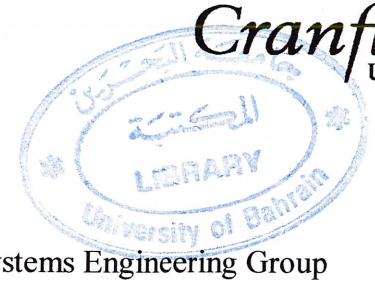
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COTS Procurement for Military C³I Systems

PhD Thesis

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ABSTRACT

Exploiting Commercial-off-the-Shelf (COTS) products in defence applications is becoming increasingly important, especially in the fast-moving field of Information Technology (IT). This thesis explores ways in which the procurement of COTS-based Command, Control, Communications and Intelligence (C^3I) systems may be improved; particularly, with respect to the use of more formal scientific techniques during the development and procurement processes.

Initially, an exploratory research survey was conducted, which identified that the area was not academically well-defined, and would benefit from some intellectual structuring. Consequently, a more focused survey, addressing specific investigation areas, was conducted, which revealed a number of potential research directions. One applicable finding concerned the Combined Operational Effectiveness and Investment Appraisal (COEIA), which the United Kingdom (UK) Ministry of Defence (MOD) has introduced to support procurement decisions. Predicting operational effectiveness is typically achieved by assigning scores to various system functions, and combining these in a weighted sum to achieve an overall figure of merit. This 'black-box' approach is considered to have fundamental limitations, especially for socio-technical C^3I systems.

Accordingly, this thesis proposes an alternative COEIA approach, based upon the notion of creating a 'white-box' model of a C^3I system, which explicitly represents the influences of technology, people and process. By simulating the interaction of competing C^3I system models, in a dynamic conflict scenario, overall system effectiveness can be measured in an open, verifiable and system-scientific approach, which would be useful to assess the impact of COTS selection on overall C^3I system effectiveness. This represents the central hypothesis of the thesis, whose attendant experimental programme has resulted in the creation of a novel white-box model for C^3I systems, using a synergistic combination of two existing techniques, and the development of a dynamic conflict simulation using the STELLA™ tool. Experimental use of this simulation, for COTS-based effectiveness studies, is considered to have established 'proof of principle' for the approach, which is perceived to have applications beyond its immediate purpose, such as offering insights to systems engineering and to the phenomenon of emergence.

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Chapter 1: Introduction

1.1 Introduction

This chapter describes the background to this thesis. It introduces the reader to the origin upon which the research work and the thesis are founded. This chapter then describes the value of the research to the field with which it is concerned, and presents an overview of the thesis structure.

1.2 The Origin of the Study

Over the last decade, there has been a rapid increase in the scale and capability of commercially-developed Information Technology (IT) products. Coupling this with an increasing need to demonstrate 'value for money' in Defence Procurement within limited budgets, and a 'front line first' philosophy, has led to an emphasis on the use of Commercial off the Shelf (COTS) products for military systems, as opposed to adopting a more conventional bespoke system development approach. This is not only a trend that can be observed in the United Kingdom (UK), but applies to the Armed Forces of many Governments, worldwide.

Recognising this trend, the author, who is a serving officer with the Bahrain Defence Force (BDF), arranged with his Government to undertake a PhD research programme in the specific area of COTS Procurement for Military Command, Control, Communications, and Intelligence (C^3I) Systems.

In 1997, the BDF initiated a PhD project, within the Computing Information Systems Engineering (CISE) Group at the Royal Military College of Science (RMCS), to conduct research into COTS-based C^3I systems. A primary goal was to investigate whether the development and procurement of such systems could be based upon a more formal scientific approach. In pursuit of this, the first half of the project concentrated upon reviewing development and procurement issues for C^3I systems, in a broad way, to address an initial exploratory hypothesis. One of the key issues uncovered from this review was the limitations of current techniques for the Combined Operational Effectiveness and Investment Appraisal (COEIA) of Command and Control (C^2) systems. Accordingly, a central hypothesis was

generated, to tackle this problem in a defined way, using a combination of techniques that were discovered as a direct result of addressing the initial hypothesis.

The project described in this thesis explores a novel and beneficial way for improving the development and procurement of COTS-based C³I systems. A coherent research framework has been facilitated through the shared knowledge and practical support from both informatics and systems engineering fields. The project was grounded in: the scientific and information systems engineering skills, knowledge and capabilities of the CISE Group, at RMCS; the author's background as a serving military officer; and the system modelling expertise of an external consultant, Prof. D. K. Hitchins.

The author was situated within CISE Group as a full-time student, and came to the project with some twenty years experience as an Electronics and Communications Engineer who had been involved in purchasing Electronic Warfare (EW) systems.

1.3 Constraints

A large part of the effort has been devoted to achieving an effective COTS-based development approach for military C³I systems, in accordance with the aim set up by the BDF to contribute an improved understanding of this field. In response to that, the author was required to investigate and structure the problem domain associated with the development and procurement of C³I systems, and gather the necessary information, before applying appropriate scientific methods. He was required to produce a thesis as a coherent and well-written piece of academic work that conveys a good understanding of the issues associated with the COTS-based procurement of C³I systems, which would be of value to his sponsor in this field. Much of the challenge of the project has lain in achieving a result that satisfies both the BDF sponsor and the academic requirement.

1.4 Contribution to Field

The outcome of this research makes an original contribution to knowledge in the area of COTS-based C³I systems. The following points are offered as the principal scholarly contributions that have been made by this research work:

(a) The structuring of the research domain for COTS-based C³I system development and procurement, which will open the road for other PhD investigations to take

place in this field. A number of candidate research directions have been identified, one of which has been carried forward by this project.

(b) The creation of a novel 'white-box' modelling technique for representing C^3I systems, which includes the influences and interactions of technology, people and C^2 process. It is based upon a combination of existing system approaches, and provides a suitably visible and abstract representation of a C^3I system to permit reasoning about its resultant properties, characteristics and behaviours. The white-box system modelling technique, devised here, is considered suitable for representing other socio-technical systems, and allows composition of models in both competing and co-operating regimes.

(c) The development of a novel COEIA white-box modelling approach. This results in a dynamic simulation model of competing C^3I system models, from (b) above, which allows C^3I system effectiveness to be measured in representative operational (combat) scenarios. A major benefit of this COEIA white-box approach is that it offers a unique opportunity for progress in measuring the impact of technology on overall C^3I system effectiveness. It is open, verifiable and system-scientific, and seems to be an eminently practicable and reasonable way ahead in this area.

The COEIA white-box modelling approach, identified above, also provides a range of other potential opportunities. For example, it could be used to specify C^3I system requirements by identifying the performance and other characteristics of equipments *as they contribute synergistically to overall C^3I system effectiveness*. This would lead to performance measures for equipments being seen, not as individual quantities, but as interactive contributors to overall effectiveness. Other uses may lead to:

- Inclusion of the effects of procurement and logistics on C^3I system effectiveness.
- A deeper understanding of the nature of emergence.
- A more formal scientific approach to Systems Engineering.

The thesis does not explore any of these possibilities in any detail but, in modelling interactive combat effectiveness, provides 'proof of principle' for that future work.

1.5 Thesis Content and Structure

The remainder of the thesis addresses:

a) The research objectives and approach.

b) The conduct of a research survey, its search results and applicable findings.
c) The white-box modelling of C^3I systems.
d) The development of a white-box simulation model to support the COEIA process.
e) The use of the COEIA white-box simulation model for C^3I system effectiveness studies, particularly with regard to COTS usage.
f) Discussion of the research survey and modelling results.
g) Conclusions.
h) Future work.

The thesis is laid out to give a logical progression from a description of the conduct of the research, through the presentation of research results and attendant discussion, to conclusions and recommendations. Chapter 2 addresses the broad aim of the study, and presents the project's objectives as two sets, explaining how the results of addressing a first set of objectives, associated with the initial phase of the project, lead to a further, more-focused set of objectives, which were addressed in the second project phase. The chapter then describes the approach followed in conducting this research. Chapter 3 describes the results of the research survey that has been carried out during the first phase of this research programme. The final section of this chapter defines the COEIA white-box modelling proposal that was adopted for the remainder of the project. Chapter 4 describes the white-box modelling technique that was devised to represent C^3I systems, and presents the different stages in creating this. Chapter 5 details the design and development of the COEIA white-box simulation model, which employs the white-box C^3I system modelling technique of Chapter 4. It also discusses some of the techniques that have been used for verifying and validating the simulation model. Chapter 6 draws together the simulation results for different types of experiments. Chapter 7 is an academic discussion of the results of the research survey, and the development and evaluation of the COEIA white-box modelling approach. It also includes a brief Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of the developed COEIA white-box modelling approach. The last two chapters (8 & 9) cover the project's conclusions and some suggestions for future work.

The thesis is intended to be as succinct as possible. A glossary of terms and abbreviations is included at the rear of the thesis, followed by a set of appendices to provide additional background and details associated with the research:

A. Theory and Tools to Support the COEIA White-box Modelling Approach.

B. Simulation Concept, Design and Development.

C. Testing the Simulation Model.

D. Simulation Results.

E. Source Material for the Simulation Model.

1.6 Publication Note

Some of the results of the research work have already been published:

[Jaber, 1999] Jaber, A. M. & Hitchins, D. K. *Emergence, Effectiveness and Procurement*. INCOSE Conference, DERA Malvern, UK, 1999 (Abstract and Presentation).

[Hitchins, 2000] Hitchins, D. K., Jaber, A. M. & Moulding, M. R. *A Systems Approach to Defence Procurement*. Journal of Battlefield Technology, July 2000.

Further publications are in preparation at the time of writing the thesis.

Chapter 2: Research Objectives and Approach

2.1 Introduction

The chapter begins by stating the overall aim of the research which this thesis addresses, and then defines the research objectives that form the foundation of the research work which has been conducted, in the form of milestones to be reached. Finally, the chapter describes the research approach which was followed to address the objectives.

2.2 Aim

The broad aim of the research was to explore ways in which the procurement of COTS-based C^3I systems may be improved; particularly, with respect to the use of more formal scientific techniques during the development and procurement processes.

2.3 Research Objectives

Sections 2.3.1 – 2.3.4 describe the objectives, and explain how an initial hypothesis, with three associated objectives, resulted in a more focused, central hypothesis with three further objectives. Finally, in section 2.3.5, an enumeration of the complete set of hypotheses and objectives is provided, for ease of reference.

2.3.1 Initial Hypothesis

The initial hypothesis follows the broad research aim identified, above, and can be stated as:

> *Formal scientific techniques have an important role to play in improving the procurement of COTS-based C^3I systems.*

In pursuit of this, the first half of the project concentrated upon understanding the various issues which should be addressed in order to provide a coherent research framework for this difficult, but vitally important, field. It was anticipated that exploring such a hypothesis would identify key areas for scientific research to support the development and procurement processes. Although the study primarily would concentrate on C^3I systems as one of many military applications, the use of COTS products in other systems would also be considered.

2.3.2 Initial Objectives

In order to address the initial hypothesis, the following research objectives were formulated:

a) **To uncover current thinking, issues of importance, and trends in COTS-based procurement for military C³I systems.** Most research projects start with some form of literature search and exploratory investigations, in an attempt to find out what is happening, and who is doing what, in the real world. This is particularly important for the military information systems field, which is driven by practice rather than theory. In the present case, the output from this initial review would address the key issues and associated risks with COTS-based procurements for military applications, with particular attention and consideration to C³I systems.

b) **To identify and explore specific areas of central importance to achieving an effective COTS-based development and procurement approach for military C³I systems.** This reflects the need to define the research domain, for this project and others that may follow. It would be based upon the need to map the requirements from the C³I 'problem' domain on to an architecture which is populated by COTS products. Ideally, if it were possible to establish Measures of Effectiveness (MOEs) and Measures of Performance (MOPs) which quantify the required properties of the C³I system, identify COTS products which are defined by suitable parameterised abstractions, and define a generic system architecture which would allow the prediction of the effects of COTS component choice on C³I system performance, then this would provide the basis for an objective engineering development approach. In addition, one might also imagine that such an approach would make demands on the procurement process which it serves, and this should also be investigated. Thus, these four areas would provide the basis for defining the research domain of interest.

c) **To identify a specific issue of significance to the COTS-based procurement for military C³I systems, which would benefit from a formal scientific approach.** Importantly, it was anticipated that the identified issue would be one which was unlikely to be tackled outside of the academic community; the goal

was to be complementary to the large investment being made by commercial organisations in this field, which is mainly of an implementation and prototyping nature.

2.3.3 Resultant Central Hypothesis

As a direct result of the research work which addressed the initial hypothesis and objectives, a fundamental need was identified, which is poorly served by existing research: namely, that of measuring the impact of COTS component selection on overall C³I system effectiveness. This led to a central hypothesis that would drive the remaining phases of this research project, and can be stated as follows:

> *It is possible to build a white (or glass) box model of a C³I system with all parts and parameters both visible and adjustable, to assess the impact of COTS selection on overall C³I effectiveness, in order to improve the Combined Operational Effectiveness and Investment Appraisal (COEIA) associated with the procurement of C³I systems.*

Importantly, the white-box C³I model would have an internal architecture and composition which can be related to the structure and components of a C³I system. It would be dynamically exercised within an enclosing COEIA white-box simulation model that would provide a competitive environment in which to assess C³I system effectiveness. This approach is substantially different from existing 'black-box' parametric approaches for COEIA, which are based upon a subjective scoring and weighting technique to achieve an overall figure of merit for a particular C³I system configuration.

2.3.4 Objectives Relating to the Central Hypothesis

The following second set of objectives were formulated to address the central hypothesis:

d) **To devise a suitable white-box model to represent a C³I system**. Such a model would need to include, in a suitably abstracted form, the influences of technology, people and process within a C³I system. This is because the model is intended to enable comparisons between Bespoke equipment and COTS

equipment, in terms of their relative contributions to command and control effectiveness and cost-effectiveness. A major challenge would be to integrate the various elements of a C^3I system into the model in a way that preserves correspondence and minimises complexity.

e) **To develop a COEIA white-box simulation model, to support C^3I system effectiveness measurements.** This would entail translating the white-box C^3I model, above, into an executable form, and providing it with a competitive environment so that its effectiveness can be assessed. In addition, C^3I MOEs, together with MOPs for the various elements of the C^3I system, would need to be defined, together with suitable operational scenarios. Furthermore, the credibility of the overall COEIA white-box simulation model would need to be established.

f) **To assess the potential utility of the COEIA white-box simulation model, through experimentation.** This would involve varying parameters of the simulation model to explore its predictive behaviour. A major aspect of this would be to consider the impact of COTS versus Bespoke equipment on the various MOEs, for appropriate operational scenarios.

2.3.5 Summary of Hypotheses and Objectives

Initial Hypothesis

Formal scientific techniques have an important role to play in improving the procurement of COTS-based C³I systems.

Initial Objectives

a) To uncover current thinking, issues of importance, and trends in COTS-based procurement for military C³I systems.

b) To identify and explore specific areas of central importance to achieving an effective COTS-based development and procurement approach for military C³I systems.

c) To identify a specific issue of significance to the COTS-based procurement for military C³I systems, which would benefit from a formal scientific approach.

Central Hypothesis

It is possible to build a white (or glass) box model of a C³I system with all parts and parameters both visible and adjustable, to assess the impact of COTS selection on overall C³I effectiveness, in order to improve the Combined Operational Effectiveness and Investment Appraisal (COEIA) associated with the procurement of C³I systems.

Central Objectives

d) To devise a suitable white-box model to represent a C³I system.

e) To develop a COEIA white-box simulation model, to support C³I system effectiveness measurements.

f) To assess the potential utility of the COEIA white-box simulation model, through experimentation.

2.4 Research Approach

In order to address the above hypotheses and objectives, the research was structured into two stages. These are outlined in the following two sections.

2.4.1 Initial Research

This stage was concerned with addressing the Initial hypothesis, and took the form of a literature search, coupled with attendance at conferences and visits to Ministry of Defence (MOD) and Defence Evaluation & Research Agency (DERA) establishments. It was conducted in three sequential phases:

(i) A general review of the state-of-practice for COTS-based development and procurement for C³I systems, to address Objective (a), above.

(ii) A focused investigation into four key areas, which were considered to provide an adequate structuring of this research domain:
- C³I Requirements Modelling and Analysis
- C³I Architectures and System Modelling
- Component Technology and Evaluation
- COTS-based Procurement Processes.

Collectively, this work addressed Objective (b), above.

(iii) A synthesis stage, where the results of the previous phases were considered, and suitable directions for further deepening research were formulated. This addressed Objective (c), above.

The results of this research are presented in Chapter 3. This concludes with the identification of the white-box modelling of C³I systems, to support the COEIA process, for further deepening research, and forms the basis of the central hypothesis. The key features of the proposed modelling approach were:

- The development of a novel white-box approach for modelling a C³I system using a combination of two existing techniques: the Layered Virtual Machine (LVM) and the Generic Reference Model (GRM).

- The use of a dynamic simulation, involving the C³I models of two competing ships (Red and Blue), to determine the overall effectiveness of their respective C³I systems (with and without COTS) under defined operational scenarios.

Further details of the uncovered theory and tools which would be used to support this subsequent modelling activity are provided in Appendix A.

2.4.2 C³I Systems Modelling for COEIA

In order to address the central hypothesis, this deepening stage of the research was structured into three phases:

(i) Hypothetical Considerations. The phase began with an academic investigation of the theory and tools relevant to support the white-box C³I modelling concept, as proposed in the central hypothesis, and justified the choice of tools and methods, which would later be used to conduct simulation experiments. The white-box C³I system modelling approach was to formulate a so-called Layered Generic Reference Model (LGRM). This comprises a three-layer LVM, representing Technology, People and C² Process, which is integrated with a GRM, involving Function, Form and Behaviour. Together, these complementary models could be made to represent any C³I system (or other socio-technical system). The final outcome was a 'static' LGRM-based C³I model that would support the white-box modelling approach for COEIA. The results of this work directly address Objective (d), above, and are presented in Chapter 4.

(ii) Simulation Model Development. This phase was concerned with developing a 'dynamic' COEIA simulation model, based on the results of addressing the hypothetical considerations mentioned above. The model was constructed using the System Dynamics STELLA™ tool, and was subjected to appropriate verification and validation checks, to ensure that it was suitable for subsequent experimental investigations. This work addressed Objective (e), above, and is

presented in Chapter 5, with additional details provided in Appendices B, C and E.

(iii) Model Prediction. The final phase of the modelling work was concerned with conducting a set of experiments in support of Objective (f), above. These employed the COEIA simulation model as a tool to judge and evaluate the impact of COTS on C^3I effectiveness, with two ships competing in a representative operational scenario. The empirical results of the tests were then subjected to statistical analysis using Microsoft Excel. They are presented in tabular and graphical form in Chapter 6, with the detailed results and analyses in Appendix D.

Chapter 3: Survey of COTS Procurement for C³I

3.1 Introduction

This chapter describes the results of the research survey that was carried out during the first part of this PhD research programme. It begins by explaining how the survey was organised. It then provides the results of initial work which uncovers the main issues associated with the COTS procurement of C³I systems, before going on to discuss some critical areas in more detail. Finally, from these considerations, it proposes the more formal scientific approach which this PhD investigation has focused upon, and which is described in the following Chapters (4, 5 and 6) of this thesis.

3.2 Survey Organisation

The COTS-based procurement of military C³I systems is not an established research field; it is topic driven by customer need rather than from academic foundation. Therefore, a major task of this PhD programme has been to define the research domain, so that issues of importance can be identified, and in-depth research may be applied where it is most likely to be of long-term benefit. Accordingly, this research survey was structured into the following three phases:

(i) Initial Exploratory Phase. This was concerned with performing a general review of the literature in relevant areas, to uncover current thinking, issues of importance, and predicted trends in COTS-based procurement for military C³I systems.

(ii) Research Domain Definition Phase. This was a second-level research review targeted at specific areas identified as being of central importance to achieving an effective COTS-based development approach and procurement process for military C³I systems, and whose aim was to contribute an improved understanding of this field. It was based upon the simplified COTS development model, illustrated in Figure 3-1, which identifies the need to map the requirements from the (C³I) problem domain, characterised by Measures of Performance and Effectiveness (MOPs and MOEs), on to a system design architecture which is populated by COTS components.

(iii) Deepening Research Synthesis Phase. Having defined and explored the research domain of interest, this final phase was concerned with identifying a specific issue suitable for an in-depth academic investigation, and proposing an approach to tackle this, based upon knowledge gained during the preceding two survey phases. Importantly, the goal was to be complementary to the large investment being made by commercial organisations in this field, which is mainly of an implementation and prototyping nature.

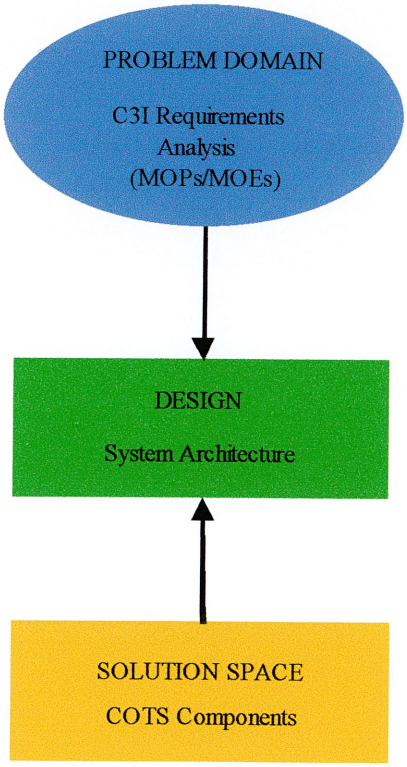


Figure 3-1 Simplified Model for a COTS-based System Development

The following sections of this chapter essentially provide the output from the three research survey phases, above:

- General Review of COTS
- C³I Requirements Modelling and Analysis
- C³I Architectures and System Modelling
- Component Technology and Evaluation
- COTS-based Procurement Process
- Summary and Resultant Research Direction

3.3 General Review of COTS

This broad review addresses a number of topics which collectively provide an introduction to the terminology, issues and activities associated with COTS-based development and procurement, particularly with respect to military C³I systems.

3.3.1 Definition of COTS

There are many definitions of COTS components, and there appears to be slight differences in their meanings, as illustrated below.

US Military standard MIL-STD-2036A [STD-2036A, 1993] defines COTS products as:
"Items which can be purchased through a commercial retailer or wholesale distributor as is, for example, equipment that is available as a catalogue item. Modified COTS equipment is COTS equipment which has been customised to conform to functional requirements. All references to COTS shall be construed to include modified COTS equipment."

The aviation sector standard DO-178B [Matthews, 1996] takes a purer commercial perspective by defining COTS software as:
"Commercially available applications sold by vendors through public catalogue listings. COTS is not intended to be customised or enhanced."

The following definition for COTS is from the Federal Acquisition Regulation (FAR) [Durante, 1995]:
"Commercial product means a product, such as an item, material, component, subsystem, or system, sold or traded to the general public in the course of normal business operations at prices based on established catalogue or market prices."

The term COTS in this PhD investigation will be considered as referring to ready-made products that can be easily obtained commercially as a whole, without modifications.

3.3.2 COTS Benefits

Use of COTS technology in military systems, and recognition of the advantages it can offer, are on the increase. These advantages can bring considerable benefits in terms of affordability and availability. COTS can help in reducing development cost and time, and offer a good opportunity to upgrade and adapt military systems to keep up with the latest civilian technology. It might also present functions and services that are familiar to the user, which will help in reducing training costs [Still, 1998].

Here is a summary of the advantages and disadvantages of using COTS technology.
On the positive side:

- Affordability.
- Initial development costs and time to launch can be considerably less than expected for bespoke systems.
- System design tends to be less complex and easier to support.
- Rugged, weatherproof and highly reliable.
- Operability and ease of training through modern and familiar interfaces.

On the negative side:

- Use of COTS technology builds a dependence upon commercial suppliers.
- As commercial technology changes, COTS-based systems become unsupportable more quickly than bespoke systems. This leads to a shorter lifetime between major upgrades.
- Commercial products are available world-wide, both to friendly nations and potential enemies.

Overall, there seem to be more advantages than disadvantages associated with the use of COTS components; the lower cost and risk of these components is usually the most significant decision-making factor in system procurement. The system costs are less because their development costs have been spread over many commercial companies and product sales. There is a lower risk of failure, or delay, since COTS products already exist, and an assessment can be made of their functionality by trying products rather than trying to imagine what they would be like from abstract specifications.

