted from it, hence the use of 'holography' in Functional Holography. More fundamentally, an important aspect of organisational complexity can be physically expressed as the sum of the coordinate points in the phase space. The greater this value, the greater the system's variety.

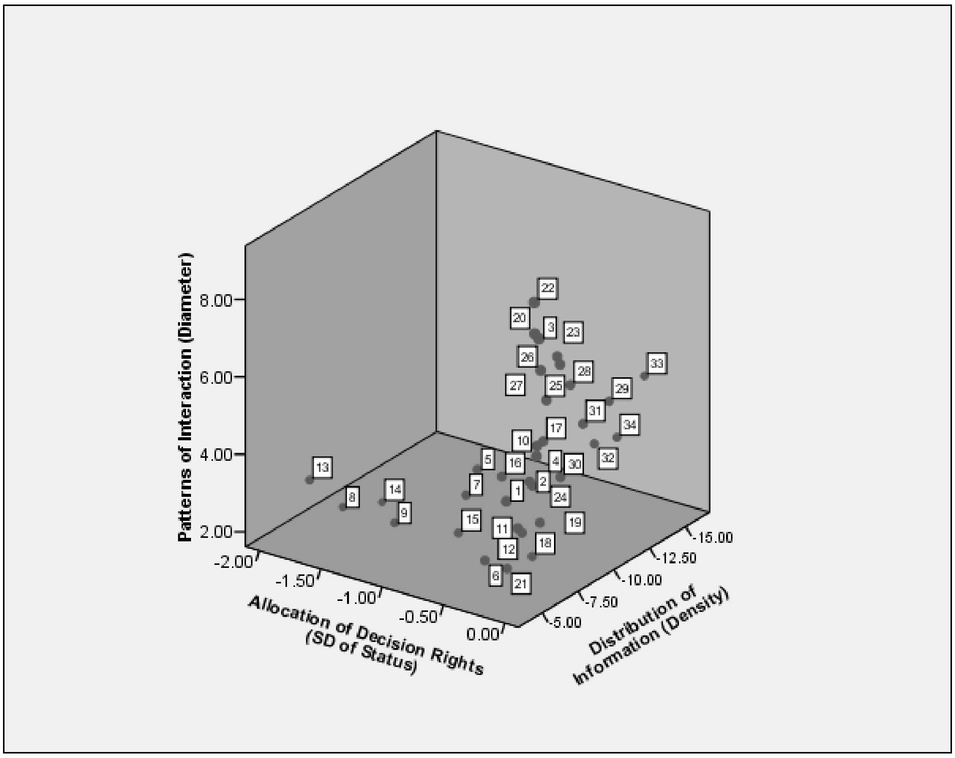

Figure 6 – Illustration of the 34 separate social network analyses plotted into the NATO C2 'phase space' in order to show the dynamical behaviour of the system.

Having fixed a real-life instance of command and control into the phase space, it is possible to study the patterns described by the motion of the point that represents the system's dynamical behaviour, at any one of the 34 time intervals. This particular instantiation of NEC shows interesting dynamical behaviour. There are clearly several clusters or regions in the space that the organisation gravitates towards on different occasions. The zones in which these clusters form are termed 'attractors' in complex systems research (see Moffat, 2003). In this case, because the clusters have formed in defined areas of the phase space they can be termed ‘fixed attractors’. Fixed attractors represent the equilibrium state(s) of the system into which it is repeatedly drawn, the prevailing behaviours when ‘everything settles down’. This does not fully describe the dynamical behaviour of the NEC organisation in Figure 6, however, because many of the other points do not fall into defined clusters at all and are instead scattered widely. The organisation is thus attracted to these other points in the space by forces whose underlying dynamics are not stable and deterministic, but unstable and chaotic. As such, they are labelled ‘strange attractors’.