3.3.3 Research and Development

The commercial sector, represented by industry, is generally more successful in research, development, testing, and evaluation than the military sector. For example, commercial Information Technology (IT) developments are indirectly helping to reduce military budgets that might be spent in such an area [TECNET, 1998]. In certain circumstances, the Ministry of Defence (MOD) would prefer not to develop its own components, but would prefer to buy computer hardware and software from the commercial sector, as long as the commercial market continues to produce the equipment that meets the military need.

3.3.4 Military-specific Requirements

The level of detail in military requirements documents varies dramatically from organisation to organisation. In some cases, there is a very detailed description of all the functionality which must be provided by the system. More commonly, it is an abstract description of system facilities. Such an abstract description gives suppliers, who have experience of satisfying military specifications for bespoke systems, the flexibility to make COTS work in a military environment.

The use of a system solution based on COTS equipment to meet military Command and Control (C^2) requirements is on the increase. The gap between military requirements and COTS products is getting smaller. The reason for this is the existence of a large number of critical infrastructures in the commercial sectors that depend on the information highway. Banking and finance, telecommunications, emergency services, airlines, and health and safety, for example, might have similar requirements to the military for their critical applications, mainly concerning security, integrity and reliability issues to carry out their business [Yavuz, 1996].

There is a need to speed up commercial security solutions for military applications. There is no reason why a mix of commercial and military-grade encryption cannot be employed to provide a secure system. Importantly, end-to-end encryption remains a good protection method and is expected to be widely used for military applications.

3.3.5 Standards

Standards, according to the International Organisation for Standards [Roby, 1996], are documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions of characteristics, to ensure that the materials, products, processes and services are fit for their purposes.

Using commercial standards in military networks would be a big benefit to the military sector by saving the cost of development and testing, as these standards could be proved and improved upon in the commercial market first, before being used for military applications.

There are a large number of commercial standards. The majority of advanced C³I systems should be based on current and evolving civilian standards, wherever possible. The main driver for selecting standard-based COTS components is to meet defence requirements for affordability, interoperability, functionality, performance, and security. This requires evaluating commercial standards to determine whether or not they are applicable to military C³I systems, and will function in a battlefield environment.

Importantly, there has been a shift in the US DoD and UK MOD procurement policies, resulting in the cancellation of some military specifications and their subsequent replacement with commercial standards. In the UK, the Future Attack Submarine (FASM) COTS policy states the policy principles that shall be used when considering COTS products for FASM combat systems and whole-ship IT, through the life of the submarine [Williams, 1999]. The policy for selection and application of standards for FASM is laid down in the FASM coherence policy [DERA, 1998]. The concerns are that commercial standards must form the basis of the FASM design, and that military specific aspects be accommodated in an affordable manner (e.g. packaging).

3.3.6 Trends

The military continue to deal within an area of varying operational requirements, constrained resources and rapid technological advancement. Such an area requires deep thinking and the ability to shape and manage change. The military will continue

to keep their budget for research, development, testing and evaluation, as low as possible, to maximise funds for equipment procurement.

The technology for hardware and software is changing very fast and will continue to do so in the next several years. The road ahead offers great promise and diverse challenges for C³I systems. Projecting trends in some key areas will assist in forming a picture of the future environment so that there is a better understanding of the challenges to be faced.

Judgements based on trends can be relatively precise for the next 1-3 years, but will become less predictable as the focus extends into the future. Furthermore, the move towards 'sensor to shooter' and joint/combined operations is having a considerable impact on the architecture and the design of C³I systems. From a standards point of view, a reduced reliance on military standards will take place, and commercial ones will become dominant.

3.3.7 Outstanding Issues to Resolve

Earlier discussions have highlighted a range of benefits regarding the use of commercially-available products, matched with the system requirements, that might result in lower-cost systems, and better performance and design-in times. This seems like a very simple solution. However, many issues lie between COTS and true military hardware. Some concern performance and ruggedness. Others concern usable lifetime, maintenance and spares problems, upgrades and availability. Still more issues involve choice of system architecture, applicable standards, and barriers to allowing the use and export of strong encryption technology [Ackerman, 1998]. However, some of these restrictions may soon change, as strong technologies become increasingly available from other sources, such as Pretty Good Privacy (PGP) encryption [Purcell, 1996].

3.3.8 Risks

There are many risks associated with the use of COTS for military applications. It is difficult to identify the operational 'zone of safety' for a COTS-based system, as COTS component behaviour is not always predictable. This can be minimised by using 'wrapping' and 'gluing' technologies. Building a system by integrating

components requires a communication interface between the components in the form of an appropriate 'glue'. The glue assists in combining the functionality of the individual components to provide the required system functionality. Component 'wrappers' are a mechanism for isolating a component from other components of the system, so that only legal output events are allowed and unneeded functionality of components is masked. All interactions with the component are made through the wrapper. The wrappers serve to isolate the component by acting as the interfaces to the glue code [Dean, 1997].

COTS products are available now and in large quantities. However, they will generally have a limited match to user requirements, as shown in Figure 3-2. The graph shows that, for a given cost, a product provides a fixed amount of functionality. Changing the requirement in later stages will cause an increase in the price; however small the increase, the cost jumps to the level of the next product in the range. At some level of functionality, this process stops and no COTS product can meet the need without modification [Still, 1998].

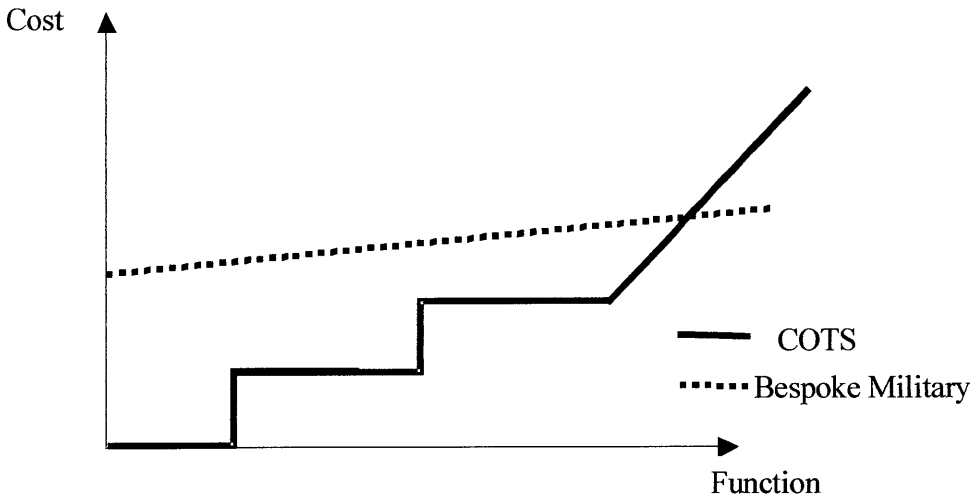


Figure 3-2 Step Cost of COTS versus Bespoke Military Costs

Open systems provide a mechanism for introducing COTS components into a system design, but can produce risk in the areas of poor inter-networking due to wrong specifications, and supplier lock-in by the use of barriers to prevent integration or

transfer to other suppliers. Integration risk occurs due to failures to define open interfaces, or application programming interfaces [O'Halloran, 1997].

3.3.9 US Initiatives

3.3.9.1 Perry Commission

The Perry Commission was set up by the US Government in 1994 to examine the possibility, in defence procurement, of buying COTS components instead of bespoke systems to expensive military specifications [IEE, 1997]. Therefore, purchase of commercially-available components is based on commercial standards, making the military standards the exception rather than the rule. As a result of this reform programme, some successful uses of COTS components in the USA have been observed. The Joint Vision 2010 (JV2010) [JV 2010, 1997], the Advanced Battlespace Information System (ABIS) [ABIS, 1997], and the Joint Warfare System (JWARS) [JWAR, 1997] open-backbone networks demonstrations are intended to show how commercially-available technology can meet the needs of key command and control decision makers.

3.3.9.2 Common Operating Environment

The US, followed by the UK and other major allies, have reached an agreement that a Common Operating Environment (COE) should be defined as a base on which to build their information systems. Accordingly, the UK has now moved towards an approach based on a common understanding of a components-based architecture, to assist in building and procuring its systems. A C²I COE architecture has been defined, and is based on common standards, products and policies [DERA, 1995].

The Joint Operations Command System (JOCS) is currently in service in the UK, which is based on the de-facto C²I COE, and is compatible with the US Defence Information Infrastructure (DII) COE. The current systems that are based on the UK COE are made up from standard Personal Computers (PCs) with standard office systems (using Windows NT), and standard communications equipment. The (DII) COE is a collection of building blocks which 'plug' into the COE just as circuit cards plug into a hardware 'backplane'. The blocks containing the operating system and windowing environment are akin to a power supply, as they contain the software which 'powers' the rest of the system. Similarly, the current US COE will also make

maximum use of COTS components, particularly in those areas of the DII COE most widely used across the DII subscriber community [DII COE, 1997].

Overall, specifying a common operating system and common set of Application Program Interfaces (APIs) is intended to be solved by the introduction of a COE. However, defining a common operating system is already proving difficult because of the rate of change within the computer industry.

3.4 C³I Requirements Modelling and Analysis

The purpose of this section is to summarise some useful methods and tools that have been used in on-going research to support the capture of requirements for C³I systems. The section begins with a formal definition statement for C³I, followed by a discussion of the attendant C² process. The requirements process is then considered, dealing with functional, non-functional, and external requirements. Finally, Measures of Effectiveness (MOEs) and Measures of Performance (MOPs) are identified, which can be used to quantify the operational performance of a C³I system, and of its primary functions.

3.4.1 C³I and the Command and Control Process

C³I systems support command and control. The main characteristic of any command and control system is the receiving of information from different sources, using this to understand the situation, and making decisions about how to employ resources. This differs only slightly for military command and control at strategic levels, where the objectives are to plan, direct, and control the available resources for a successful mission. Thus, understanding a generic decision-making process is fundamental in establishing sound requirements for a C³I system.

3.4.1.1 C³I Definitions

The abbreviation of C³I can be divided into three layers. The first one is 'C²', which stands for Command and Control. This is mainly used for making military decisions. The second one is 'C', which stands for Communication. This means passing information between military users. The final one is 'I', which stands for Intelligence; any information of use to the military users. The above definition is general in its meaning.

There is a three-part definition of a C^2 system. The first of these consists of the physical parts: the equipment, software, people, and their associated facilities. The second part is structure, which includes organisation, procedures, protocols, and concepts of operation and information flow. The third one is the C^2 process; this covers the functionality, or what the overall socio-technical system is doing.

The move towards battlefield digitization, 'sensors to shooters' and joint/combined operations, is making demands for a universal definition for C^2. The US DoD definition of C^2 is "the exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, co-ordinating, and controlling forces and operations in the accomplishment of the mission" [CFJO, 1997].

3.4.1.2 Command and Control Process

The above C^2 definition shows that the overall C^2 process, which represents the dynamic part of the system, is conducted by a static part comprising a combination of humans and machines. A generic C^2 process can be categorised as one of three types.

The first type is the 'procedural human process' [Hitchins, 1997], which contains plans and strategies that lead to decisions. This can be described by a sequential cyclic process as shown in Figure 3-3. The process starts at 'situation assessment' and moves towards 'monitor progress', and it will end the cycle if the mission is accomplished.

The second type of C^2 process is the 'intuitive human process' [Klein, 1989], which is used by commanders under time pressure to make their decisions. This leads to an initial (fast) decision without reviewing all options, followed by further fast decisions as the situation unfolds.

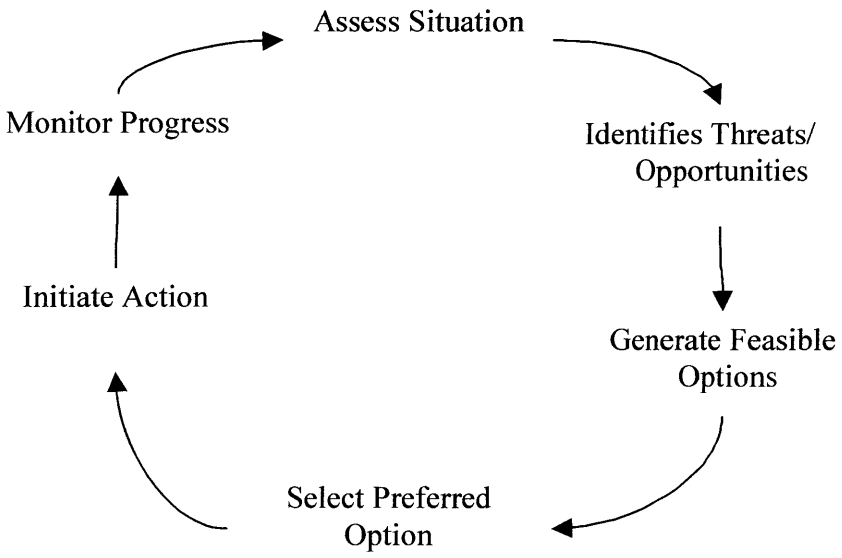


Figure 3-3 The C² Decision Circle (Naive Decision-Making)

3.4.2 C³I Requirements Process

In order to allow the acceptance of COTS solutions in C³I systems, it is very important to define the requirements according to what is available in the marketplace. It is essential not to 'gold plate' the requirements and to go for the best value, and that may mean comparing disparate solutions. This, in turn, will determine the choices available in the solution space. However, this 'reverse engineering' of the requirement will have a great impact on military procurement policy and standards. The use of COTS components in the strategic C³I military domain makes their security requirements critical. System requirements tend to be complex and difficult to be determined due to different types of influences, such as organisations, people, and policies. As a consequence, it is difficult to get the requirements right at the first attempt. Therefore, starting to build the C³I system with the core requirements, and adding the rest in later stages, might be more useful and practical. This is often called 'evolutionary development' or 'incremental acquisition' [DERA, 1995].

3.4.2.1 Process Definition

The requirements process may be broken down into a number of activities such as requirements elicitation, requirements expression, requirements management, and

requirements justification [Pratt, 1996]. This research survey has concentrated on the requirements elicitation phase.

Requirements are established through intensive interviewing with a formal definition of the operational function. This allows risk to be identified and acceptance criteria produced. Functional requirements describe what the system must do, while non-functional requirements consider the quality attributes of the functional requirements. External requirements, or constraints, are those imposed by other systems or by a parent organisation. A common example of the latter type of requirement is the need to be compatible (interoperable) with existing databases, applications or other systems in use within the organisation; they have special significance for military C³I systems with the increasing levels of integration resulting from battlespace digitization.

3.4.2.2 Methods

There are many different methods and techniques that can be used to capture the user requirements, and these can involve direct observation of existing systems in order to overcome any shortfalls. Capturing the user requirements is a major focus of several methodologies including Soft System Methodology (SSM) [Pratt, 1996], Enterprise Modelling [Houghton, 1994], Use-cases [Rumbaugh, 1994], and House of Quality [ASI, 1992].

Soft System Methodology (SSM) was originally developed by Peter Checkland [Checkland, 1990]. This methodology is designed to establish the desired criteria in areas where the problem domain is 'soft' or ill-defined. It uses the term 'problem' to indicate the area under analysis; however, its thinking process is not solution oriented. For example, SSM can be used in sponsor-driven academic research to resolve the potential conflict between the customer and the academic requirements of the study. It also involves processes which give an insight into complex problematic systems with humans as integral components, and encourages tailoring the approach according to the nature of the problem under investigation.

Enterprise Modelling techniques appear to be suitable for modelling C³I systems. When performing requirements elicitation, the most important benefits of Enterprise models are their ability in helping to define the initial scope and boundaries of the

system; for example, by encouraging a debate between different stakeholders, discovering issues which were left uncovered, and improving the understanding of the problem and potential solutions.

Use-case Modelling is an analysis technique for eliciting, understanding, and defining functional system requirements. Use-cases help define the entity behaviours necessary for representing a complete flow within a system. [Jacobson, 1994] stated that a use-case "is a generic description of an entire transaction involving several objects". [Rumbaugh, 1994] identifies that use-cases describe behaviourally-related functionality by adding a context to the analysis and design. This intellectual tool seems to be important in developing an outside view of a system, when combined with other techniques for human-computer interaction, and it can help to define systems with high usability. It is widely used by designers and developers for building applications in areas such as banking, insurance, defence, and telecommunication, which might contain hundreds of use-cases.

3.4.2.3 External C³I Requirements

The C²I COE, as discussed in section 3.3.9.2, will provide the infrastructure for future command and control systems with maximum use of COTS components, and is defined with a set of primary technical objectives [DERA, 1995]. These include intra-domain interoperability, application portability, and consistency of user interface. On the other hand, DERA has suggested similar C³I operational requirements [Matthews, 1996], such as adaptability (to change operational scenarios in the short term), ease of upgrade (to provide long-term planned supportability), and affordability. All these requirements have been supported by the following business requirements: speed of procurement; 80% solutions but with considerations of the impact of the capability shortfall; and design for change.

3.4.3 Measuring C³I System Effectiveness

When attempting to determine the effectiveness of C³I systems, it is necessary to consider the boundaries of a C³I system, the functionality offered by it, and the operational scenario in which it must operate.

Dealing with the boundary between the military forces under the influence of the C³I system and the system itself will lead to MOEs of the C³I system, which address several functions working together towards C² mission accomplishment. Timeliness, in general, is a good MOE, which depends upon the control window available. In real-time missions, planning must be completed in a short time period and in accordance with the commander's needs. Therefore, both time available and objective of mission can be related to this MOE. A second MOE is mission effectiveness, which is the degree to which a C³I system is able to achieve its designated mission. Other MOEs are cost and casualty exchange ratios, which are widely used in the strategic context and in wars of attrition. A final MOE is cost effectiveness, which is generally used to choose between options.

At the sub-system level, that is within the boundary of the system, are MOPs of the functions. They are system-related measures that address system performance parameters. Examples of MOPs for each command and control function are [Sovereign, 1988]:

Accuracy is a MOP for the sensing function, to identify the enemy by location.

Non-surprise is a MOP for the assessment function, to identify whether or not a target is currently a threat.

Probability of enemy defeat is the most general MOP for selecting courses of action.

Flexibility is an appropriate MOP for planning.

3.4.4 Combined Operational Effectiveness and Investment Appraisal (COEIA)

In the UK, the development of a military project is conducted in stages in accordance with a well-defined set of procedures known as the 'Purple Book' [DCDS, 1992]. An element of these procedures is the dossier system for the presentation of a new equipment to the approving authorities. An essential part of that dossier is the COEIA. The COEIA compares different options for a system from both effectiveness and cost/risk viewpoints. An important element, therefore, of the COEIA is the Operational Effectiveness Assessment (OEA).

In support of COEIA, DERA is currently undertaking research into the assessment of the effectiveness of Naval C³I systems, with the aim of defining a set of metrics for use in the OEA element of COEIA [Young, 1998]. Using a consolidated set of

metrics, a set of corresponding values, a structure for the metrics, and relative weights for the metrics set, will provide assessment for the operational effectiveness and performance of the system.

The metrics proposed in the DERA study are independent of sensor performance in order to measure the contribution of the C³I system to the overall effectiveness, and are defined as measurable characteristics of a system to which at least two scores can be assigned. These metrics, which are essentially MOPs using the terminology of Section 3.4.3, are grouped into the capability (function) areas of picture compilation, situation assessment, resource allocation, resource direction, planning, human-computer interface and communications.

Each metric has an associated scale. Scales represent a set of elements, with associated units where appropriate. A metric's 'score' is a position on a scale. The scale is of two basic types; enumerated and positive real numbers.

It is important to understand the difference between the terms 'score' and 'value'. A metric is scored against a scale. The value of a score is a measure of the usefulness associated with the score; the contribution that the score makes to the overall effectiveness of the system. Value functions are used to transform each metric's score into a measure of contribution towards overall system effectiveness (value).

After the scores for the metrics are converted into values, they are added in a weighted sum, to determine an overall figure of merit. The 'weight' of a metric reflects its relative importance to overall system effectiveness.

3.5 C³I Architectures and System Modelling

This section discusses the design dilemma for defining a C³I system architecture, which interfaces between a set of information sources and sinks, to achieve secure, robust, and effective operation. Particular attention must be paid to predicting the effect of combining different kinds of components on the overall behaviour of the system, and on the system qualities such as reliability, performance, and maintainability. For example, C³I performance is related to the way in which

information travels from one destination to another one, taking into consideration the effect of time delay on decisions to be made.

3.5.1 Architecture Definitions

Architecture is defined by Chambers Dictionary as "the art or science of building; structure; style of building; structures or buildings collectively; overall design of software and especially hardware of a computer or local network; organisation; framework (Greek: architekton, master builder)." An alternative engineering view of architecture is defined as the organisational structure of a system or component [IEEE, 1990]. Various views exist in the open system area. The US DoD is currently working to achieve a definition consisting of three types of architecture. The architecture structure recommended by the Joint Task Force (JTF) to develop a road map for 'Simulation Based Acquisition' (SBA) consists of three inter-related architectures: Operational, System, and Technical. These are summarised [Lutz, 1999] as:

- **Operational Architecture** is a description of the operational elements, assigned tasks, and information flows to support functions.
- **Systems Architecture** This defines the physical connection, location, and identification of the key nodes and networks, and specifies system and components performance parameters.
- **Technical Architecture** identifies the services, interfaces, standards, and their relationships. It also provides the technical development guidelines for the whole domain of the system.

The above architectural approach is currently under development and requires some time to establish its utility and robustness.

3.5.2 Kinds of Architectures

Architectures, in general, appear in different forms. One type typically evolves to have several layers, which might represent a series of entities such as people, products, and software and hardware components. A second type of architecture, which is widely used, is made of clusters and links; therefore, it is called a 'cluster' architecture. In this type of architecture entities are formed into tightly coupled clusters, which are then linked 'loosely' to each other. By their nature, such

architectures may become complex, high entropy, and high internal energy. On the other hand they can improve system performance.

3.5.2.1 Multi-Layer Architecture

A general purpose multi-layer architecture can be built using any number of successive layers. One common example is the Layered Virtual Machine (LVM) approach, which is a widely established technique for managing the complexity of software and hardware interactions that take place in a computer system [Allworth, 1981]. A simple example of this is illustrated in Figure 3-4. Typically, at the lowest level, one might represent the computer hardware as a layer upon which an operating (software) system executes. This operating system will manage the hardware resources, and may provide common services, such as communications and data management, to the application software that resides in higher-level layers.

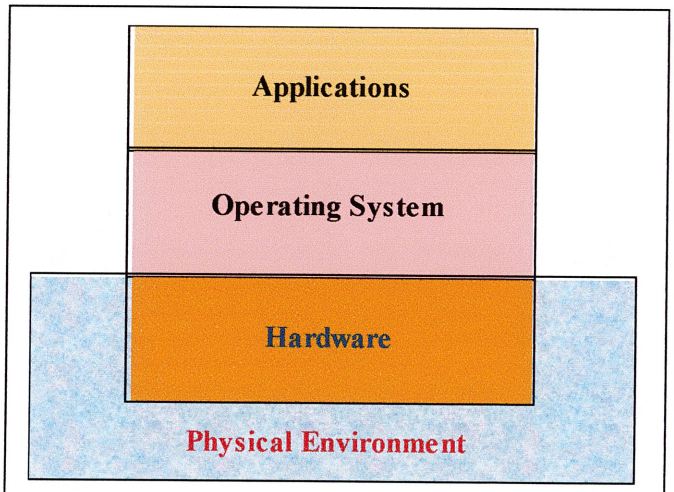


Figure 3-4 Layered Virtual Machine Model for Computer Systems

In principle, any number of layers is possible and, above the hardware layer, each software layer can be considered to use the services of the layer below, to provide services to the layer above. In essence, each layer adds to the layers below to create a 'virtual machine' upon which the software in the layer immediately above can execute.

3.5.2.2 Clustered Architectures

A clustered system architecture is a way for organising and grouping things to fulfil some collective purpose. One example of a clustered architecture is a hierarchical approach, in which there is a central node surrounded by others. A second example is a distributed architecture, where each node can be a part of another network. These are illustrated in Figure 3-5.