The presence of attractors suggests a much more fundamental source of an organisation’s dynamical behaviour which is related to the problem space itself. The fact that the organisation is drawn or otherwise propelled into different regions of the phase space indicates that, like a ball rolling across a surface containing dips and hollows, the environment possesses a defined ‘causal texture’ (e.g. Emery & Trist, 1965). This is a classic sociotechnical systems concept that maps across to the study of complexity in terms of its ability to provide a conceptual road map of the attractors (strange and/or fixed) that reside in the environment. Fixed attractors might reside in what are referred to as the ‘placid random’ and ‘placid clustered’ environments. In both these cases, the underlying environmental dynamics are fundamentally stable and therefore lend themselves to more rationally designed organisations, such as classic C2. Strange attractors seem to reside in what are termed the ‘disturbed reactive’ and ‘turbulent field’ environments. In both cases, the underlying dynamics are more disorganised and chaotic, thus prompting the requirement for an organisation that can better track those sorts of dynamics, e.g. NEC. The reader is referred to Stanton et al., (In Press) where these dynamics are further considered from a time-series point of view, and also to Monge and Contractor (2003) for a set of social network concepts which no doubt could shed further light on the dynamic behaviour of these networks.

To summarise, the maximal amount of information about an organisation’s dynamical behaviour has been reduced by the NATO approach space to three variables. Mapping social network metrics onto these three variables advances the approach space, turning it into a phase space within which the dynamical behaviour of organisations can be visualised. The twin concepts of phase spaces and dynamical behaviour derive explicitly from the concepts and methods found in complex systems research.

9 Conclusions

9.1 What is Complexity?

Complexity is about there being several parts, about difficulty, dynamism, interconnection, change, uncertainty, fuzziness, teamworking, information throughput, the equifinal expedient of there being multiple ways to achieve multiple end states, of evolution and of adaptability. It is about emergent properties, phase spaces, critical points, transitions, chaos, bifurcations and sensitive dependence on initial conditions. It is also related to algorithmic complexity, logical depth, computational equivalence, cybernetics, variety and information theory. This list is by no means exhaustive and attached to each of them is an often formidable array of individual concepts forming a considerable theoretical legacy. In the course of trading strict scientific rigour for innovation, we have not presented this legacy in significant detail but we do acknowledge its presence. Complexity is itself complex. In this report we have merely tried to resolve this from an ergonomics perspective, firstly by distilling the multifarious nature of complexity through three overlapping views:

- There is the attribute view, in which complexity is about the multi-dimensional problem space through which ergonomics is travelling. Here we showed how this multi-dimensional space could be collapsed into three critical variables in order to create a defined ‘problem space’.

- Then there is the complex theoretic view, which deals with the quantification of certain aspects of complexity. Here we showed how the metrics provided by this approach readily complement existing mainstays in ergonomics methodology, allowing a better judgement to be made about whether one entity or phenomena is numerically more complex than another.

- Finally, and above all else, there is the complex systems research view. The domain of ‘true complexity’, of the emergent phenomena occurring at the edge of chaos, and the phenomena which require a new set of tools and approaches in order to diagnose what is going on and what to do about it. Here, complexity has been related to the ‘approach’ that is needed to match putative ‘problems’. Complex problems (i.e. those that are unfamiliar/unstable/unknowable) require systems to be configured in certain ways (i.e. peer-to-peer interaction, devolved decision rights and widespread dissemination of information). Complex problems also require ergonomics itself to be configured in certain ways, for its various ‘approaches’ to match its various ‘problems’.

9.2 Rocket Science vs. Human Science

If complexity is rising, as we argued at the outset, where has it come from and what does it mean for ergonomics? Many fields, the study of complexity among them, cite the enduring legacy of the Apollo lunar missions as the sine qua non for coping with complexity. Here was a phenomenally complex human endeavour which, at base, contained many of the critical dimensions familiar to ergonomists working in large projects: 1) it used brand new technology, 2) it possessed a clear understanding of the underlying engineering and physical principles, 3) it had well specified goals and 4) it was created from scratch (Bar-Yam, 2004a, p. 222). In the case of Apollo, the brute force application of Newtonian cause and effect logic worked, and in spectacular fashion, so much so that:

"The rocket has become the apotheosis of mechanism: the biggest, fastest, most complicated machine there ever was, inciting the same kind of awe as a blue whale. And 'rocket science' remains shorthand for the most demanding kind of thinking there is…" (Spufford, 2003, p. 10).

Except not according to complexity scientists. No one would deny that Apollo is complicated (certainly not NASA who refer to the spacecraft as 'the most complicated machine ever built'). The point is that this invocation of complexity resides right back at the dictionary definition level, where there can be no doubt that Apollo is made up of a huge number of individual parts and has high levels of difficulty associated with its design, manufacture and use. The paradoxical assertion that despite all this it is still not complex can be resolved by asking the following question:

Is the Apollo space program complex in the sense that there are 'emergent behaviours exhibited by interacting systems operating at the threshold of stability and chaos'?

The answer, clearly, is no. At least that was not how it was designed. The same could be said of many similarly complex systems that were coming to fruition in the Apollo era. Nuclear power and process control, for example; these form the foundational backdrop to current day ergonomics, with many long established tools and techniques born in this period and whose legacy is still felt today. Like Apollo, these systems used new technology based on a clear understanding of underlying laws and theories, had very specific goals and in most cases were built from scratch. They too were superficially complex, to sometimes extreme degrees, but they were also a long way from operating at the edge of chaos. On the contrary, for the majority of ergonomics history, indeed, for much of scientific history, emergent properties and chaos have been universally viewed as paradoxes (Boguta, 2005), or in the case of ergonomics, as problems (Norman, 1990), ironies (Bainbridge, 1983), human error (Reason, 1990), catastrophes (Perrow, 1999) and automation 'surprises' (Sarter & Woods, 1997). Ergonomics, therefore, has in all but name been grappling with complexity for a long time. Although appearing as disparate problems scattered throughout the problem space they all have one fact in common; they can be unified under the common heading of complexity. As such, do they represent 'the border to a vast world that science has assiduously evolved to avoid' (Boguta, 2005)? Possibly. It is certainly the case that although the zeitgeist of Apollo persists in the large scale projects that ergonomists work in to this day, one thing that has not persisted is Apollo's success, as Table 9 shows. It is against this backdrop that large scale endeavours such as NEC are perhaps better considered.

Table 9 – Large scale project failures

System	Approx effort (years)	Approx. cost	Aspirations*	Outcome
Taurus computerised share trading system for the London Stock Exchange	3	£75m	“Paperless trading and computerized shareholdings […] reduce time […] bigger and better”	Scrapped
Channel tunnel	6	£4.6bn	“One of the seven wonders of the modern world”	80% cost overrun
Computerised dispatch system for the London Ambulance Service	1	£1.5m	“More efficient […] automation […] greater capacity”	Scrapped**
National Air Traffic Control system	<10	£339m	Existing system had “Functional limitations that would compel any modern engineer into laughter […]”	Delayed and over budget
NHS Computer System	10	£12bn	“A grandiose IT project [that would] transform the NHS”	Reduced capability

* Aspirations derived from popular media via the BBC News website (www.bbc.co.uk/news).

** The failure was further implicated in the loss of 20 lives

As for the dichotomy between human versus rocket science, what this mapping to complexity suggests, despite its analogous and tentative nature, is a fundamental re-think in the way in which NEC is perceived, designed and made ready for operational use. Instead of a techno-centric view of NEC (in which capability is viewed in terms of technological advancement) a human-centric view is required as a counter-balance. Most, if not all, failure of equipment to meet operational expectations can be laid firmly at the door of this techno-centric perspective and a concomitant failure to take the human-centric view into account. In this report that human-centric view has been enhanced by the mapping across of concepts drawn from the physical sciences. As a conduit for knowledge to flow between disciplines the aspiration for this work is that information flows in both directions.

9.3 The Promise of Complexity

What this survey has aimed to do is reveal the double edged sword of complexity. As ergonomics problems continue to venture further out into the post-Newtonian world of unfamiliar, unstable and unknowable areas of the problem space, it is emergent behaviours and edge of chaos phenomena that enable entities, artefacts and systems to succeed rather than fail. The phenomena that for the past 50 years have been viewed as problems, ironies, paradoxes and surprises are now closer to the phenomena required to cope with complexity. As several military orientated books on this emerging topic have highlighted, the most adaptable component within these complex sociotechnical systems is the human. It is they who, given the right initial conditions, will generate the adaptive emergent behaviours necessary to successfully move a system around its particular phase space, ensuring that problems and approaches are matched, and by these means rapidly evolving systems that do not merely survive but actively turn events to their advantage. The promise that complexity holds for ergonomics is that "it is exactly this nonlinearity that presents the possibility of obtaining a disproportionate leverage from a given action" (Smith, 2006, p. 40).