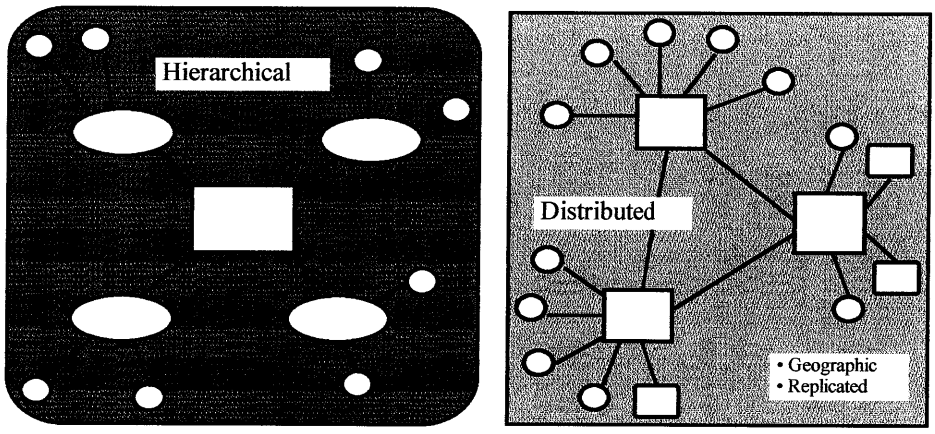


Figure 3-5 Clustered Architectures

3.5.3 System Models

System models allow us to reason about the characteristics of a system, using appropriate abstractions. Two examples are given, below; one of which is applications specific; the other, general purpose.

3.5.3.1 ISO Open Systems (7 layer) Interconnection Model

The International Standard Organisation (ISO) employs a multi-layered architecture to define a seven-layer model to reason about network communication protocols [ISO, 1984]. The model is more formally called the Open Systems Interconnection (OSI) model as shown in Figure 3-6. Each layer can be regarded as black box with well-defined inputs and outputs, and each layer builds upon the services provided by the layer below, to provide expanded services to the layer above.

Physical connections between nodes travel down one side of the 'U', through the physical medium, and up the other side. However, each layer has its own protocol which logically communicates horizontally to its opposite number. The three lowest

layers have dual purposes, enabling relay of information from node to node, across networks, etc.

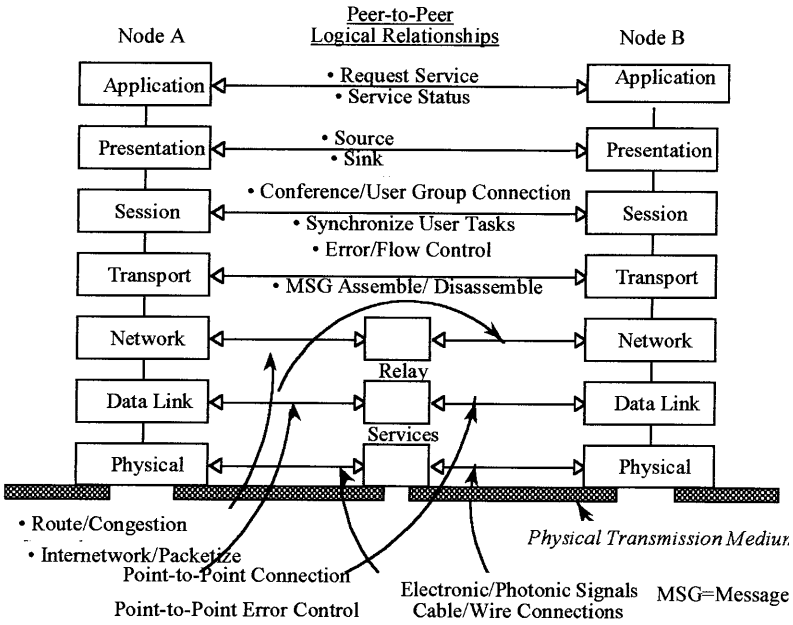


Figure 3-6 The (ISO) Open System International Layered Protocol

3.5.3.2 The Generic Reference Model (GRM)

This model has been invented and developed by Professor Derek K Hitchins as a reference for any system to assist systems engineers in designing, checking, and evaluating their systems for completeness [Hitchins, 1997]. It is type independent and scale independent.

The model consists of three parts. The first is the *Function Model*, which describes the 'doing' of any system, and comprises three parts: Mission Management (collect information, set/reset objectives, strategies and plan, execute plan, and co-operate with others if necessary); Resource Management (acquire, store, distribute, convert and utilise, and discard excess/waste) and Viability Management (survival, synergy, homeostasis, evolution and maintenance). The second part is the *Form Model*, which consists of three parts: Structure, Influence, and Potential. The final part is the *Behaviour Model*, which proposes how behaviour might be selected, and it is the most complex of these three first-level models.

The GRM presents an 'internal' view of any system which can be thought of 'Being', 'Doing', and 'Thinking', as shown in Figure 3-7. The GRM also can be used for understanding the idea of emergence, which has been expanded to include emergent Properties, Capabilities and Behaviour (PCBs):

- Properties are those observable and measurable features that can be seen or deduced from outside the system, such as all-up-weight, overall failure patterns, colour, centre of gravity, etc.
- Capabilities define the envelope of what the system is able to achieve, and might include maximum altitude, top speed, maximum fire rate, etc., and these are identified with conditions under which the capability might be observed.
- Behaviours identify the way in which the overall system responds to stimulus, and might include reaction times, rules of engagement, etc.

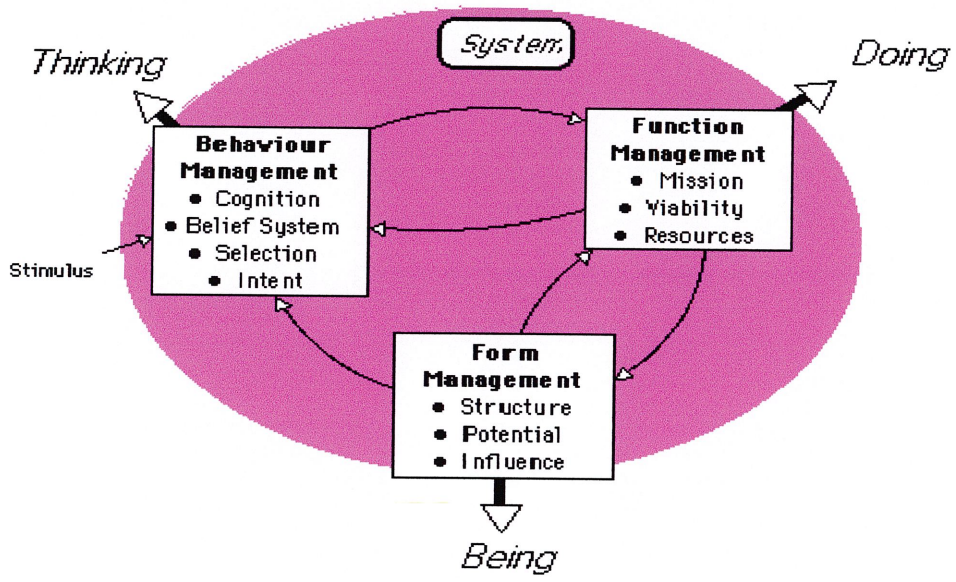


Figure 3-7 The Generic Reference Model

3.5.4 Open Systems and Standards

The use of an open systems approach to develop military information systems is becoming very important for improving the quality and performance of such systems. However, the acquisition plan should move towards adopting open systems standards that are 'plug-and-play' compatible for COTS procurements.

The basic idea of open systems is the use of interface standards, in the form of APIs, data formats, or protocols in the engineering and design of systems. Many different definitions have been offered for open systems. For the purpose of this research study, an open system is defined as follows:

"An open system is a collection of interacting software, hardware, and human components, designed to satisfy the stated needs, with the interface specification of components fully defined, available to public, and maintained according to group consensus, and in which the implementation of components are conformant to the specifications." [SEI WWW, 1997].

3.5.5 Component Selection and Architecture

The system architecture defines the components and the interaction between them. A COTS product selection process is essential in the design phase, as shown in Figure 3-8, in order to find the best ways for components to fit within an architecture. COTS components behaviour is not predictable. Hence, to hide the details of the interface of the component from external components and ensure component upgrade and substitution, the design will treat the selected components as a black box and deal with the issue of integrating them to provide the required functionality. The components will be placed within a wrapper, and all interactions achieved through the wrapper. This type of architecture is known as a components-based architecture [Stavridou, 1997].

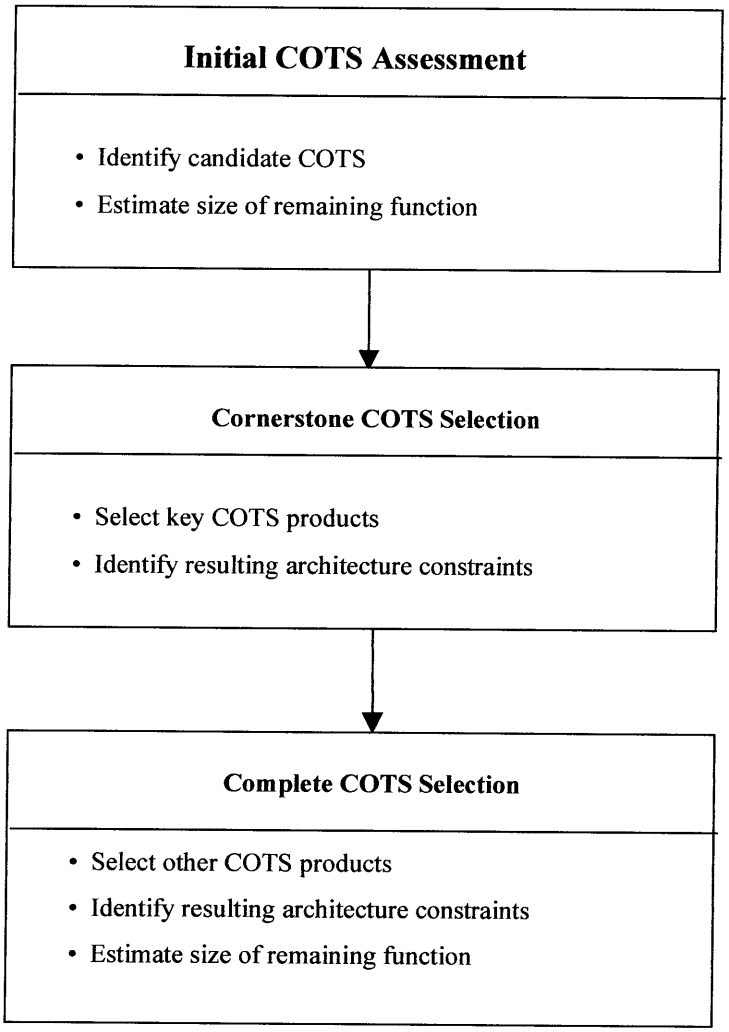


Figure 3-8 COTS Product Selection Process

3.5.6 Evolution within Architectures

There is always a need for component upgrading, due to product and technology advances. Accordingly, controlling the architectural integrity and system stability during the system maintenance life cycle, which might be of the order of a few tens of years, is an important issue. An appropriate architecture for COTS-based C³I systems would allow any support swapping and replacement of components with a minimum amount of effort, so that the effort required to make the change is proportional to the size of change. Furthermore, it should have an ability to accept different kinds of components.

3.6 Component Technology and Evaluation

Evaluation is a tool which is designed to support certain types of decisions. Such decisions include 'fitness for use', make/buy decisions, specifying and characterising components, finding out system properties, validating of components, and making architectural, design, and requirements decisions.

The rate of change in technology and new releases of components makes the evaluation a continuous process. Moreover, the behaviour of most components is unpredictable due to a lack of detailed specification by the vendor. As a result, there are a few potential roadblocks to the practical adoption of COTS components for military applications.

This section broadly summarises a series of important evaluation methods for COTS components, and their assistance to the system design in order to fulfil the system requirements.

3.6.1 Evaluation Strategies

Component evaluation needs to take place in a clearly defined context in which those components will be used. This means that the requirements of the system should be thought out, and be clearly distinguished and prioritised. The system architecture must also have been developed, as well as identifying the key technology and the pool of products from which choices can be made.

The need to evaluate components is to measure whether they provide the services that they claim to provide according to their user manual, brochure, or a published interface document such as a published API. In other cases the evaluation might take place according to what standards the component is based on. By comparing the strengths and weaknesses of standards and components with respect to the system needs, a decision can be made for using a particular component, based upon the evaluation result. This type of evaluation is sometimes called validation or conformance testing.

A second type of evaluation is to determine how far the components can demonstrate the qualities that are necessary for the system. Evaluation of this type, which deals

with non-functional requirements, is difficult because of an incomplete understanding of non-functional requirements, coupled with inadequate tools and techniques for determining whether a component meets expectations.

There are a number of evaluation criteria for COTS products, some of which are real-world approaches, such as multi-page checklists and weighting schemes for those components that meet the requirements. A special report covering the proceedings of the first workshop on COTS-Based Systems, held at the Software Engineering Institute (SEI) in June 1997, summarised a number of different approaches for COTS products and technology evaluation, which employ three different strategies:

- **Progressive filtering** consists of a sequence of filtering stages; each stage will reduce the set of components to be tested for the next round. Early filters provide an initial screening through analysis of product documentation and specifications, to eliminate less fit components. Intermediate filters may involve stand-alone testing and, finally, later filtering may use integration and field-testing. This approach, hopefully, will increase confidence that the selected components are likely to fulfil expectations.
- **Puzzle assembly** focuses on the interaction between components for smooth integration, in order to determine the characteristic of the system. The components will fit together as would a puzzle.
- **Keystone identification.** This method can be used when a specific component meets the requirements, and there is a lack of other alternatives, or constraints imposed by the existing system. A keystone need not be a component. It might be a strategy for component selection, for example an open system strategy, or it might be a standard such as that from the Object Management Group (OMG) [Oberndorf, 1997].

3.6.2 Risk Management

Using a particular COTS component, based upon the evaluation results, is in most cases associated with some risk. This occurs because it is hard to understand the behaviour of those components for a number of reasons. For example, incomplete documentation issued by the vendors, in addition to the use of complex interfaces.

Therefore, it is essential to use components within their 'zone of safety' to minimise risks for that choice to an acceptable threshold level.

3.7 COTS-based Procurement Process

This section addresses and discusses the overall system procurement process and issues which are significant in that process for COTS-based C³I systems. Special attention is paid to the need for a new approach for COTS procurements.

3.7.1 Impact on Process Definition

The current acquisition policy for a COTS procurement process has been defined by some military organisations. In the UK, for example, the Future Attack Submarine (FASM) combat system and whole-ship IT system design process is likely to be radically different to current procurement practice. It will be based on design-to-affordability criteria using non-developmental items such as COTS where feasible; resulting in a COTS-based design. This approach has the potential to reduce the development costs and timescales [DERA, 1996].

In the UK and some other countries, processes based on the Downey principle, or its variants, have procured most of the defence systems. In some cases the development time is so long that the resulting system can be out of date by the time it has come into service. This frequently happens due to problems with the definition of requirements at an early stage in a project, resulting in pre-production changes to the specification which delay system delivery. This situation is gradually changing, and is particularly noticeable in the area of Command Information Systems (CIS). Most CIS are now constructed from standard office computers (PCs), with Windows NT, and standard communication equipment, thus reducing procurement delays.

Defence planning is a long-term business. Major procurements of defence technology, in the UK, occur infrequently, replacing 15-20 year-old technology that is, by then, obsolete, unreliable and often impossible to maintain. The procurement cycle seems to take a minimum of some 10 years for major systems, and may take considerably longer. COTS technologies in the IT area may have a half-life of 1.5-2 years. Clearly, this presents a major incompatibility, since it may take at least that time to derive a specification of requirements, using current practices. For this

reason, the UK Government has devised and adopted an alternative approach, called Smart Procurement [MOD WWW, 1998], and this is discussed in section 3.7.2.4, below.

Importantly, COTS-based software can be the main driver in the whole procurement process, and it is clear that the capabilities of COTS-driven software will have a great impact in determining the overall requirements.

3.7.2 COTS Procurement

The procurement of COTS-based systems for military applications can be seen as a set of activities involved in deciding what system should be purchased, choosing the right supplier or suppliers for that system, and signing a contract for the supply of the system. It is very important because an increasing number of computer-based military systems, such as C³I systems, are created by integrating components, which are bought from other suppliers.

3.7.2.1 Types of Systems

Bespoke systems are specially developed to meet a set of requirements, such as turnkey systems. Most control systems where the hardware is controlled by software components are bespoke with some COTS components included. Command and control systems are still largely bespoke, but with an increasing percentage of COTS components. On the other hand, 'COTS systems' are commercial products where the system specification is developed by the product developer. The vast majority of commercial information systems, where access to large amounts of information is needed, fall into this latter category, and many military applications in this area have moved, or are in the process of moving, towards COTS systems [Forsyth, 1998].

3.7.2.2 Policy and Guidance

The overall policy for dealing with the application of COTS should be reviewed, modified and changed, to achieve a better use of COTS components. This means understanding all the issues associated with COTS usage. In particular, we need to know how the acquisition profile could benefit from the opportunities offered by the commercial market, the relationship with the supplier needs to be reviewed,

appropriate use of standards must be made, and additional measures should be taken for maintenance.

3.7.2.3 Acquisition Regulations

What is needed is a procurement policy based on widely supported open standards that allow fast system delivery, with an increased chance of meeting the original requirements. While the system is in service, incremental development will take place to make sure that COTS functionality is delivered in a step-by-step fashion as requirements change. An overall improvement in the match with the operational requirements may be achieved, even if only 80% required functionality is obtained. This is clearly shown in Figure 3-9, which compares the area between an evolving requirement slope and functionality-achievement lines for incremental and 'Big Bang' development [Matthews, 1996].

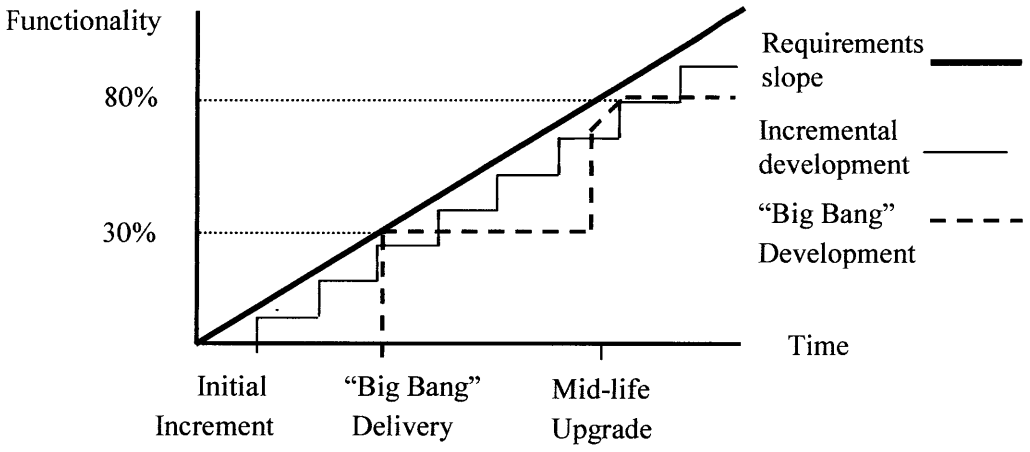


Figure 3-9 Requirements Match Comparison of Incremental and 'Big Bang' Developments

3.7.2.4 Smart Procurement

One of the first conclusions to emerge from the UK's Strategic Defence Review (SDR) [MOD WWW, 1998] was the need to introduce the best of modern commercial management techniques into the procurement of defence equipment. For this reason, the then Defence Secretary George Robertson announced the introduction of 'Smart Procurement' at the start of the current administration, seeking to exploit the conclusions that had emerged from the SDR.

The Smart Procurement picture emerges slowly. In some areas potential successes have been achieved. For example, as shown in Figure 3-10, the procurement cycle has been reduced by about one-third, by merging some of the approval stages. Where the previous cycle was, say, 21 years, reducing it to 14 years, or less, may be a major success from some perspectives, but it is still not sufficient to make good use of COTS. COTS in IT has a typical half-life of eighteen months to 2 years. Consequently, further refinement of Smart Procurement is needed to address this issue.

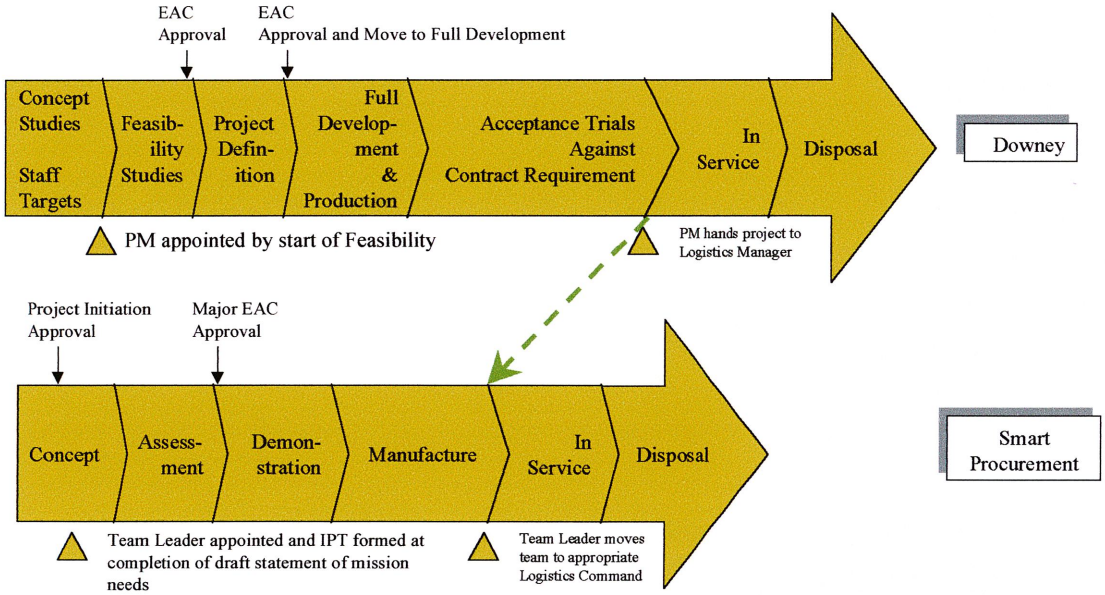


Figure 3-10 Comparing Downey and Smart Procurement

3.7.3 Commercial and Military Standards

Over the years, military standards have been used mainly with bespoke systems, in order to build a rugged system. All of that is changing, by increasing access to commercial state-of-the art technology to meet future needs. The US DoD currently has more than 35000 military standards and specifications. A recent review of military standards resulted in a large percentage of these being cancelled, modified, or replaced by commercial standards [Matthews, 1996]. The military demands for using commercial standards are increasing, so that computer system components from different vendors are able to communicate and exchange information. There are a large number of commercial standards. Therefore, it is important to use selection

methods for evaluating those standards against certain criteria, according to the context in which they will be used.

3.8 Summary and Resultant Research Direction

A number of potential deepening research areas can be identified from the survey presented in this chapter, which could improve the overall situation for the development and procurement of COTS-based C³I systems. For example:

- Requirements engineering using Enterprise Modelling techniques.
- Exploitation and assessment of commercial security mechanisms.
- Wrapper technology for dealing with legacy systems/components.
- Procurement risk modelling techniques.
- Procurement process modelling for incremental acquisition.

However, there appears a more fundamental need which is poorly served by existing research: namely, modelling the effect of COTS component selection on overall C³I system properties. Without such predictive capabilities, achievement of COTS component selection would be based upon, at best, past experience and experimental prototyping, or, at worst, upon parochial vendor-derived recommendations. Inevitably, this is a very difficult modelling goal, which is unlikely to be solved in the short term. Nevertheless, any progress made towards achieving this goal would be a significant contribution to this field.

Something of the inherent difficulty can be observed here, when the efforts undertaken by DERA Portsdown in support of the COEIA process for Naval C³I systems, as discussed in section 3.4.4, are considered [Young, 1998]. Their approach to assessing the effectiveness of a C³I system was based upon subjective measures of performance (MOPs), against arbitrary scales, to define values which were weighted together to achieve an overall figure of merit, using a Multiple Criteria Decision Analysis (MCDA) technique that could provide some understanding of the impact of the weights employed. This, consequently, was a black-box technique that took no account of the architecture of the system, or of the command process that would be employed, although there were hints of both in the measures that were adopted. The obvious concern of such a parametric black-box approach is that, having calibrated

the model using one or more existing systems, how confident could one be of the model's predictions for proposed new systems for which no actual performance data was known?

A more scientific approach to a COEIA would be to formulate a white-box model of a C³I system which includes, in a suitably abstracted form, influences of technology component performances, system architecture, and command and control process. In addition, the model should also include some representation of the humans who perform integral functions within a C³I system and who, consequently, can have a significant impact on overall system effectiveness. Finally, some overall measures of effectiveness (MOEs) for the (socio-technical) C³I system, such as those identified in Section 3.4.3, should be devised, using one or more defined operational scenarios.

Importantly, a major potential benefit of this scientific white-box modelling approach is to be able to experiment with the model, and to refine its properties in a way which extends the theoretical understanding of this C³I domain. Adjusting the weights of a parametric black-box model is unlikely to yield the same degree of theoretical insight.

As a result of the above considerations, it was concluded that the remainder of this PhD programme be targeted towards developing a COEIA white-box simulation model to carry out effectiveness measurements for a defined scenario within the naval C³I domain. The COEIA simulation would represent the white-box C³I models of two task forces (Blue and Red), fighting each other via a dynamic conflict model. The modelling experiment would be performed in two phases:

- Starting with Blue and Red identical, the dynamic model should result in equal effectiveness, Blue on Red and Red on Blue.
- Holding Red fixed, as a reference, vary any element in Blue (technology, e.g. radar; or human, e.g. behaviour; or process, e.g. decision mechanism), and compare the effectiveness of Blue and Red.

Of course, the feasibility of such an approach was predicated on the development of a suitable white-box model of a C³I system. Two major issues needed to be addressed:

- An architectural framework for the model, which accommodated interactions between the major C³I system components. An adaptation of the Layered Virtual

Machine (LVM), introduced in section 3.5.2.1, was proposed for this, representing technology, people and (command and control) process; cognisant of the fact that such LVMs could be composed (both co-operatively and conflicting) in a way exemplified by the ISO Open Systems Model of section 3.5.3.1.

- Semantics for the component layers of the model, to reveal their properties, capabilities and behaviours. The Generic Reference Model (GRM), of section 3.5.3.2, was selected for this role, recognising that this integration of the LVM and GRM would be a significant task. Moreover, incorporation of decision making processes, such as those defined in section 3.4.1.2, and other human behaviours, would also be needed.

Accordingly, the white-box modelling of COTS-based C³I systems, to support the COEIA process, was adopted as the primary focus for the deepening research of this PhD investigation. Further details of the theoretical underpinnings of this approach, outlined above, are presented in Appendix A, together with some details of the STELLA™ System Dynamics tool that was employed to construct the simulation (see section A.7).

The following three chapters in the main body of this thesis now present the results of the modelling work, progressing from the integration of the LVM and GRM to produce a white-box C³I system model, via the development of the dynamic COEIA white-box simulation model, to the experimental use of that simulation model to investigate the effects of COTS items on C³I system effectiveness.

Chapter 4: White Box Modelling of C³I Systems

4.1 Introduction

In the previous chapter it was concluded that this PhD investigation would focus on the white-box modelling of COTS-based C³I systems, to support the COEIA process. It was proposed that this work would be founded upon the idea of using a Layered Virtual Machine (LVM), more commonly found for structuring complex software systems, to provide a framework for modelling the interaction between technology, people and process within a C³I system. Within this framework, the Generic Reference Model (GRM), which is an established technique for representing a wide variety of systems, would be employed to model these three C³I component layers, in order to determine the emergent properties, capabilities and behaviours (PCBs) of the overall C³I system. This chapter presents the results of this modelling activity, which leads to the formulation of a novel Layered Generic Reference Model (LGRM) for representing a C³I system, and which will form the basis of a COEIA white-box simulation model to investigate the effect of COTS on overall C³I system effectiveness. Throughout the modelling work, a naval warfare scenario is assumed.

4.2 LVM for C³I Systems

Ultimately, there was a need to model the way in which technology influences the effectiveness of the overall (socio-technical) C³I system. By applying the principles of the LVM approach, described in Chapter 3, to a socio-technical information system, it was possible to postulate a three-layer model, as illustrated in Figure 4-1, comprising Technology, People and Process layers. Each layer depends on the services provided by the layer below, to provide expanded services to the layer above.

Within Figure 4-1, a technology layer creates a substrate on which people (or operators) act individually, and in groups or teams. Above the people layer is a process that the humans are carrying out. The process in our case is Command and Control (C²). For example, technology may sense some stimulus from the environment, and present information to the human. The human uses experience, knowledge and training to interpret the information. That interpretation is used to further the C² process at the top level that is being conducted by people organised into groups or teams.

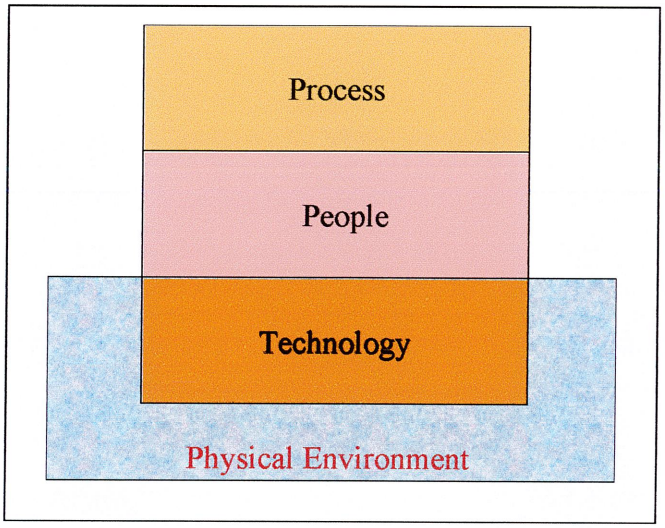


Figure 4-1 Layered Virtual Machine Model for C³I Systems

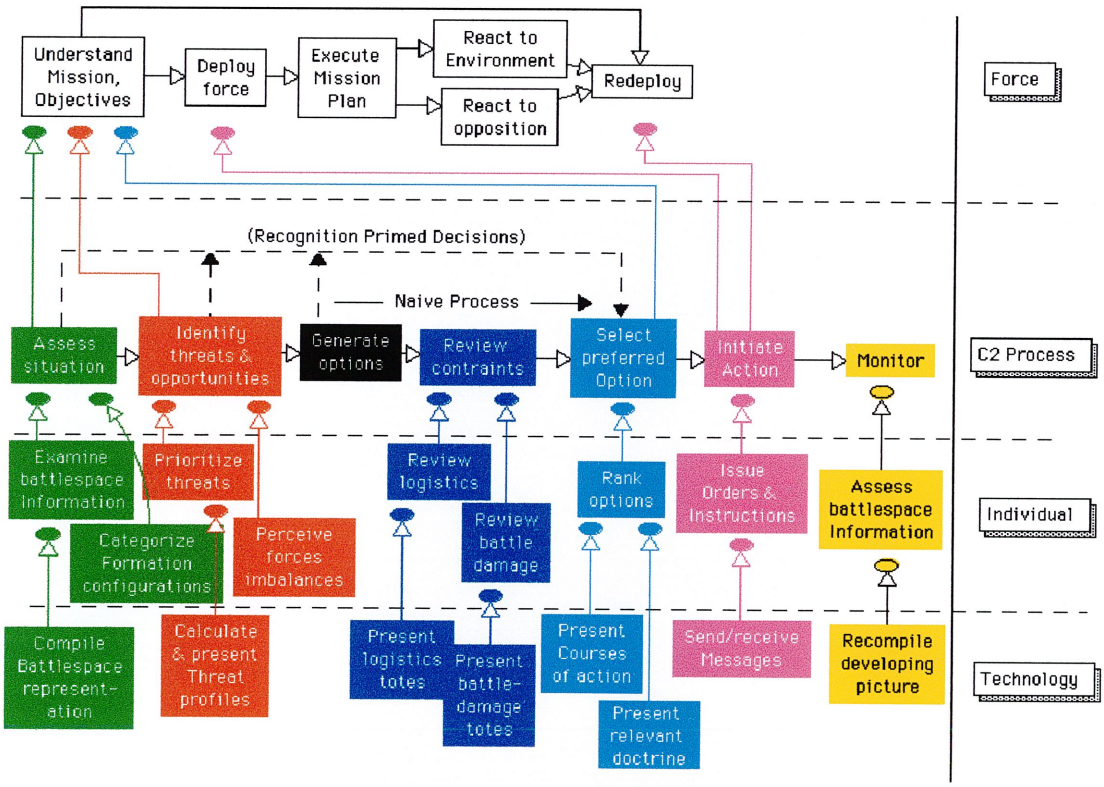


Figure 4-2 Virtual Model for a Naval C³I System

The development of the LVM approach started with an attempt to create a virtual C³I system model, based on the naval view of life and conflict, as shown in Figure 4-2. The model consists of four layers labelled Technology, Individual (People), C² Process, and Force. Each layer receives services from the layer below in a unidirectional flow. The model uses verbs to describe each layer as undertaking tasks (doing things). It does not present opportunities to reflect human behaviour.

Difficulties arose with the virtual model, as follows:

- Linking the C² Process layer and the Force layer, because the interaction between the C² process and the Force layer was going to be limited. At one level of abstraction, the C² Process simply senses what is occurring in the conflict, works out what to do next, and issues fresh orders.
- Unidirectional flow upward proved limiting, e.g. 'Initiate Action' in the Process layer had no connection to the Technology layer. Evidently some actions must involve ship technology, e.g. navigation, weapons deployment, etc.
- Proving completeness. It was difficult to envisage how completeness might be assured, e.g. 'Review Constraints' in the Process layer had, as inputs, Review Logistics and Review Battle Damage. It is not reasonable to assert that these are the only constraints. For instance, weather might be a constraint, or any number of things that could not readily be forecast
- The Individual (People) layer allocated tasks to individuals, but it was not apparent how the performance of such tasks could be represented without assuming 'perfect' humans. For example, could humans make mistakes, could their performance be less than 100%?

Solving the difficulty of tying the Force level of the virtual model to the C² level, led to composing three-layer LVMs, representing individual ship platforms, rather than establishing a new Force level in its own right. Figure 4-3 illustrates this point. In other words, creating two co-operating LVMs to represent a minimal Task Force resolved the Force level problem. The Platform C² Process layers possess inter-C²-Process interaction capabilities (true for real platforms). It also means that one cannot sensibly express the Effectiveness of a single Platform C² Process, but must consider the Effectiveness at the Task Force level, which seems correct.

It should be noted that Figures 4-2 and 4-3 suggest that the Force C² Process provides top-level operations to an external higher-level HQ function, in order to accept a mission, report on a mission, abort a mission, etc. This higher-level HQ function would not be represented within the LVM model for a C³I system.

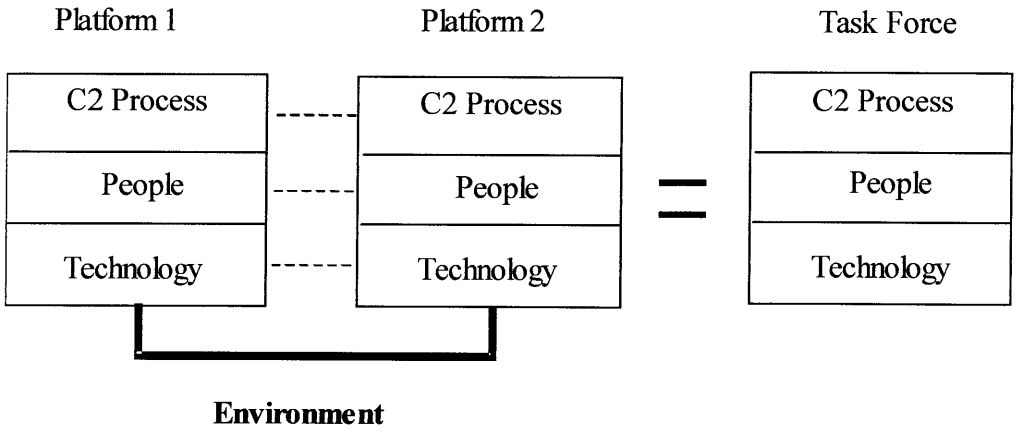


Figure 4-3 Composing Layered Virtual Machines

Figure 4-3 also indicates how two or more Layered Virtual Machines (LVMs) can interact. Physical connections and interactions occur upwards and downwards within LVMs, and logical connections form laterally. So, people in one LVM would logically connect with their counterparts in another, while their physical connection went downwards through the technology, through the physical connection and upwards through the other technology layer. Similarly, processes can interact logically as well as physically. One LVM process might, for instance, formulate a plan that is conveyed to another LVM for its process to execute that plan.

An alternative view of interacting LVMs is shown in Figure 4-4. Here, there is nothing intrinsically to suggest that the two LVMs are co-operating; they could equally be in conflict. In either event, they form an interacting relationship. However, it is not reasonable to employ the interacting LVMs, as they stand, to determine either effectiveness or emergence, since the LVMs are not full systems; they are frameworks. It was, therefore, realised that the three layers of the LVM have to be populated in such a way that it could represent a complete system and could also evince human behaviour, where relevant. Otherwise, it would never be clear if the

C³I model were finished; a not uncommon situation in some approaches to modelling. This would be the role of the Generic Reference Model (GRM), as suggested in Chapter 3.

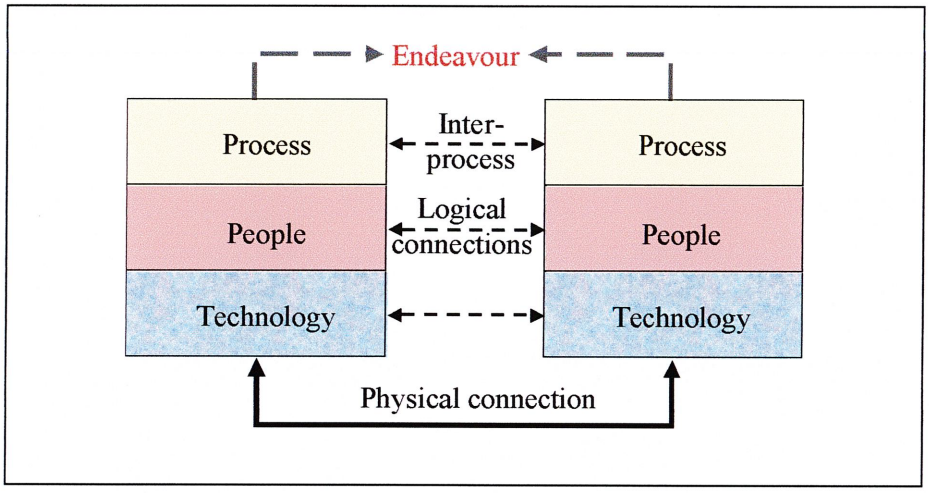


Figure 4-4 Interacting LVMs for C³I Systems

Overall, the two interacting LVMs provide:

- Information flow and handling mechanisms upwards and downwards.
- Logical connections horizontally between corresponding layers.
- Conceptual representation of co-operation and/or competition in the conduct of some endeavour.
- Conceptually, the ability to go beyond information interchange. There is nothing, in principle, to prevent physical interchange between LVMs.

4.3 C³I Boundaries

It was necessary to consider the boundaries of a C³I system, and the functionality offered by it, before any mapping of the GRM on to the LVM could take place. Some references identify naval C³I as a "Command System embedded within a Combat System" [Shellard, 1985]. Others view C³I as "the management infrastructure for defence and war" [White, 1989]. There is no hard and fast rule about where the C³I system starts and ends. By analogy with the body, the human eye may be considered as a part of the brain, or not. Anatomically, eyes are within the same enclosure that covers the brain. So sensors could be, reasonably, part of the C³I. Similarly, the central nervous system includes motor and sensor nerves, allowing us to react and

strike in one movement. One could reasonably include weapons in the C³I boundary forming a so-called 'Battle System'. This was the assumption made. Consequently, sensors and weapons were considered as part of the technology layer of the LVM.

Having defined the conceptual C³I boundary, the following sections will:

- Identify which of the three GRM models (Form, Function, and Behaviour) is most applicable to each LVM layer, taking into consideration their sub-headings.
- Combine the LVM and GRM into a Layered GRM (LGRM).

4.4 Integrating LVM and GRM

The previous section has demonstrated that a LVM, comprising technology, people and C² process layers, is a useful framework for representing a C³I system. This approach shows the various parts of the C³I system in their respective layers, while the interconnections between those parts establish the basis for a systems architecture. The next step in the research was to model the individual layers, using the GRM.

One potential way to use the GRM was to identify, within each layer, 'systems' of interest, and to use the GRM to model each of these. Figure 4-2 provides a starting point for this. To identify a system, we may simply describe a C³I feature as 'a system for compiling a picture'; 'a system for processing data'; 'a system for assessing a situation'; and so on. These systems may mutually interact at any level. They may exchange information. They may interact via their mutual environment. They may absorb resources, and emit 'waste', where waste in some cases may be a desired physical outflow. They may execute a plan to seek their own resources. They may reconfigure themselves, and they may translate or move. Each GRM must satisfy the definition of 'system': an open set of complementary, interacting parts with properties, capabilities, and behaviours emerging both from the parts and from their interaction. Properties are stable features of the system such as mass and capacity, while capabilities represent limits to system functional abilities, such as maximum speed, range, and lethality. Behaviours are system responses to stimulus, such as a strategy to accomplish a mission.

This approach was considered, at the outset, to be too complex. If each of the squares of Figure 4-2 were represented by an individual GRM, and the various GRMs were mutually interacting, then the whole would be large, with many potential states.

A much simpler way of employing the GRM, within the LVM architecture, was to consider each layer, of Figure 4-1, as a single GRM that may operate upon a substrate provided by another GRM. This would reduce the complexity of the resulting model, and was the initial approach that was explored. Each layer was viewed as a system in its own right, so there would be a technology system, a people system and a process system. The three GRMs, one per layer, would then be connected upwards from technology, to people, to process. Although this approach sounds sensible, when it was investigated, not all the LVM layers needed all GRM components; for example, the Technology layer did not need the Behaviour model of the GRM. In short, the mapping did not work comfortably.

An alternative, more abstract, way of employing the GRM within the LVM architecture, was to consider the three layers of Figure 4-1 as one system represented by a single GRM. This reduces the complexity of the resulting model, and was the final approach that was adopted, given the inherent difficulty of this C³I modelling task. Thus, the modelling plan was characterised by the following major activities:

- Identify compatibility and incompatibility between the LVM and GRM.
- Resolve any incompatibility.
- Determine the final C³I system modelling configuration.

4.4.1 Compatibility between LVM and GRM

The first step was to investigate which of the three GRM models (Form, Function, and Behaviour) is most applicable to each layer, taking into consideration that, at least, the first or the second model should exist in each layer. This was achieved by considering which of the three LVM layers provides a sensible 'home' to the three GRM models. The GRM comprises, at the first level, Form, Behaviour and Function, all overlapping after the style of a Venn diagram, to emphasise that the elements are not separate (see Appendix A for further details).

The Form model intended to address more than technology; for example, cohesion applies to gregarious people as well as to pieces of technology. If, in mapping Form to the Technology layer, parts of the Form model were left over, with no home, then the missing elements would need to be incorporated elsewhere in the overall mapping process. The LVM Technology layer offered no sensible home for Behaviour. The LVM People layer offered a home for Behaviour, but was less than ideal for Function and Form. Even then, Behaviour did not entirely correspond to a layer title of 'People'. In the mapping process, it became apparent that it was not individual people that mattered so much, as their behaviour. If this could be represented, it would show how they responded to/interpreted information from the technology and how they went about making decisions in the C² process based on those interpretations. The Process layer corresponded well, but only to the Mission Management portion of Function, leaving the other two parts, Viability Management and Resource Management, without specific homes in the LVM framework. Viability, involving as it does synergy, maintenance, evolution, homeostasis and survival, clearly affected many aspects at all levels.

- Synergy would have to be built into the mapping by associating items using arrows to show co-operative interactions.
- Maintenance was taken to apply to all levels, obviously with respect to technology, but also for humans and process.
- Homeostasis would need to come about by the development of causal loops during the mapping process.
- Evolution was excluded from the simple mapping, but would appear later in the dynamic simulation modelling (Chapter 6).
- Survival would also be addressed in the dynamic simulation model.

4.4.2 Resolving Incompatibility

The second step was to overcome the difficulties in integrating the LVM and the GRM, which then led to the Layered Generic Reference Model (LGRM), illustrated in Figure 4-5. This was achieved by identifying the interactions between the different parts of the three GRM models with their parts in each layer, as follows:

1. Cohesion amongst people, excluded by the one-to-one 'pouring' of the Form model into the Technology layer, was identified, instead, in the inter-relationships between the elements of process, which were represented. In effect, the arrows in the model that showed the passage of information also showed coherence, *and* synergy. Similarly, the arrows connecting the process elements in Resource Management imply synergy, interrelationship and cohesion.

2. Resource Management and Viability Management were seen as more properly applying to all three layers of the LVM. Technology is a resource, people are a resource, and the C² process is a resource. Resource Management and Viability Management were, therefore, mapped as an 'envelope', surrounding all three layers of the LVM, rather than occupying any one layer.

3. Within the centre layer, People and Behaviour, it proved useful to characterise the elements of Behaviour as Influences on Behaviour and Behaviour Management. This was useful because it allowed Behaviour Management, which had elements of sequence, to connect comfortably upwards to C² process, while Behaviour Influence reflected more comfortably downwards into technology and external influences such as weather. In this way, it was possible to couple the 'stovepipes' in the Technology layer to the sequences in the Process layer.

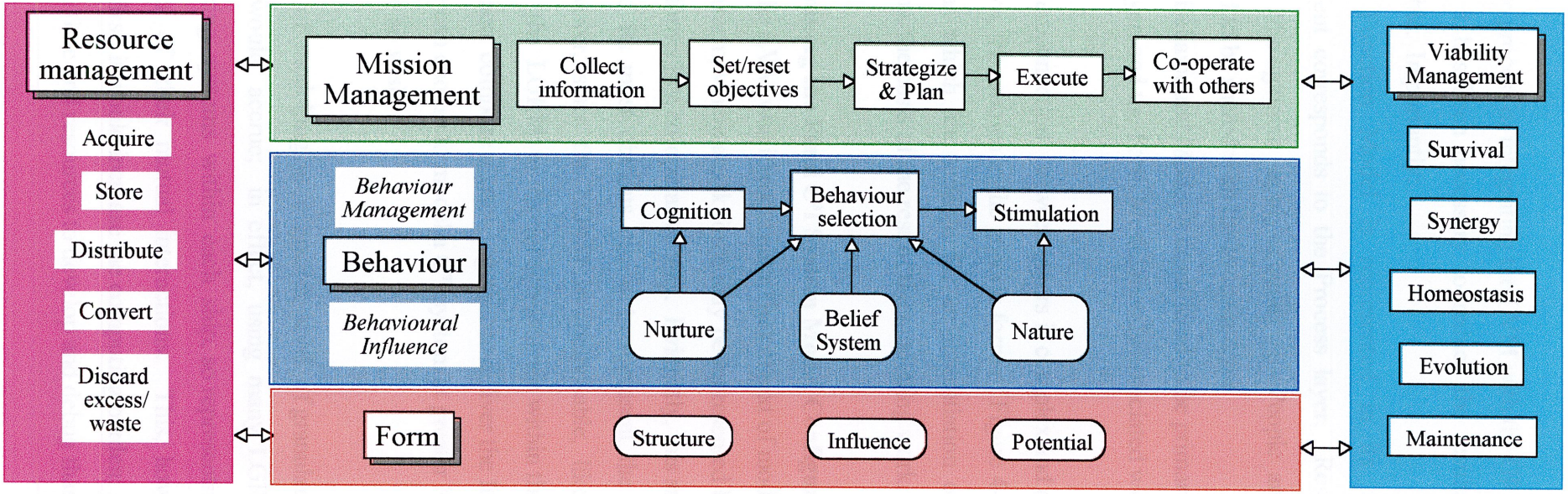


Figure 4-5 Layered Generic Reference Model (LGRM)

Accordingly, a decision was made to represent each ship platform with only one LGRM. This must result in a more coarse approximation. A significant issue is that of representing all the people on the ship in one LGRM. This would be reasonable only if all were of the same culture, held the same beliefs, operated within the same ethical and moral framework, had received the same training, and operated within the same disciplined rules of behaviour. Similarly, one LGRM incorporates doctrine, ethics and morals as applying to every one. This seems to be reasonable, to a first-order approximation, because the simulated time of any simulation run is intended to be a few hours at most, during which ethics and morals are unlikely to change for an individual or a team. It is, therefore, a necessary assumption of the simulation model that these conditions apply. This is the approach that will be adopted in the following chapter.

The final modelling decision that had to be made concerned the way in which the COEIA white-box simulation model would be configured, to support C³I effectiveness studies. It has already been indicated, in Chapter 3, that this would comprise two forces, Red and Blue, engaged in a dynamic conflict scenario. Evidently, it would be possible to have Red and Blue forces comprising several ships, each with their own LGRM. Again, because of project constraints, it was decided to employ the simplest arrangement possible, that of Red and Blue forces each comprising a single ship. These two LGRMs would then be inter-connected, as discussed in section 4.2, to create a combat configuration.