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Appendix B Discussion with Complexity Specialist

The stated aim of this work is to try and get the human factors community in touch with the concept of complexity. This deliverable is intended to serve as a vehicle through which certain initial ideas can be disseminated and discussed. Consistent with this is the following dialogue between Dr John Ardis, HSG Complexity Specialist, and the author of the report (Dr Guy Walker). The dialogue has been extracted from a larger process of review and it aims to provide some insight into the challenges, as well as the opportunities, involved in cross-disciplinary research of this sort.

John Ardis [JA]: This seems like an ambitiously titled document!

Guy Walker [GW]: For human factors the mapping to complexity (in the way described in the report) probably is quite ambitious.

JA: In Section 3 you assert the existence of five fundamental parameters or attributes of complexity, but without proper justification.

GW: The reference to David Woods' chapter entitled 'Coping with complexity' (1988) is one of the all too few pieces of work that come near to complexity, as a distinct concept, within our field. When human factors people talk of complexity what they tend to mean is some combination of these five factors. Obviously, that's not the case all the time but as a way of structuring the HF literature, and representing the way in which complexity is commonly described in our field, it is a start.

JA: Section 3.6 talks about a problem space through which the field of human factors is travelling. This contains assertions that could be seen as having questionable logic.

GW: It is very much a first stab for an HF audience who are likely to be encountering the idea of a 'problem space' for the first time. We take our lead from the varied CCRP literature on command and control for this, which could also be seen as putting forward assertions based on questionable logic – there is no explicit reference to underlying concepts (even though they exist in organisational science, see HFI DTC report reference HFIDTC/2/WP1.1.2/1). This reveals something fundamental about the mapping we have attempted between HF and complexity, which is that we have had to rely on varying degrees of analogy to make specific points. Some allowance has to be made for this in exchange for the innovation it presents to our field.

JA: Reductionism is rational IF (if and *only* if) it stops dividing before the point where such division means that the model is not representative. The text suggests there had been a conspiracy to avoid representation.

GW: We wouldn't want to give that impression. The wider issue seems to be couched in a mismatch between reductionist approaches and complex problems. This has been a topic in classic sociotechnical and organisational literature for many decades. It is not a conspiracy but it is certainly a paradox which seems very hard to overcome.

JA: Following on from that, in Section 5, surely 'non-wicked' problems can derive from the stated regime?

GW: Yes they can. It is a question of matching approach/regime to the fundamental nature of the problem. Reductionist approaches are certainly a perfect match to particular types of problem. It is important to point out that we don't think the complex systems approach to be suitable for all human factors problems, but to those that are pointing into the complex region of the problem space. The approaches discussed are, at bottom, contingent. The matching of approach to problem seems to be a pertinent challenge – in human factors as elsewhere.

JA: …this would relate to the idea of transitive complexity[4] then?

GW: Yes. I don't think we are saying that problems are either complex or non-complex. They seem to me to contain (or at least be possible of containing) parameters that are not strictly independent (i.e. non-orthogonal), that can run in parallel to each other and be subject to simultaneous change. I suppose the methodological challenge, certainly from a human factors point of view, is not only for our methods to match our problems, but to track the dynamics of those problems.

GW: The idea of transitive complexity is an interesting one for HF. Even when talking in the language of systems theory HF tends to see the world in hierarchical strata of sub and super-ordinate layers (e.g. Reason's 'Swiss Cheese' error model, Abstraction Decomposition Spaces etc). The complementary idea of interacting sub-systems is one that we have tried to put across in this report. In terms of transitive complexity, though,

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[4] Transitive complexity is an expression coined by Ardis (2008, unpublished doctoral thesis on *Complexity in Strategic Intelligence*) to describe the degree of complexity between a local complex system and the global complex system of which it is a constituent. Local complex systems have internal complexity as well, and the global system's complexity is the sum of all complexities, transitive and internal, of its constituents as well as its transitive complexity to any external set of systems. It is a useful idea when considering the relationship between a set of hypotheses that are potentially valid in the generation of a strategic or grand strategic intelligence product where there are multiple sources, sparsity, incompleteness, opacity, dissonance and deception.

could the global system's complexity be more (or perhaps even less) than merely the sum of all its constituent complexities? How are those constituent complexities measured?