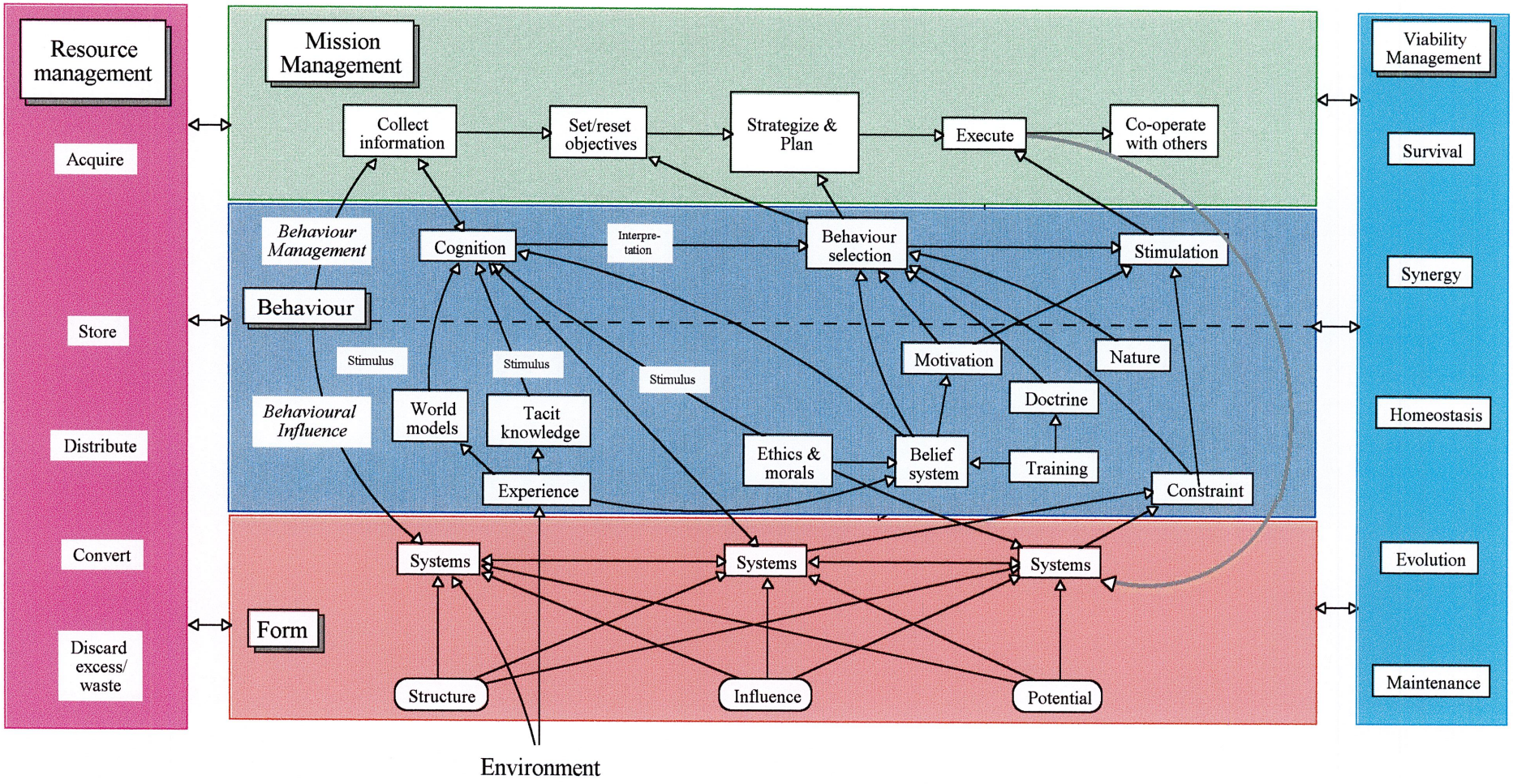


Figure 4-6 LGRM with Connections between Layers for a C³I System

4.4.4 Applying Checkland's Formal Systems Model

At this point it was possible to recreate the conceptual model of Figure 4-4, but now using two interacting LGRMs, designated Red and Blue, in place of the two LVMs. Since any GRM represented the internal view only of a system, it was apparent that each LGRM also represented only an internal view. The question arose: does connecting two LGRMs as an interacting pair constitute a complete system? To address this issue, Checkland's Formal System Model[1] rules [Checkland, 1989] were applied to one LGRM when it was interacting with another LGRM. The results are presented in Table 4-1, below.

FSM Statement	Layered GRM
S must have some mission	Mission Management in the top layer.
S must have a decision making process	Strategize & Plan in Mission Management.
S must have components that interact with each other such that the effects and actions are transmitted through the system	The interactions are shown by the arrows connecting the layers.
S must be part of a wider system with which it interacts	This needs Blue and Red interacting as shown in Figure 4-4 but with LGRMs.
S must be bounded from the wider system, based on the area where its decision making process has power to enforce an action	Same as above condition.
S must have resources at the disposal of its decision making process	Resource Management on the left hand side of Figure 4-5.
S must either have long term stability, or the ability to recover in the event of a disturbance	Viability Management on the right hand side of Figure 4-5.
Components of S must be systems having all the properties of S (subsystem)	Form Model in the bottom layer.

Table 4-1 Early-stage Testing of the LGRM as a System

[1] For completeness, this is described in Appendix A.

From the analysis it was concluded that:

- An isolated LGRM is an open system, with inputs and outputs that would enable its operation. Only with such inflows and outflows can a system interact with the environment, exhibit effectiveness, behaviour and emergence.
- Only with interacting LGRMs can either, or both, constitute complete systems.
- Therefore, the minimum COEIA white-box simulation model for C³I effectiveness studies, comprising two interacting LGRMs, is a formal system model in Checkland's terms.

4.5 Summary of LGRM Properties and Proposed Use

The LGRM:

- Represents the internals of any system in a dynamic, layered form.
- Provides mechanisms to maintain its own viability, and to distribute and utilise internal resources.
- Can be used to illustrate the many interactions between parts within a system.

Causing two LGRMS to interact causally, however, enables each of them to represent a complete system, since each provides the 'wider system' context for the other, essentially by providing inflows and outflows. If the two LGRMs are identical, then each still provides the wider context for the other, but without the need to represent different systems. With two identical interacting LGRMs, each representing the same C³I system, one LGRM can act as a dynamic reference model for the other. This is the approach that will be adopted in following chapters, where two identical interacting LGRMs, for Red and Blue ships, each representing a naval C³I system including weapons and sensors, will be set to engage each other in combat. As will be shown, the resultant COEIA white-box simulation model can demonstrate:

- The effectiveness of either Red or Blue, using a variety of MOEs.
- Differential measures such as Casualty Exchange Ratios and Cost Exchange Ratios.
- The likely results from investments, in support of COEIA.

Chapter 5: Simulation Model Development

5.1 Introduction

In Chapter 4, the Layered Generic Reference Model (LGRM) was introduced as a novel white-box model of a C^3I system, which represents the influences of technology, people and process on the overall properties, capabilities and behaviours (PCBs) of a C^3I system. Chapter 4 also suggested that two LGRMs would form the basis of a COEIA white-box simulation model, which would be used to investigate the effectiveness of C^3I systems. The principle was that each LGRM would represent the C^3I system of a single ship platform (Red and Blue), and that these would compete in a defined naval scenario, to determine the relative effectiveness of the two systems. The purpose of this Chapter (5), is to convey how this COEIA white-box simulation model concept was eventually translated into a dynamic (executable) simulation model, produced using the System Dynamics STELLA™ tool. In addition, it also addresses the Verification and Validation (V&V) measures that were applied to gain confidence in the results from this dynamic simulation model, so that it could be employed in the model prediction and sensitivity analysis experiments covered in Chapter 6.

The development of the simulation model proceeded in the following fashion. First, the modelling objectives and the test scenarios were defined. Secondly, the LGRM was instantiated to produce a static model. This involved deciding what features of a naval shipborne C^3I system would be represented. Thirdly, this static model was then used to guide the development of the full dynamic simulation model, using STELLA™. Finally, this dynamic model was then subjected to V&V. The following sections of this Chapter describe the results of these activities. Necessarily, the descriptions of the simulation model development and V&V are presented in outline form, but further details of these can be found in Appendices B and C, respectively.

5.2 Modelling Objectives

The immediate purpose of the simulation was to evaluate the likely impact of introducing COTS on Command and Control (C^2) effectiveness. The preferred situation was naval defence, and a reasonable choice, therefore, was to simulate a naval engagement that would stress C^2 sufficiently to present a worthwhile evaluation.

5.3 Mission Types and Test Scenario

5.3.1 Mission Types

Mission types, or scenarios, are an important element of our modelling approach because of their influence on the measures assigned to assess the impact of COTS on C^3I system effectiveness. Other studies [Robson, 1998] have employed the following set of mission types:

a) Operation against enemy forces;
b) Protection of maritime trade;
c) Nuclear deterrence;
d) Combat operation against land;
e) Naval force in support of diplomacy;
f) Fishing protection;
g) Drug interdiction;
h) Oil and gas field patrols;
i) Maritime counter-terrorism;
j) Disaster relief;
k) Search and rescue;
l) Salvage;
m) Ordnance disposal;
n) Pollution control;
o) Hydrographic surveying; and
p) Peace keeping

5.3.2 Test Scenario

A simple scenario was used to represent an engagement between two ships, Blue and Red. This is sufficient to establish 'proof of principle', which is the objective in the first instance. The two ships are set up some 100nm apart and closing. Rules of Engagement are initially set to Engage. Both ships are identical, and both have identical weapon systems with missiles, Electronic Support Measures (ESM), jammers, radar, C^2 displays, etc. They also have battle damage repair teams and on-board maintenance facilities.

With the two ships mutually engaged in a specific scenario it is possible to observe and evaluate the C^3I effectiveness of either ship. If Red Ship is used as a reference,

Blue Ship effectiveness over time will be affected by the ability to sustain damage, repair damage, maintain equipment and, of course, maintain effective decision-making. Logistic re-supply will impact effectiveness where there is ability, or inability, to maintain the technologies as time passes, and as failures and damage accrue.

Ideally, identical ships in identical situations would be expected to exhibit identical C³I effectiveness. In the real world, chance would take a part, as one ship inflicted serious damage on the other, first. The notion of identical C³I effectiveness is valuable, however. If Red Ship, say, is maintained as a standard, or reference, then Blue Ship may be changed with respect to that reference. Any consequent change in effectiveness will be attributable to the change, allowing some sensible measure of effectiveness.

Red Ship would act as a control, or reference, but one which is, nonetheless, changing dynamically as it interacts with Blue Ship. In principle, it would be possible to make identical changes to both ships, and see what effects accrue. Since many of the most useful measures of effectiveness are exchange ratios, this possibility turns out to be impractical since, with mirror image ships, the exchange ratio is always 50:50. In practice, therefore, it is more useful to hold one ship constant while varying the other.

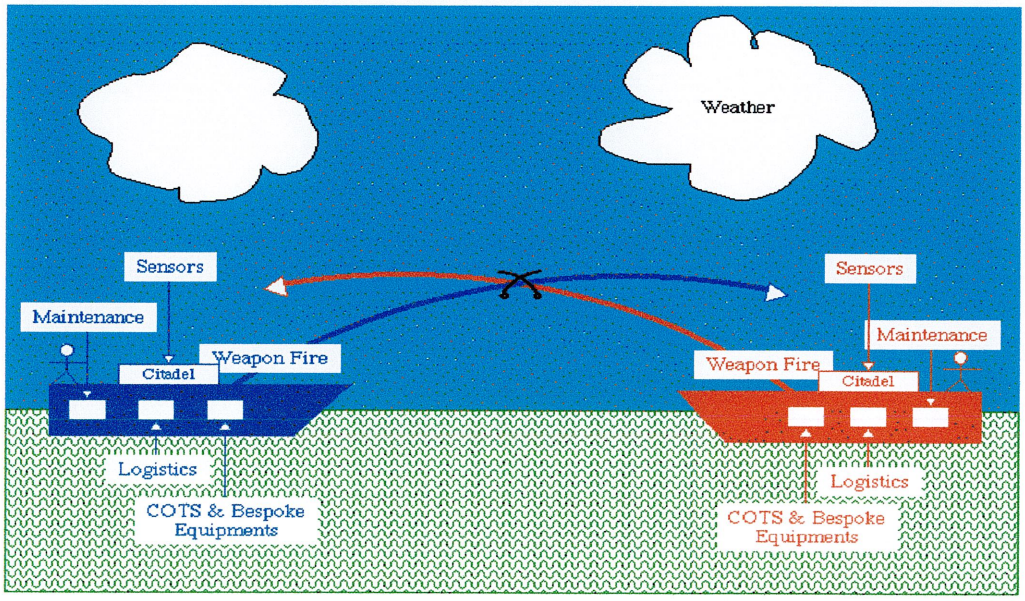


Figure 5-1 Rich Picture

As a minimum configuration, then, the whole model must incorporate two ships, interacting vigorously (within a scenario) in a representative environment, including weather, weapon attack, etc, so as to flex the components of C³I effectiveness. From a scientific experimental viewpoint, then, one ship may act as a dynamic reference for another. The implementation of the two ships and their environments in STELLA™ provides the complete model. The scenario, therefore, consists of two task forces (Blue and Red) each represented by one platform as shown in the 'Rich Picture' representation of Figure 5-1, fighting each other in a dynamic conflict model.

5.4 Building the Model

5.4.1 Static Model Structure

The first step in the model construction process was to develop a model that is a simple representation of the LGRM created in Chapter 4. Only the most significant elements of the C³I system were taken into account and represented as layers in the model. Since the objective of the simulation was to establish proof of principle, it was both unnecessary and unwise to introduce too much detail. While the simulation was intended to represent conflict between two ships, neither ship need be represented in terms of the sort of physical structure as shown in Figure 5-2. Instead, items in each ship were grouped into the three layers of Technology, People, and C² Process.

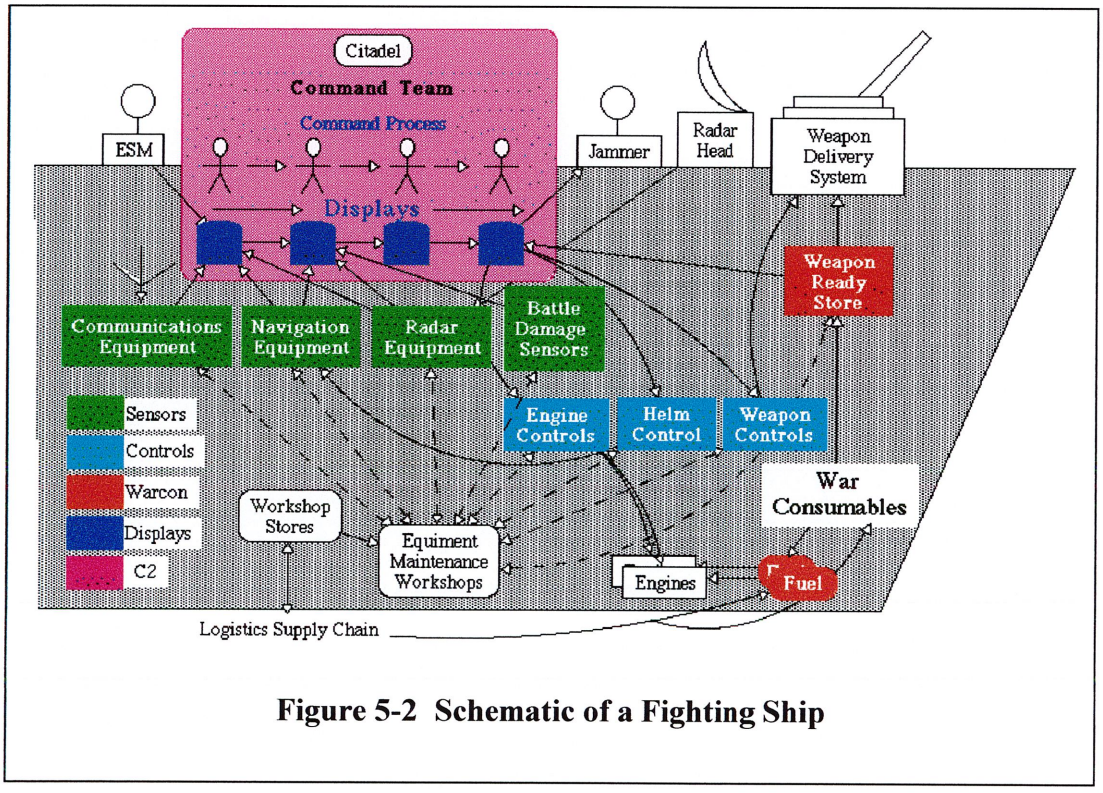


Figure 5-2 Schematic of a Fighting Ship

Many of the elements that might be represented by one LGRM are visible in Figure 5-3. Elements of Technology, People and C² Process are all in evidence. However, scale and granularity have to be established before any conformal mapping can take place.

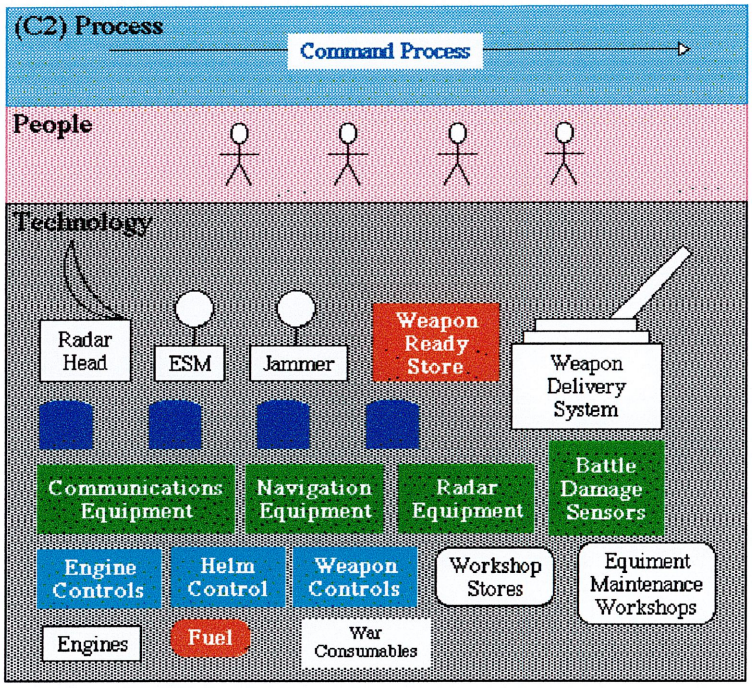


Figure 5-3 Ship Schematic in Layers

A typical applied LGRM within the naval C³I domain is shown in Figure 5-4, which is based on the LGRM of Figure 4-6. In creating this instantiation, changes took place in the Technology layer and the C² Process layer, leaving the middle People layer with no changes necessary. In the Technology layer, particular equipments have been added, reflecting a naval shipborne C³I system. In the C² Process layer, two types of decision process (which have already have described in section 3.4.1.2 of Chapter 3) have been used: Naïve Decisions and the Recognition-Primed Decisions.

When instantiated in this way, it was then possible to include many of the internal connections within the LGRM, as shown in Figure 5-4. Finally, it should be noted that the full static model comprises two such LGRMs: one for Blue Ship, the other for Red Ship, interconnected.

In summary, the instantiated LGRM for a naval shipborne C^3I system has the following main characteristics:

- The Form layer contains the technology as a number of 'stovepipe' equipments: sensors, processors, displays, weapons, ship's controls, etc.
- The Behaviour layer shows the GRM Behaviour Management model rearranged into a sequential process at the top of the layer, with a variety of inputs at the bottom of the layer. This arrangement facilitates joining downwards to Form, and upwards to Mission Management. Note the presence of Experience, connected to the outside world, and Doctrine. This enables the crew to learn, and to change their behaviour, within doctrinal rules, according to how much damage the ship was suffering, for example.
- The Mission Management layer shows a generic C^2 decision-making process, with a difference. The conventional C^2 Process is shown: assess situation; identify threats & opportunities; generate all options; review all constraints; select preferred option; initiate action; and monitor. In addition, Klein's Recognition Primed Decision-Making (RPD) is included, too [Klein, 1989]. Conventional decision-making is thorough, but can be slow. RPD is experience-based and very fast. RPD is the mode employed by an expert under time pressure. In the model, when the time available for decision-making is small, Mission Management switches from conventional to Recognition-Primed decision-making.

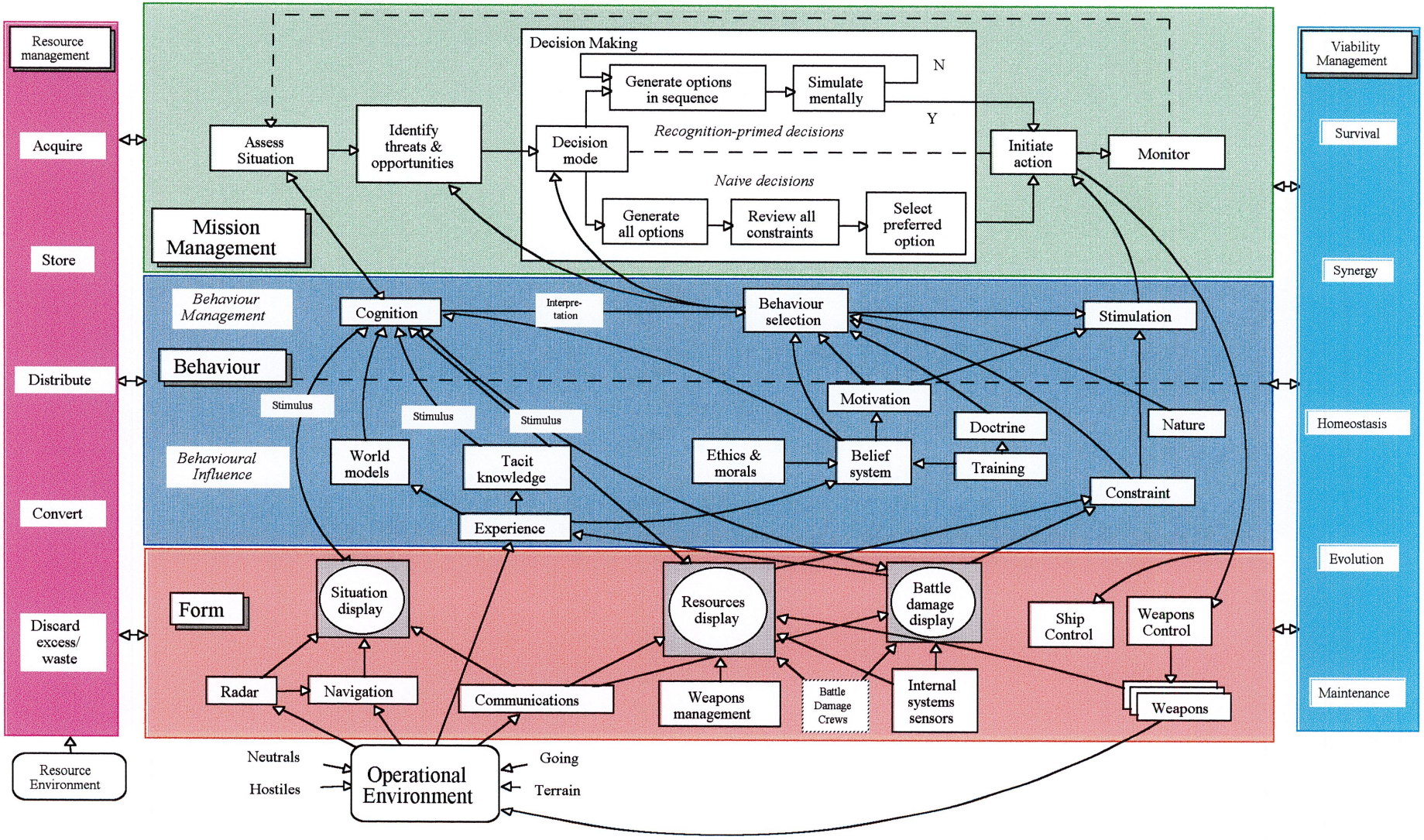


Figure 5-4 Typical LGRM Instantiation for a Naval Shipborne C³I System

Notes that the figure represents only one ship. A full model contains a second, identical LGRM and the mutual interconnections to enable relative navigation, sensor operation, sensor jamming, target detection, weapons firing, damage infliction, etc.

5.4.2 Model Complexity

To represent the introduction of COTS, and to determine what effect that might have on C^3I effectiveness, the simulation must be able to represent individual components that could be either COTS or Bespoke systems (hereafter, referred to simply as Bespoke). Further, it must be able to represent the mutual interactions of such components, since these contribute to the emergent effectiveness.

People and processes must be represented in sufficient detail to explore the potential of people or process variation, either to moderate, or be moderated by, the effects of technology variation. On the other hand, the characterisation of people is particularly controversial. The model complexity must, therefore, be such as to minimise the effects of incorrect or inadequate 'people' characterisation.

Cost effectiveness and exchange ratios are to be measures in the model. A comprehensive cost model must, therefore, be created. This must identify the difference in overall costs between two ships; one being all Bespoke while the second commences as all Bespoke after which one item of technology is replaced with a COTS alternative. The cost model must accurately reflect not only the different capital costs, but also the different spares maintenance and logistic support costs of these two ships.

5.4.3 The Dynamic Model

The dynamic model was developed in STELLA™ with a one-for-one correlation to the LGRM of Figure 5-4, as far as practicable, and the following descriptions should be read in conjunction with that Figure. Full details of the model development are given in Appendix B.

Each layer of the LGRM was developed in sequence, as follows:

(i) **Technology Layer.** First, the Technology layer was developed, together with an external environment. That included weather that was able to affect received radio and radar signal strengths. A Lorenz Weather Source [Gleick, 1988] was taken from a separate simulation that used Edward Lorenz's original equations, those which were amongst the first indicators of the emerging science of Chaos/Non-Linear Dynamics. The same weather is applied to Blue and Red forces indicating that, while weather affects performance, it is not a Red/Blue differentiator in the model. A simple scenario was represented, with two ships engaging each other, starting at 100 nautical miles separation on a reciprocal course and closing. Only one of the ships was modelled in the first instance. Transmitted signals were received in turn by the same ship, presuming inverse 4^{th} power attenuation. The ESM system received signals similarly, experiencing inverse square law attenuation. Jamming power also fell off according to the inverse square law, and was treated as additional noise to reduce the signal-to-noise ratio.

Situation, Battle Damage and Resources displays, weapons, communications (internal and external), internal system sensors, and controls for firing, and for navigating, were added to the sensors at the technology level.

Both COTS and Bespoke versions of the radar, jammer, ESM, weapon and displays, together with their respective maintenance systems, spares and costs, were included, together with controls to select any, or all, to be either COTS or Bespoke.

(ii) **People Layer.** The People layer was developed in connection with the other two layers, so that it can send, receive, or view different kinds of information from the technology layer, and to enable the C^2 process. Cognition, Behaviour Selection, and Stimulation were represented simply in Behaviour Management.

The LGRM requires the representation of several 'soft' factors in the Behaviour/People layer. Precise values for such soft factors as Belief and Training, Experience, Stimulation, and Cognition are not known. In the model, those for Cognition and Stimulation are represented as graphical input functions, which represent the general 'shape' of the parameter, and are illustrated in Graphs 5-1 and 5-2, below.

Experience, for example, impacts on Cognition. In the scenario, Experience is gained as the ship is struck by enemy fire. Clearly, the first hit is the most significant, in terms of concentrating attention and focusing cognition. Subsequent hits will have a reducing effect in general line with Fechner's Law [de Neufville, 1974]:

$$U = K \log S \qquad [5.1]$$

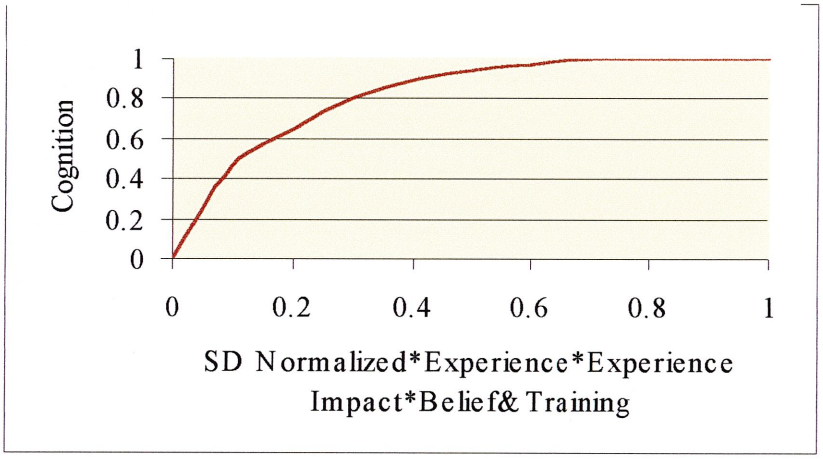
where U is utility function
K is a constant
S is the intensity of stimulus

The value for K is not known. Whether the curve is logarithmic is not known, either, in our situation. The general shape of the curve, in Graph 5-1, is reasonable, however, in view of Fechner's Law.

In STELLA™, the curve shapes are malleable. Such curves are used as test and sensitivity inputs. If varying the curve shape makes little difference, the model is not sensitive to small changes in the parameter. If the model is sensitive to small changes, further research would be necessary to establish a better understanding. Both Red and Blue Ships have identical graphical input settings, which also tends to balance out the effect of imprecise curves.

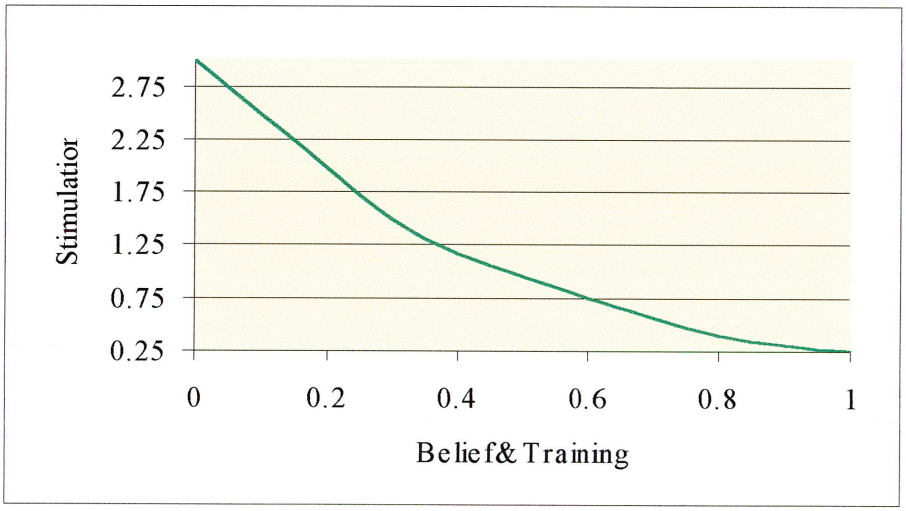
Cognition is not just dependent on Experience. It is dependent on there being sufficient information to assess, and sufficient training and experience to recognise, the meaning or interpretation which should be put upon that information as shown in Graph 5-1. In this instance, then, the Situation Display presents information, Experience is used to interpret the data, scaled by Experience Impact, and Belief and Training assist in interpretation. Experience Impact could be used to feed in the effects of successive runs, to represent the effects of 'situational learning'.

Graph 5-1 Cognition Dependency Chart



Stimulation relates training to response time. Within the LGRM, Stimulation is the degree and/or 'urgency' with which Behaviour impacts Function and Form. Graph 5-2 shows Stimulation as a function of Belief and Training. This is based on the fact that well trained operators take shorter times to react, while on the other hand a less trained operator can take a long time to react.

Graph 5-2 The Effect of Belief & Training on Stimulation



Constraint was represented as the number of crew, spares, and weapon rounds available. Behaviour Influence included Experience, potentially enabling the operators to modify their behaviour, and Training, to represent their level of competence:

- Experience reflects the ability to learn and adapt behaviour accordingly. In this instance, experience is gained through being hit by the enemy. The more Blue is hit, the greater the level of recorded experience. In the model, the C^2 team starts with 50% experience level and a maximum value of one by learning from experience. Experience has two major impacts. First, it improves cognition; being hit enhances awareness. Secondly, it affects rate of closure with the enemy, to the point that Blue will withdraw if hit too many times.
- Belief & training are central to C^2 performance. Belief maintains the C^2 team as a cohesive, focused group while Training enhances the efficiency and discipline of that group which is vital for continued operation under adverse conditions.

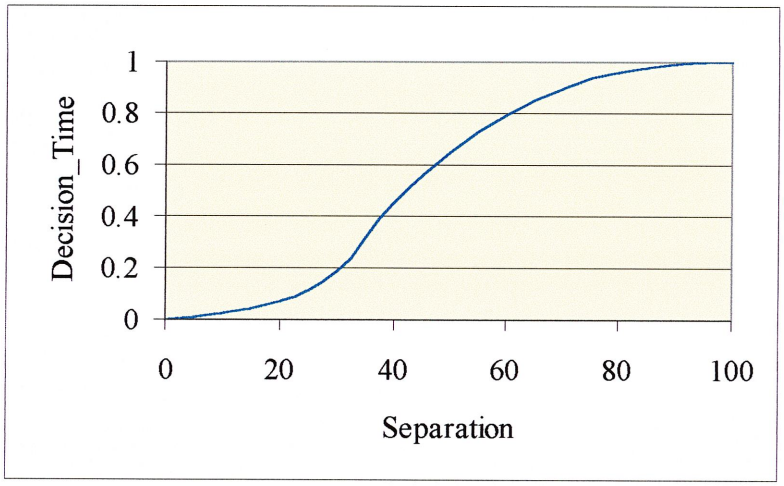
Rules of Engagement, and Crews were added to Behaviour at the People layer. Doctrine was incorporated in the Rules of Engagement. They can be set to engage, hold, or disengage.

(iii) **C^2 Process Layer.** The Process layer was developed separately, with two archetypal decision methods being represented in it. One decision mode, Naïve, followed the classic approach of sequential C^2 processes: Assess Situation, Identify Threats and Opportunities, Generate Options, Review Constraints, Select Preferred Option, Action and Monitor. The second decision mode, Klein's Recognition Primed Decision making (RPD) [Klein, 1989], invokes a much faster decision: Assess Situation, Select Preferred Action, Action and Monitor.

The normal decision mode was Naïve. When the two ships drew close, time became too limited for Naïve decisions, and the Process layer switched to RPD.

The switching mechanism was chosen so that, if a commander is short of time, he or she goes to RPD. Graph 5-3 explains the graphical function of the decision time in the model. Shape was chosen principally for ease of experimentation, and held constant on both ships. As the separation between Red & Blue forces reduces, the time to make useful decisions also decreases. At some point, essentially set by this graph and Decision Mode, the amount of time will be so little as to encourage commanders to revert to RPD, otherwise known as naturalistic decision making. It is experienced-based, fast and effective when the decision-maker is an expert under time pressure [Klein, 1989].

Graph 5-3 Decision Time as an S-Curve



The C^2 Process layer also received intelligence about the enemy through the ship's ESM system. The simulation assumes that Intelligence is derived from the ESM receiver when the ESM Signal to Noise Ratio (SNR) rises above a sensitivity threshold, and the ship is separated by more than the primary radar range. Intelligence from ESM is passed to Situation Assessment.

(iv) **Joining the Layers**. The three layers were then interconnected using the original LGRM of Figure 5-4, as a guide. Situation Display was connected downwards to sensors, which sense the outside environment, and upwards to Cognition. A connection was then made from Cognition to Assess Situation.

Resources display and Battle Damage display were connected to Constraint. Constraint was connected to Decision Mode via Behaviour Selection, and to Initiate Action via Stimulation.

Finally, to close the loop, Initiate Action in the top layer was connected to Weapon Control and Ship Control in the Technology layer to connect these layers in a downward sense, with process orders and instructions feeding into technology for weapons firing, ship controls and damage repair.

The unilateral model was then tested by connecting its outputs, suitably modified and attenuated, to its inputs. In this way, received information is passed to a display, where an operator interprets what he or she sees, before employing that interpretation in the C^2 process. This example shows how the layers are joined in an upward sense; technology, to people, to process. The LGRM single ship model was then duplicated, to represent a second ship. Cross-connections were finally made between Blue Ship and Red Ship outputs and inputs, to complete the basic, cross-connected model.

(v) **Cost Calculations**. Three major system categories carry costs; personnel, equipment, and facilities. Two types of equipment are used, Bespoke and COTS. For COTS, it is considered that both primary equipment and spares are less expensive than for Bespoke. In addition, faulty COTS equipment is replaced with a spare one and the faulty items discarded. Bespoke equipment is considered expensive by comparison with COTS and, in consequence, repairs are executed by module replacement. Defective modules are then repaired, if possible, while the restored equipment is returned ready for reuse. (Bespoke Line Replaceable Unit (LRU) Stock).

For Bespoke equipment, a more extensive suite of test facilities is, therefore, necessary, and technicians have to be trained to a higher level - both invoking extra costs. It is also presumed that both COTS and Bespoke equipment have no differences in performance for the short period of the engagement. However, it is possible to represent the effects of progressive performance improvements over time. This was appropriate to represent periodic upgrades to COTS, or

mid-term upgrades to Bespoke equipment. Accordingly, a cost model was developed so that capital, operating and maintenance costs could be calculated 'on the fly' as the ships closed and engaged.

A top-level view of the STELLA™ model for the C³I system of Blue Ship is presented in Figure 5-5. This illustrates that the simulation maintains the three layers of the LGRM, as interconnected models. It will be noted that the LGRM Resource Management and Viability Management functions are not present on this diagram; they are handled elsewhere in the STELLA™ model, as described in Appendix B. It should also be noted that a computer-readable version of the entire simulation model is provided on a CD-ROM, attached to Appendix E. This CD-ROM also contains a public-domain STELLA™ viewer, which allows the full details of the model to be displayed and explored, as well as supporting its execution.

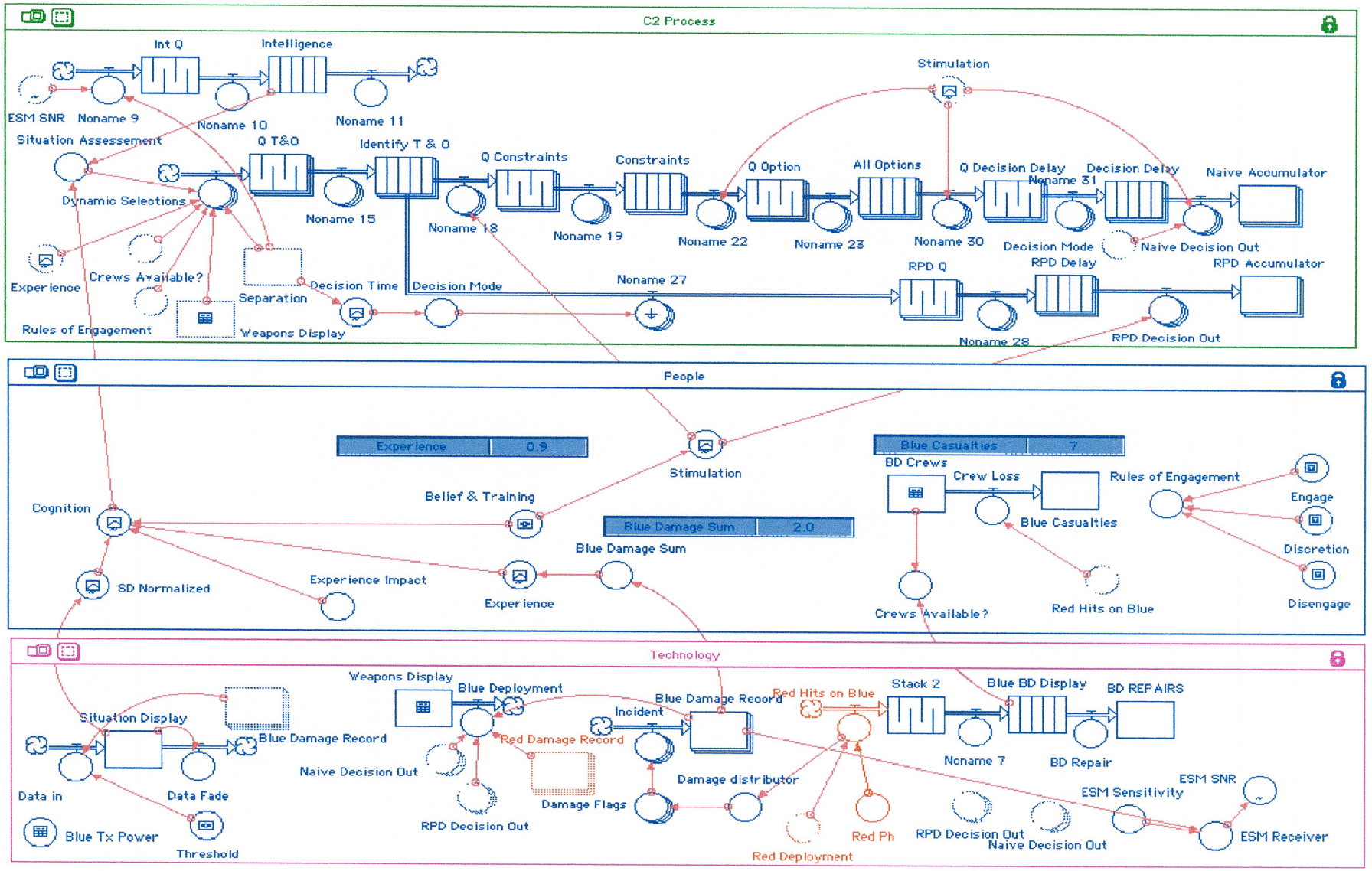


Figure 5-5 Extract from STELLA™ Model for Blue Ship, Three Simulation Layers, Showing Interconnections

5.5 Selecting MOEs for Assessing COTS Impact on C³I Effectiveness

Of the many MOEs which have been introduced in Chapter 3, and discussed in Appendix A, no single MOE appears adequate to address or reveal the expected effects of substituting an item of COTS for a Bespoke item. Reasons include:

- Uncertainty as to the differences between COTS and Bespoke items. Difference might be in cost, or performance, or reliability, or all three.
- Uncertainty about the interaction effects, which substituting COTS might have on other systems, maintenance organisations, logistics, etc.
- Uncertainties about the life-cycle effects of introducing COTS, which might not only have a shorter expected life, but also a continual upgrade path.

For these reasons, it was considered prudent to choose a suite of complementary MOEs, calculated, as follows:

a) **Blue Cost Effectiveness (BCE).** This can be measured in several ways; the model uses an approach that conceives the combat costs as a proportion of the capital cost of the ship. Combat costs include the costs of weapons fired, casualties, damage and damage repair, non-repairable spares, repair of failures, etc. The whole is brought within the range 0-100% as follows:

Blue Cost Effectiveness =[(Blue Capital Cost—Blue Combat Costs) ÷ Blue Capital Cost]*100% [5.2]

Capital costs include the outlay on equipment (Bespoke or COTS), spares, test facilities, etc. Red cost effectiveness can be measured in the same way. For two identical ships this should result in identical Blue and Red cost effectiveness.

b) **Cost Exchange Ratio.** The second MOE is aimed directly at cost exchange ratio, which can be described as follows:

Cost Exchange Ratios =[Red Combat Costs ÷(Red + Blue Combat Costs)]*2 [5.3]

For two identical ships, this gives a value of '1'. Values of exchange ratios above '1' show advantage to Blue, while values below '1' favour Red Ship.

c) **Casualty Exchange Ratio.** A third MOE is casualty exchange ratios. This follows the same approach as cost exchange, but is confined to numbers of Blue and Red casualties, respectively.

d) **Return on Capital Employment.** A fourth MOE is Return on Capital Employment (ROCE), which can be described as follows.

Generally

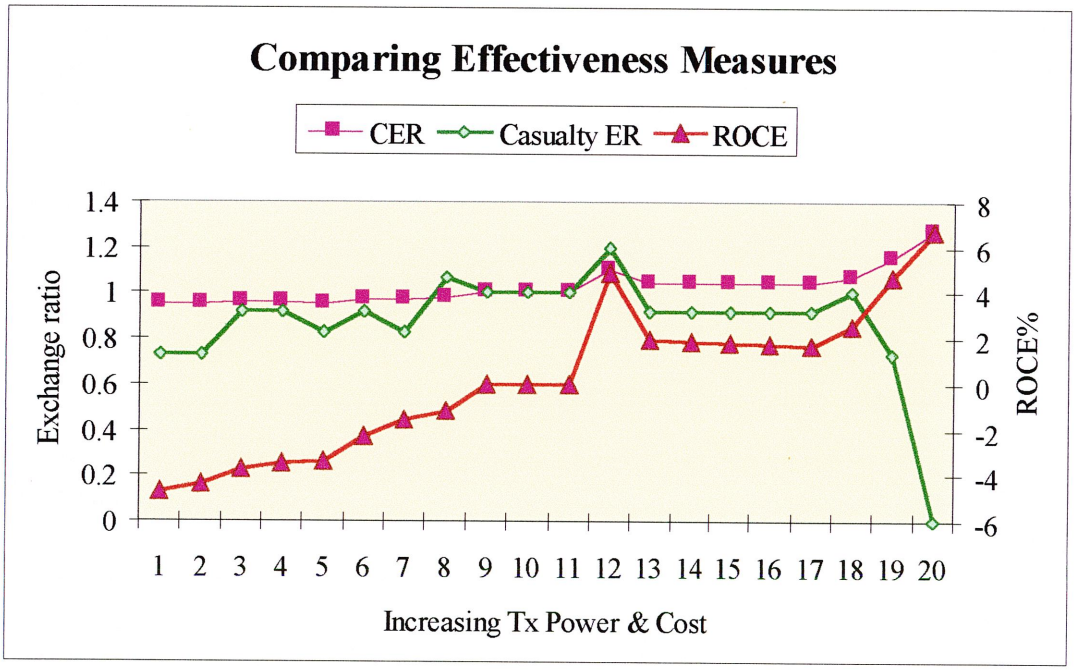
Rate of Return = [(Profit — Losses)/ Investment]∗100%

So, the Return on Capital Employed (ROCE) for Blue ship is:

Blue ROCE = [(Red Combat Cost — Blue Combat Cost)/ Blue Capital Cost]∗100% [5.4]

It was considered appropriate to analyse all four measures of effectiveness, simultaneously, when testing the model. This would provide a perspective on the results obtained, both to assess model behaviour, and to assess the results from the experiments using the model, once verified.

Graph 5-4 Three MOEs Resulting from Increasing both Tx Power and Cost



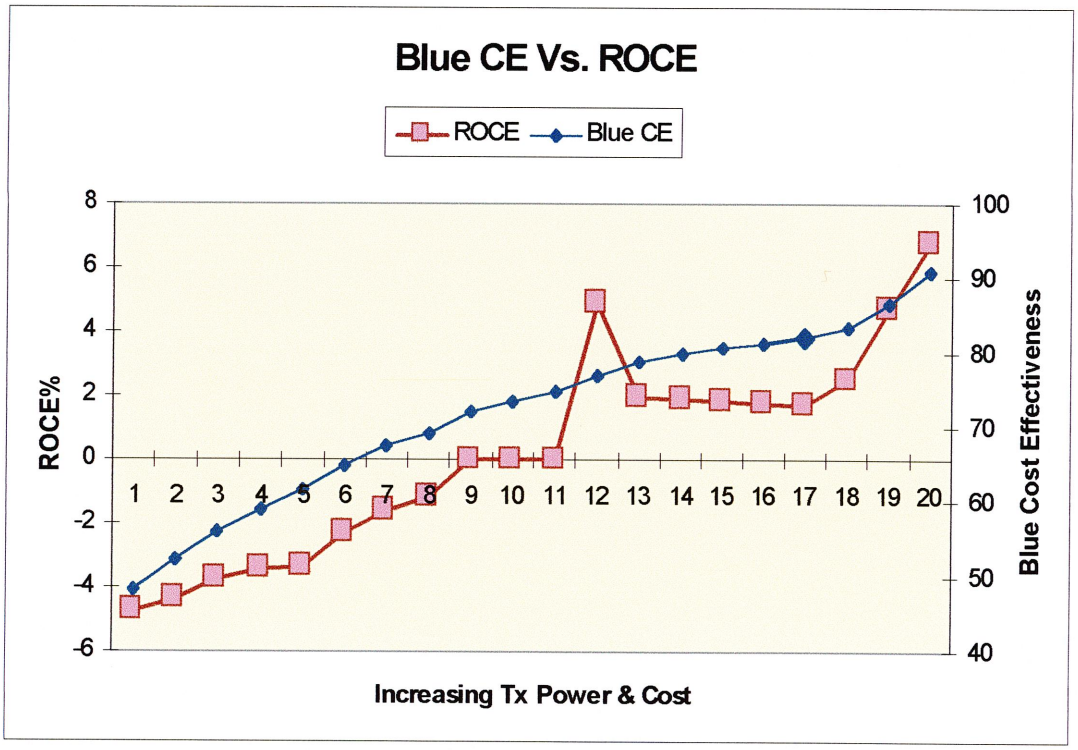
The fourth MOE (ROCE) is mission-dependent, and also is close to the damage-exchange ratio used in war gaming. Graph 5-4 shows return on capital employed, together with cost exchange ratio and casualty exchange ratio in a test simulation

explaining the effects of increasing both transmitter power and transmitter costs in 20 equal steps.