JA: The global complexity can only be the sum of constituent complexities (and of course this is more than the complexity of the components, but must reflect the relationships between them, however one chooses to scale them), but they have to be measured *consistently*. How one measures complexity is a matter of choice, but it is always a challenge to compare the complexity of different systems, because one may not be measuring like for like even if the analysis algorithm is consistent. Two systems with differing architectures, rates of change, or instructions may appear to have identical degrees of complexity at a given moment in time, and this is not likely to have any real significance. Major differences in degree of complexity are more likely to have some significance, but often knowing a system is dissipative or fractal is of more interest. The reader is advised to treat complexity as a qualitative characteristic of a target system unless there is good reason to do otherwise; in due course, the various interested communities may elect a common method of gauging complexity. One should not hold one's breath.

JA: Moffat covers the relationship between complexity and NEC rigorously and this is essential reading for those that would claim to describe the science. You do cite him, but not extensively. Why?

GW: We have read and been greatly inspired by Moffat's work in this area. It is interesting, because looking at it from a human factors point of view Moffat's book (Complexity Theory and Network Centric Warfare, 2003) does not come into touch with human issues in a way that our field would necessarily recognise. This is reflected in the report. For example, human factors does not routinely speak in terms of information entropy or decision making in the purely game-theoretic sense. That is not to say that it shouldn't or couldn't, or even that we are being critical of this approach. It merely serves to highlight the difficulties in language and perspective that we face in trying to map different fields across to each other.

JA: The references to Ashby, from a complexity point of view, seem incongruous.

GW: Ashby's work is very relevant to Bar-Yam's ideas about 'multiscale variety', an interesting concept that maps well onto the sort of human factors problems we have encountered in NEC. We have to acknowledge again that full weight of Ashby's cybernetic work cannot be brought to bear in the context of this report, but at least the possibility of it being relevant is now raised. Incidentally, having surveyed the literature we have found the work of the New England Complex Systems Institute (from which Bar-Yam derives) to be especially relevant to the proximal concerns of human factors. We fully acknowledge that there are other equally dominant schools of complexity and that our focus on human factors means we have been selective.

JA: You don't mention explicitly the work of the Santa Fe institute (e.g. thin agent models), thermodynamic similes, entropy, open, closed or dissipative systems and the various other sub-domains familiar in the domain of complexity.

GW: This is because we are not asking the question 'what is complexity' and 'how do all these core concepts map to human factors'. Instead we are saying 'here is the way human factors uses complexity and the sorts of problems that prompt the use of the word, what concepts from complexity seem immediately useful?' This is a difficult balancing act. We have consciously decided to fall down on the side of being highly selective, and pointing the reader to the set of core concepts that go beyond these initial insights. To be fair, thermodynamic similes, forest fire metaphors, sand-piles and all the other examples of complex phenomena are well rehearsed in the C2 literature and have still failed to gain real traction in HF. In order to address this (and we firmly believe complexity to be of major importance to HF) we take a different route to cross-disciplinary overlap. Instead of working our way from core concepts to practical application we work backwards, from application to the set of concepts (core or otherwise) that speak towards these proximal concerns.

JA: Perhaps this report is not so much a conduit as a trans-disciplinary model. The point here is not to claim to allow this as the vehicle through which data from practitioners flows, but that it is an initial model, drawing parallels and suggesting similarities and vernacular. Other experts can then adapt, criticise, copy and argue about the example you present.

GW: I think that sums it up very well. Looking over the cross-disciplinary border this is what complexity looks like from an HF point of view. You are quite right, we have deliberately strayed off the path of conventional human factors and the insights are likely to cause argument and discussion. In adapting, criticising, copying and arguing perhaps both fields can negotiate their way towards a very useful synergy. It is certainly the case that HF could greatly benefit from the insights provided. I hope this report is a start.

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