Such a simulation would be used to explore the effects of annual/periodic upgrades to COTS, for instance. Graph 5-5 shows the relationship between BCE (Blue Cost Effectiveness) and ROCE in the same scenario of increasing radar power and cost.

Over the same period of time, the two effectiveness measures show an increase in value for both BCE and ROCE, but ROCE generally appeared more erratic and was not chosen as a prime measure. It is still calculated with the model and can be viewed as necessary.

Graph 5-5 Measures of Effectiveness Comparison



5.6 Verification and Validation (V&V)

Verification and Validation (V&V) measures have been applied to the development of the COEIA white-box simulation model, in order to gain confidence that it is suitable for use in the planned C^3I effectiveness investigations. Verification is process-oriented, and attempts to answer the question 'are we building the product right?' Validation, on the other hand, is product-oriented, and addresses the question of 'are we building the right product?' [Lacy, 1992]. In this instance, verification is the process of determining if the LGRM has been correctly translated into a simulation model, using STELLA™. The validation process is a much more difficult task. A model is said to be valid if it is an accurate representation of the real world, from the perspective of the intended use of that model. Conventionally, this is done by having Subject Matter Experts (SMEs) review the model, and its outputs, both during and after development. Difficulties arise, for example, because the model may seek to predict future real world situations for which little, or no, experimental data is available.

5.6.1 Verification

Verification was considered, in this instance, to be primarily concerned with ensuring the structural integrity of the model. It was achieved by an incremental integration and test approach; that is, progressively testing the growing group of modules as each new module was added.

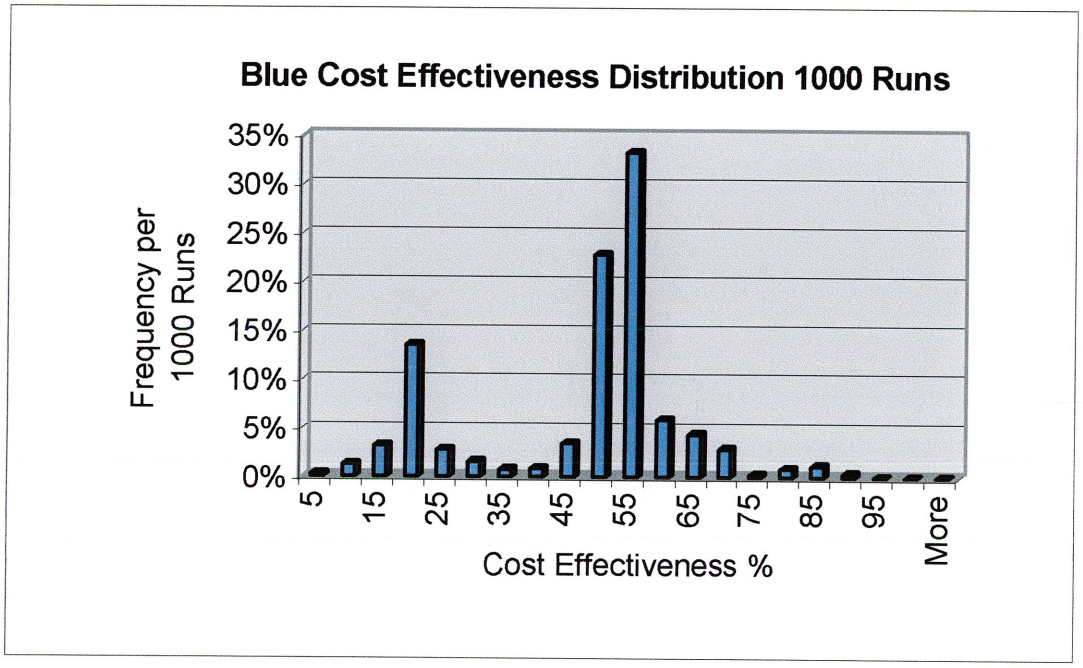
Similarly, the outputs of the LGRM portion of the model, which represents one ship, were suitably modified and fed back to its inputs to simulate the interaction before duplicating the LGRM to represent a second ship and cross connecting them. This obviated any unexpected and irrational behaviour on joining the two models, and also established that sensible compatible figures were being used for, say, corresponding transmitter powers and receiver sensitivities. Nominal values for performance and cost were chosen for two reasons: first, this was considered sufficient to establish 'proof of principle'; secondly, the model will neutralise the effects of any values that are marginally incorrect, since they will be the same for Red and Blue ships.

5.6.1.1 Statistical Variability within the Simulation

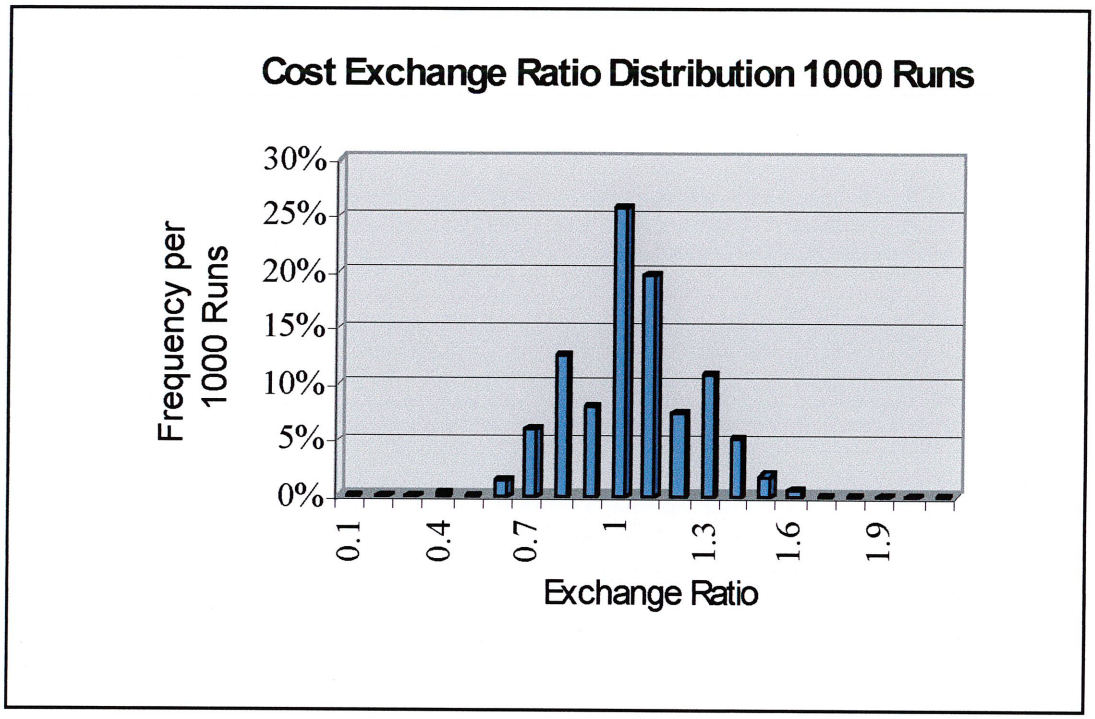
The simulation model contains a number of random variables, representing such factors as kill probability for missiles, detection probabilities, etc. On a run-to-run basis, different results would be expected due to random variation alone. In practice, the random variables are generated from a fixed seed number, which is the same for each variable in Blue Ship, and its correspondent in Red Ship. This gives identical results for Blue and Red on each run, given that both ships are set with the same parameter values. Clearly this is less than ideal, since particular seed values could be presenting atypical results. On the other hand, it would take a large number of runs (e.g. 10-20,000) to establish mean values for each point on the sensitivity graphs of Chapter 6.

It was considered important, therefore, to explore the effects of statistical variation in the model. To make this as practical as possible, unsynchronised random numbers were used for the damage distributor element of both Blue and Red ships, by deletion of the seed numbers, with the following effect. Different patterns of variability emerged for each of the three measures of effectiveness being investigated. Samples of 100, or even 500, runs resulted in different histogram patterns for each of the measures (see Appendix C); but each was stable over 1000 runs. The results from 1000 such runs, for the three parameters, are shown in Graphs 5-6 to 5-8.

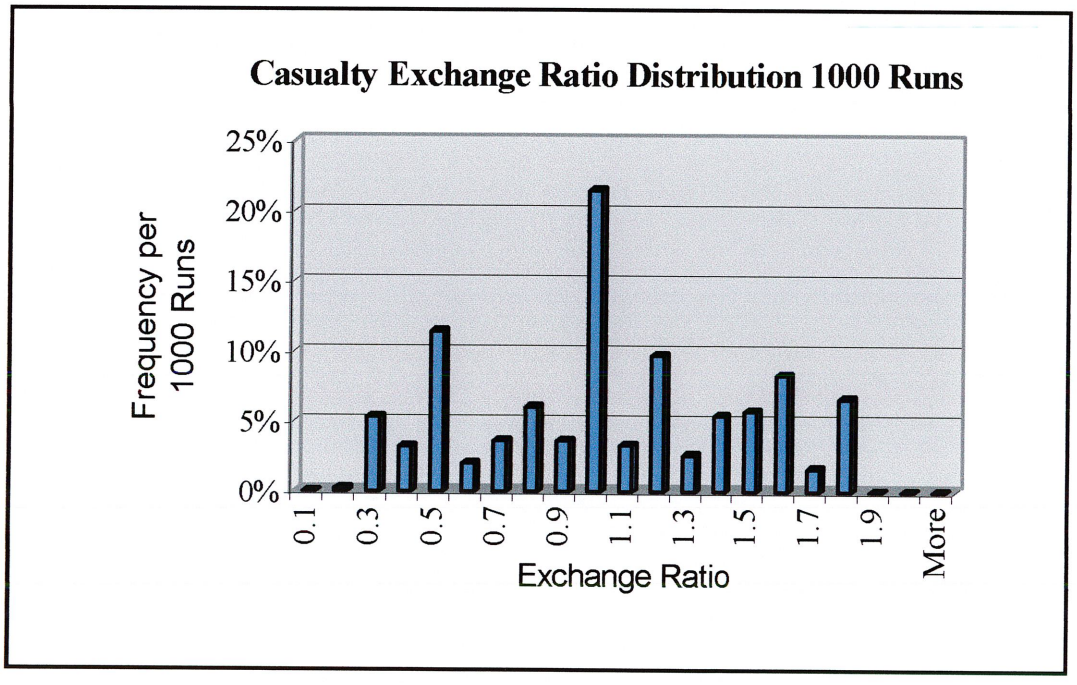
Graph 5-6 Blue Cost Effectiveness Over 1000 Runs with both Ships Set to Bespoke (same for Red)



Graph 5-7 Cost Exchange Ratio over 1000 Runs with both Ships Set to Bespoke



Graph 5-8 Casualty Exchange Ratio out-turn over 1000 Runs with both Ships Set to Bespoke



Further analysis was carried out to visualise the degree of variability of each parameter developing general statistics and histograms for the 1000 runs as follows:

- Each parameter shows a broad distribution of results about the mean, mode or median value.
- Cost exchange ratio shows the nearest approximation to a normal distribution.

The differences in the patterns were expected, and are explained in Table 5-1, below.

Measures of Effectiveness MoEs	Statistical Summary			Comments
	Mean	Mode	Median	
Blue Cost Effectiveness	44.9	49.1	49.7	Histogram was bimodal. This reflects the low probability (2%), but high cost, of being sunk by the enemy.
Cost Exchange Ratio	1.0	1.0	1.0	The distribution results show both ships are identical. It represents symmetrical costs, or the distribution of biased costs. There is a potential for either Red or Blue to be sunk. On the other hand, most of the damage inflicted by both ships is somewhere in the middle.
Casualty Exchange Ratio	1.0	1.0	1.0	This distribution also shows symmetrical results, which means that both ships have identical casualties.

Table 5-1 Summary Table - both Ships Bespoke

5.6.1.2 Verifying the Effects of Introducing COTS

Exploring the effects of introducing individual items of COTS on these distributions and, hence, measuring their relative contribution to effectiveness in simulated combat proved relatively straightforward, given the complexity and the sophistication of the COEIA white-box model. In the first experiment, Red was held constant, all equipment being Bespoke, and a single facility in Blue was changed from Bespoke to COTS: the resulting changes in C^3I effectiveness were attributable to the single change. See Tables 5-2 and 5-3 for the corresponding results for 1000 runs in each case, first choosing radar COTS and then weapon COTS. The results suggest that many items of COTS make a relatively small difference, when viewed against the

wide distribution, inherent in effectiveness measures. This is clearly shown in Table 5-2 where only the Radar was COTS.

Measures of Effectiveness MoEs	Statistical Summary			Comments
	Mean	Mode	Median	
Blue Cost Effectiveness	44.3	54.2	49.6	Minor changes with respect to w.r.t. Table 5.1 for equal ships.
Cost Exchange Ratio	1.0	1.0	1.0	No changes w.r.t. Table 5.1. No performance changes, equipment and maintenance costs only.
Casualty Exchange Ratio	1.0	1.0	1.0	As above in Cost Exchange Ratio.

Table 5-2 Introduction of COTS Radar into Bespoke Blue Ship

In the Table 5-3 only the weapon equipment was COTS in the Blue Ship and, in this instance, there is a distinct difference, arising because many weapon rounds are deployed during a simulated engagement, and each weapon round is significantly cheaper than its Bespoke counterpart.

The number of runs needed to produce a statistically consistent set proved higher than expected. Initially it had been expected that 100 runs, or at the most, 200 runs, would be sufficient. This was not the case (see Appendix C for further test results). That it took 1000 runs to produce a consistent set of statistics is evidence of the complexity of the model, and of the variety of non-linear interactions within it. (STELLA™ provides the facility to draw causal loops for models. When tried, the facility became grossly overloaded and, therefore, was not used for this model. This serves to indicate model complexity and potential non-linearity.)

Measures of Effectiveness MoEs	Statistical Summary			Comments
	Mean	Mode	Median	
Blue Cost Effectiveness	55.9	74.0	66.4	Significant changes w.r.t. Table 5.1 due to the effect of firing many missiles each at a lower unit cost.
Cost Exchange Ratio	1.3	1.5	1.4	Significant changes w.r.t. Table 5.1: variation in number of missiles fired during engagement.
Casualty Exchange Ratio	1.0	1.0	1.0	No changes w.r.t. Table 5.1 because casualty exchange ratio is a pure number and there is no costs associated with it and COTS missile presumed to have an identical probability of hit to Bespoke missile.

Table 5-3 Introduction of COTS Weapons into Bespoke Blue Ship

5.6.1.3 Justifying a Single Run as a Basis for Analysis

Ideally, from the foregoing discussion, there should be many runs. Practically, within the limits of STELLA™ and time, one run was used in many instances to explore different COTS versus Bespoke issues. In so doing, the random number seed in the damage distributor for both ships was chosen to provide similar results to those obtained over 1000 runs for the above three parameters (i.e. avoiding the extremes of the distributions). This seems to be a practical solution to the problem of having to undertake a very large numbers of simulations (20000 - 30000) to represent growth in performance over 20-30 years, which will follow in Chapter 6. However, full runs of at least 1000 simulations were, and should always be, used to support anomalous or counter-intuitive results from a single run.

5.6.2 Validation

In the limit, it is not possible to validate the simulation model completely. This would require two real ships engaging each other in a situation and under circumstances precisely as described in the simulation model, to compare results. This would be wildly expensive, dangerous and impractical. However, the model can be validated, in a practical sense, by observing whether it produces the behaviour and metrics that a SME would anticipate in given circumstances.

Accordingly, an attempt has been made to reconcile the results of the modelling work with expectation and Naval domain expertise, in order to validate them. In this respect, Table 5-4 illustrates the results of matching the model's measurable characteristic elements against the RN/DERA consolidated command metrics set [Young, 1998]. The table shows that, overall, there is a good match between the LGRM components of Figure 5-4, and the forty-six RN/DERA metrics. This means that the LGRM, suitably instantiated, has an internal (white-box) structure which exhibits high correspondence with the Naval C^3I domain, as defined by the SMEs who produced the RN/DERA metric set.

It will be noted that Interoperability, from the RN/DERA metric set, is not well served by the LGRM instantiation developed here. In Young's study, Interoperability indicates the ability of two systems to exchange and use information, and is an issue which should be considered in further work, beyond this PhD investigation. Essentially, it is a system issue that might be considered at the force level, if two or more co-operating platforms, and not one as in our current case, represent each (Red and Blue) force. Importantly, the LGRM has the capability and potential to achieve this by composing co-operating C^3I systems, as discussed in Chapter 4.

LGRM Instantiated for a Naval Shipborne C^3I System

	Consolidated Metrics Set								
	Picture Compilation	Situation Assessment	Resource allocation	Resource Direction	Planning	HCI	Alerts	Interoperability	Communications
Situation Display	●				●	●			●
—Radar	●								●
—ESM									●
—Naviagation	●								●
—Communications	●							●	●
Resources Display			●			●			●
—Weapons Management			●						●
Battle Management Display		●				●	●		●
—Internal System Sensors		●	●	●			●		●
Weapons Control			●			●			●
—Hard kill				●					●
—Soft Kill (Jammer)				●					●
Ship Controls			●	●		●			●
—speed				●					●
—direction				●					●
Belief System		●	●		●				
Cognition						●			
Training		●							
Doctrine		●							
Experience		●							
Constraint			●						
Behaviour Selection					●				
Stimulation		●					●		
Rules of Engagement									
Assess situation		●							
Threats &Opportunities		●							
Generate Options			●		●				
Review Constraints			●		●				
Select Preferred Option			●		●				
Initiate Action				●			●		
Monitor Action				●					

Table 5-4 Validation of LGRM Instantiated for a Naval C^3I System

5.7 Overall Simulation Model Credibility

This COEIA white-box simulation model, presented within this Chapter, has been developed to enable comparisons between Bespoke equipment and COTS, in terms of their relative contributions to C^3I system effectiveness and cost-effectiveness. In practice, the simulation model has capability and potential beyond this intended purpose. In particular, it possesses fundamental properties which encourage confidence in its credibility for this and other C^3I system modelling applications:

(i) Using the white-box modelling approach enhances credibility, by providing transparency and simplicity.

- Transparency makes it possible to experiment with the model, refine its properties and extend the theoretical understanding of this C^3I domain.
- Model simplicity comes from structuring the C^3I domain into manageable parts. This is provided by the LGRM, and derives from the synergy of its LVM and GRM foundations.

(ii) Including people and process within the model enhances credibility. A C^2 or C^3I model, that excludes people, their behaviour and the processes they execute, must lack credibility.

- Including people will enhance credibility provided proper account is taken of their innate human characteristics, behaviour, and variability.
- Including process will enhance credibility provided the process is representative of the different ways that people behave under different conditions.

These properties should also offer potential benefits for the modelling of other socio-technical domains, beyond C^3I systems. However, such an investigation is outside the immediate scope of this thesis, which now continues with the experimental use of the developed COEIA white-box simulation model, to predict C^3I system effectiveness, particularly in relation to the use of COTS-based equipment. The results of this are presented in the next chapter.

Chapter 6: Model Prediction of COTS Impact on C³I Effectiveness

6.1 Introduction

The previous chapter has outlined the development, and verification and validation, of the COEIA white-box simulation model, and showed that introducing single items of COTS into Blue Ship altered the balance between Blue and Red Ships. That alteration of balance was observed as three different, complementary C³I effectiveness measurements. In this chapter, the simulation is employed as a tool to judge and evaluate the impact of COTS on C³I system effectiveness. The simulation represents an engagement between two ships, Blue and Red. The two ships are set up some 100 nautical miles apart and closing. Rules of Engagement are initially set to Engage. Both ships are identical, and both have identical equipments with Missiles, Radar, ESM, Jammers, C² Displays, etc. They also have battle damage repair teams and on-board maintenance facilities.

Measurements and testing started by altering single items, and then altering additional items of equipment for the Blue Ship only, to judge overall effectiveness. Supplementary experiments show the effect of technology ageing on equipment performance and failure rate. They also explore the effect of frequent COTS upgrades on performance over an extended period and on the trades-off. All measurement outcomes are shown in tables and graphs. It must be stressed that the numbers scored for measures of effectiveness are scenario-dependent, and describe that effectiveness in that configuration and situation only. The actual values are, therefore, largely irrelevant; it is the relative behaviours of the two simulated ships which provide sensible results. Further details of the simulation data inputs and measurement outcomes are contained in Appendix D.

6.2 Using the Model

The model was used to explore the effects of COTS in different equipment on the overall effectiveness. Initially, both ships are set up to be identical. Red Ship then acts as an interactive reference for Blue Ship. With both ships the same, each will provide identical measures of effectiveness (MOEs). Red Ship was then held constant with all Bespoke equipment, and only one item in Blue Ship was changed from Bespoke to COTS. By running the model again, any change in the measures of effectiveness is attributable only to that one change. This test was repeated for each item in the Technology layer of the

model, to look for any differences in results due to that particular single change, thus allowing their individual and combined effects on the MOEs to be recorded. Table 6-1 illustrates the results of this. The effect on an MOE is defined as the difference in overall effectiveness when changing from Bespoke to COTS. Accordingly, the effect for each item of COTS was calculated by subtracting the new values measured for the three measures of effectiveness from the initial values with no change (i.e. for the Bespoke system).

Technology Layer Individual COTS Components	Measures of Effectiveness (MOEs)			Effects on MOEs		
	Blue Cost Effectiveness (a)	Cost Exchange Ratio (b)	Casualty Exchange Ratio (c)	(a)	(b)	(c)
None (Bespoke)	49.5%	1.0	1.0	0	0	0
Radar	49.2%	1.0	1.0	-.3%	0	0
ESM	49.6%	1.0	1.0	.1%	0	0
Jammer	49.6%	1.0	1.0	.1%	0	0
Weapons	66.1%	1.4	1.0	16.6%	.4	0
Display	49.4%	1.0	1.0	-.1%	0	0
Sum of the separate effects (see note)				16.4%	.4	0

Note: the individual effects have been summed to provide a basis for later comparison.

Table 6-1 Effects of Changing One Facility at a Time in the Technology Layer from Bespoke to COTS

The results in Table 6-1 can be explained as follows:

1) Since introducing a COTS item did not change its performance, but only its various costs, the experiments so far have no effect on casualty exchange ratio.

2) Selecting an item to be COTS in Blue Ship also changed the corresponding maintenance arrangements. During the short time of simulated engagement (some 2 hours), however, the probability of failure occurring is low, so neither COTS nor Bespoke maintenance would necessarily be activated.

3) Weapons show a marked difference under cost exchange ratio because they are fired during an engagement and, unlike the other technology elements, weapons are consumables. Firing many, cheaper, weapons should, and does, impact on cost exchange ratios.

4) Blue cost effectiveness includes the capital cost of spares and test facilities for COTS and Bespoke technology, respectively. Selecting a COTS radar for example, may reduce the cost *vis-à-vis* a Bespoke radar, but the spares and test costs may prove greater. Hence, Blue cost effectiveness may fall or rise on selecting a 'cheaper' COTS device.

It was possible, given such a comprehensive model, to explore much further. For instance, it was possible to evaluate the effects of changing more than one item at a time, or even to go 'all COTS'. Table 6-2 illustrates the changes in effectiveness brought about by introducing pieces of COTS together, rather than separately.

	COTS Components	No COTS (a)	Radar and ESM COTS	Radar, ESM and Jammer COTS	Radar, ESM, Jammer and Weapons COTS	Radar, ESM, Jammer, Weapons and Display COTS (b)	Total Effect = (b) – (a)
Measures of Effectiveness	Blue Cost Effectiveness	49.5%	49.4%	49.5%	66.7%	66.8%	17.3%
	Cost Exchange Ratio	1.0	1.0	1.0	1.4	1.4	.4
	Casualty Exchange Ratio	1.0	1.0	1.0	1.0	1.0	0

Table 6-2 Effects of Varying all Blue Ship Technology Components to COTS

Here, the results of the experiment indicate that there was no effect on casualty exchange ratio, but changes in cost exchange ratio started to emerge when all items were altered. All changes were to Blue's advantage. The total effect is calculated by subtracting the three values measured for MOEs, when all items switched to COTS, from the initial ones with no change (i.e. the Bespoke system).

The individual scored values for effects on MOEs due to a single change, when added together (Table 6-1), are not the same as the values measured for the same changes when introduced simultaneously (Table 6-2). This arises from synergies between the various technological components which, in effect, create a non-linear, complex model[1].

This is an important result. Effectiveness emerges from the interaction between many parts in the model, and is not attributable exclusively to any one part. Effectiveness is, therefore, an emergent property of (in this case) one ship interacting with another. Effectiveness also varies throughout a simulation run, and could be measured at any stage. Consequently, effectiveness is a complex, dynamic emergent property of the interaction.

The model, thus, offers a sensible way to judge the change in effectiveness brought about by introducing an individual piece of COTS. The model even accounts for inadequate or excessive spares holdings, both of which will reduce cost effectiveness (running out of spares stops vital equipment working, rendering the ship vulnerable).

6.3 Technology Ageing

The set of experiments of this section demonstrate that, in a dynamically advancing technological environment, keeping the same technology equates to moving backwards, as competitors introduce newer technology. This demonstration is achieved by measuring the effectiveness of Blue Ship, which is held constant, while Red Ship has its performance and costs increased. Red Ship weapon was chosen to illustrate the effect, so only Red Ship weapon was enhanced.

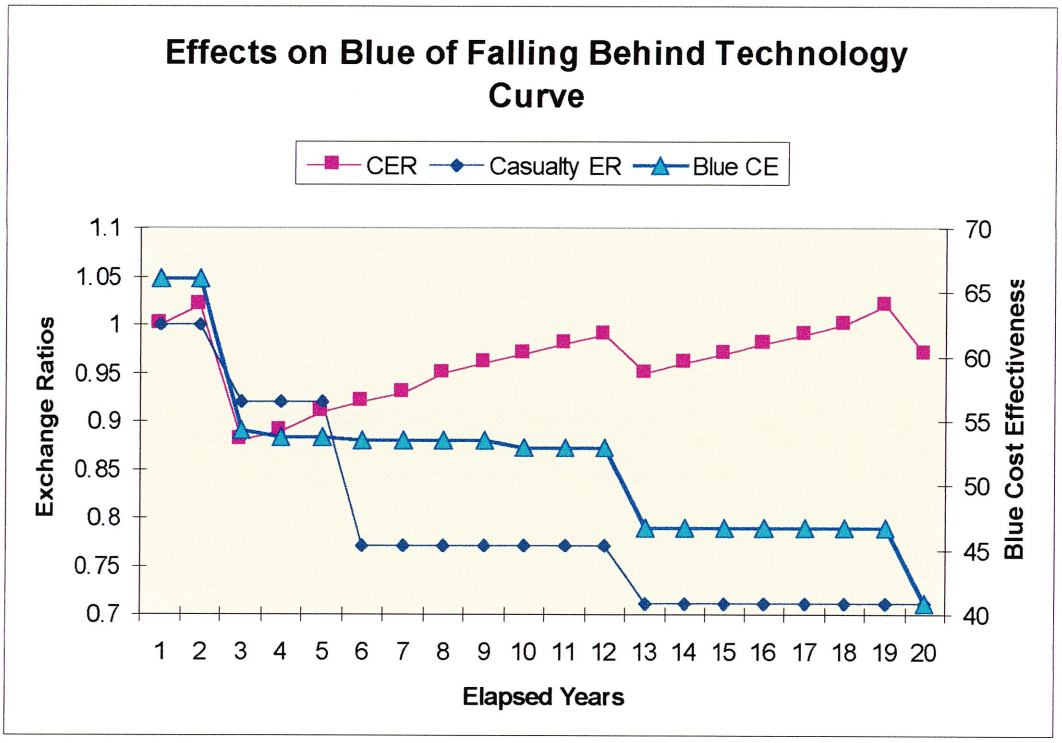
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[1] Note that the present model does not account for any networking deficiencies, which might arise from introducing one item of COTS into a network of Bespoke equipment.

6.3.1 Technology Ageing Experiment

In this experiment Blue Ship was held constant throughout, and all equipment was Bespoke except the weapon was COTS. Red Ship was also equipped with the same Bespoke equipment and COTS weapon. In the experiment the Red Ship COTS weapon was evolved over 20 years. Over that time its performance, measured as the Probability of Hit (Ph), doubled. Each increment was accompanied by a price increment. Graph 6-1 illustrates this simulated situation.

Graph 6-1 Blue Falling Behind Technology Effectiveness Measures



The graph starts with both exchange ratios equal to 1. As Red Ship missile Ph and cost increase, all three MOEs change from Blue Ship's perspective. Casualty Exchange Ratio declines steadily from unity (50:50) as the Red Ship weapon Ph increases. Although Blue Ship capital cost does not change, Blue cost effectiveness declines because its combat costs increase as it receives more damage from Red weapon. On the other hand cost exchange ratio 'saw-tooths', but most of the time does not exceed unity. Overall, the Red Ship has significant advantage from Year 2 onwards, suggesting that Blue Ship technology should not be allowed to slip more than two years behind the advancing technology curve (in this scenario).

6.3.2 Sensor Failure/Network Breakdown

The experiment here introduces a COTS radar with a high failure rate into Blue Ship. Since COTS is based on replacing faulty items, during the engagement, Blue Ship radar will be out of service on occasions due to lack of spares.

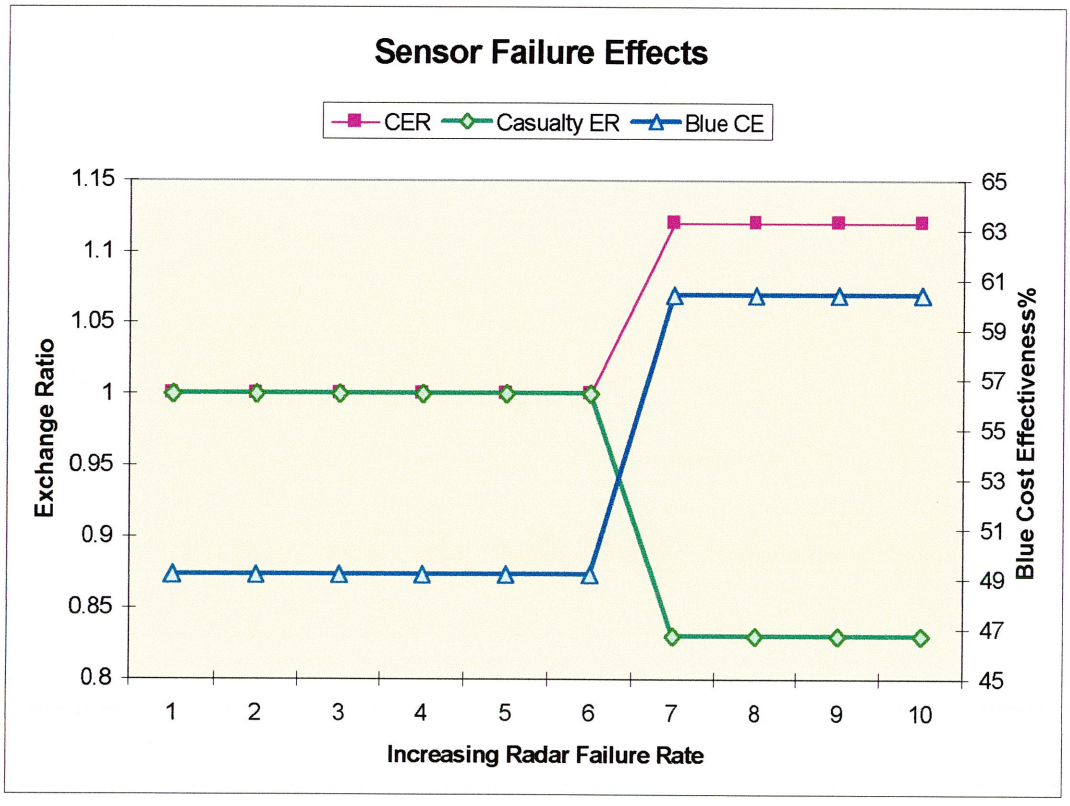
As shown in Graph 6-2, the greatest effect is on the casualty exchange ratio. The graph starts with both exchange ratios equal to 1. This situation will pertain as long as the radar failure rate does not cause any failure during the two-hour engagement. As the failure rate increases, there comes a point at which failure occurs during the Blue/Red two-hour engagement. At this point:

a) Casualty exchange ratio falls because Blue cannot see Red, so cannot fire. Red can see Blue, so fires and causes Blue casualties.

b) Cost exchange ratio rises because Blue cannot see Red, and cannot fire expensive missiles. The cost savings from not firing many missiles outweigh the cost of damage inflicted on Blue by Red.

c) Blue cost effectiveness rises for the same reason as in (b).

Graph 6-2 COTS Radar MTBF Effectiveness Measures



The results of this experiment clearly illustrate the importance of reading the three MOEs together; any one taken on its own may be misleading.

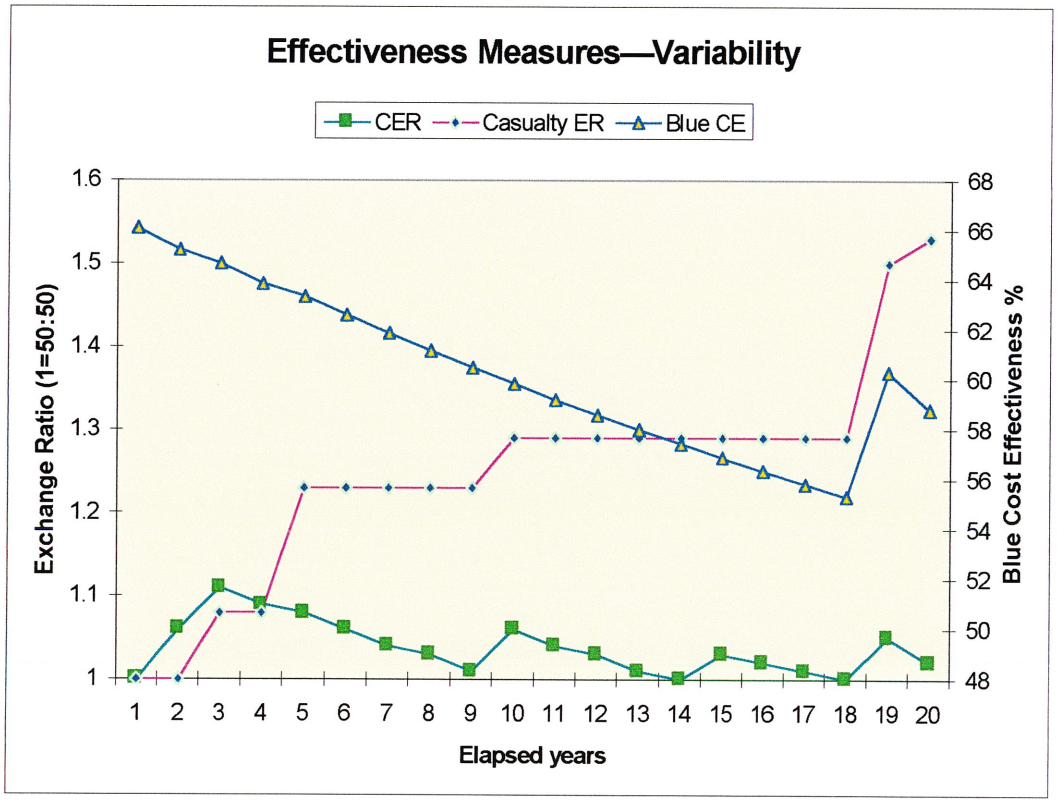
6.4 Technology Update

Military systems tend to have a long in-service life: fifteen to twenty years would not be unusual, and mid-life updates take available combat platforms out of service for a significant time. The next series of experiments explore this issue by considering the regular, incremental updating of equipments. In this case, the Blue Ship's C³I system undergoes 'so-called' continual updates.

6.4.1 Missile Upgrade

The experiment was set up with Blue and Red ships identical. In both cases all equipments were Bespoke, but the missile was COTS. Red Ship was held in this configuration throughout, as the dynamic reference. Blue Ship COTS weapon was evolved over a simulated 20 years period by increasing both Blue COTS missile Ph and cost in 20 equal annual increments. Graph 6-3 illustrates the results of this.

Graph 6-3 Enhancing Blue Ship COTS Weapon by Continual Upgrade over 20 Years



In Graph 6-3, the cost/performance profile, which determines the proportional performance and cost of each annual upgrade, was adjusted until the cost exchange ratio remained at about unity over a simulated life of 20 years. Over that same period, the other two effectiveness measures show an increase for casualty exchange ratio (as Ph rose) and decrease for Blue cost effectiveness (as Blue costs rose). This nicely shows the differences between the three measures, and why it is important to consider all three at the same time.

Casualty exchange ratio climbs steadily from unity (50:50) as the weapon performance increases, and Blue cost effectiveness falls as Blue Ship fires increasingly expensive weapons. At increment 19 there is a discontinuity, as the performance of the weapons goes through a threshold and damages Red Ship such that it can no longer inflict damage on Blue. Results from this kind of experiment could be used to identify target performance parameters for weapons, for example.

6.4.2 Seeking COTS Radar Optimum Power Density

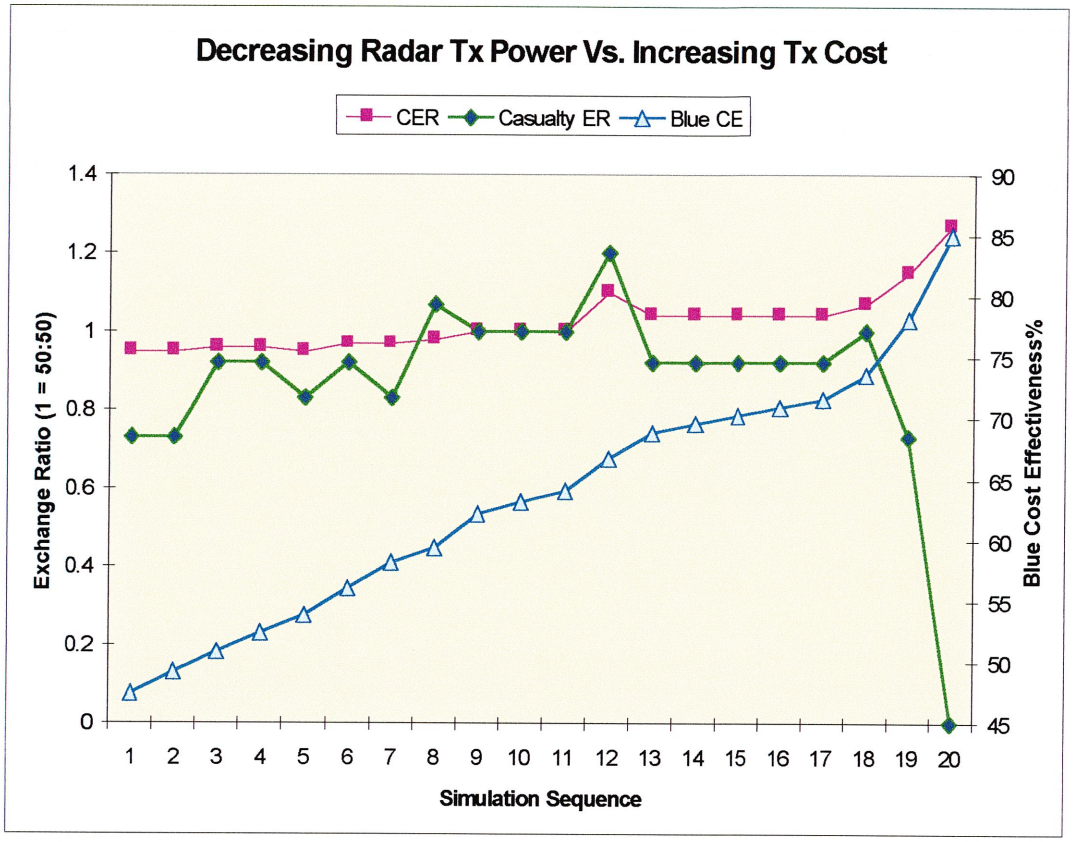
The model can be used to experiment with potential investments in Electronic Protective Measures (EPM) by using, for example, frequency hopping or spread spectrum or phased array techniques. This was demonstrated by spending more money in upgrading Blue radar regularly, to improve radar performance by reducing its radiated power at increased cost.

In Graph 6-4, Blue cost effectiveness shows continuous increases throughout the simulation because the capital cost is always increasing. This experiment suggests that the radar cost and transmitter power would, ideally, be within the values corresponding to simulation sequence 12 to 16, to maximise all three cost effectiveness measures. In general, the experiment suggests that there are optional combinations of radar cost and power density, if these two parameters are varied independently.

The results presented in Graph 6-4 can be rationalised, as follows. In this scenario, the radar transmitter power density makes Blue Ship's radar less detectable by the enemy and gives Blue advantage over Red. This slightly improves both exchange

ratios. Nearly at the end of the simulation, casualty exchange ratio falls to zero. This means zero Red casualties (i.e. Blue Ship cannot see Red Ship, so has not fired).

Graph 6-4 COTS Radar Value for Money



6.5 Trades-off

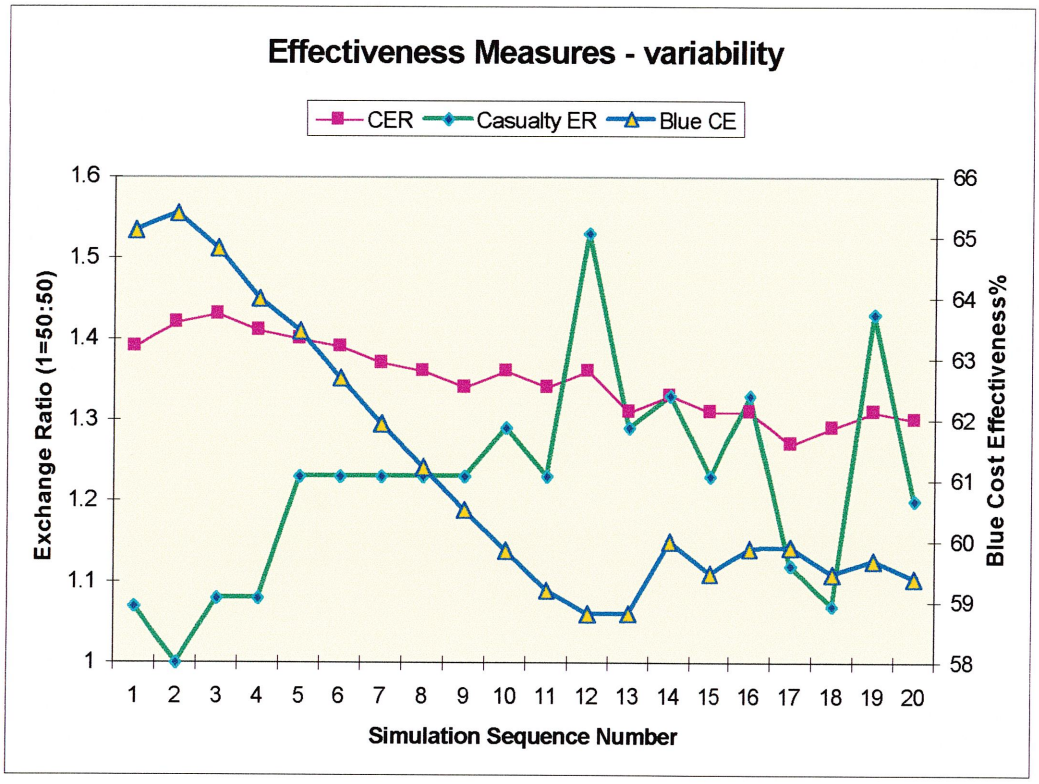
6.5.1 Trading Technology vs. Training Costs

The model provides intriguing possibilities for trading technology against training, and for evaluating the contribution of experience. As an example, it is possible to simultaneously increase the missile performance and cost while reducing the amount spent on training, to see if there was any potential for trade-off.

To analyse what might happen, Red Ship was held constant and set to have a similar COTS missile to Blue. Blue Ship was then evolved by improving Blue COTS missile performance in terms of the 'Probability of hit' (Ph), while missile cost rose correspondingly. Simultaneously, training costs were reduced from a high to a low value. The consequent effectiveness measures are shown in Graph 6-5. The graph suggests that different measures of C³I effectiveness might lead to different conclusions. Cost exchange ratio falls steadily as missile cost and performance rise.

Casualty exchange ratio is variable, suggesting that, as the training level falls, there is reducing situation control. Blue cost effectiveness falls steadily, as the cost of the missile increases.

Graph 6-5 Trade-off Analysis, Rising Weapons Performance and Cost vs. Falling Training Costs

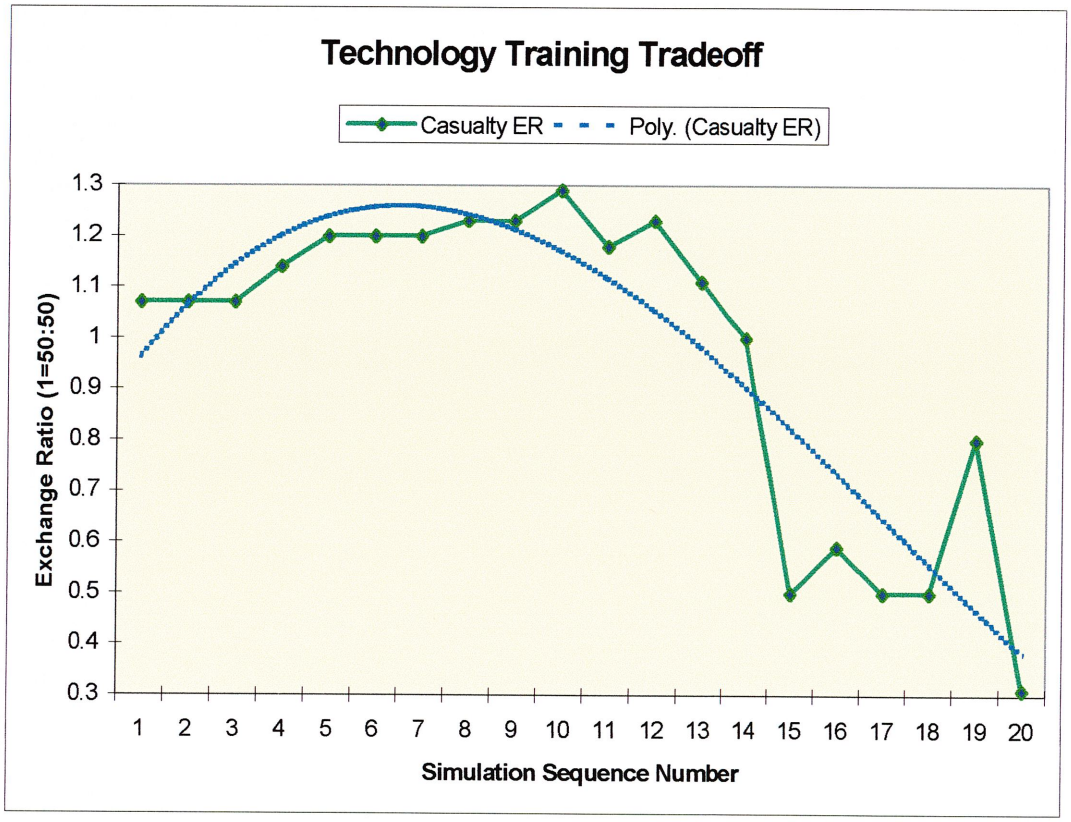


Graph 6-5 suggests a dilemma emerging from the experiment. On the one hand, increasing Blue weapon performance and cost, while reducing training costs, results in increasing casualty exchange ratio in Blue's favour at least up to the set of values corresponding to the simulation sequence number 12. On the other hand, both Blue cost effectiveness and cost exchange ratio indicate reducing economic benefit from the trade; Blue cost effectiveness, in particular, falls to a low value, also at increment 12.

The results from this experiment are, therefore, inconclusive in that different measures of effectiveness suggest different trade-off optima. The next experiment progressed the same trade-off further, using only one of the three MOEs. To find the optimum balance for how much it would be sensible to spend in such situations, casualty exchange ratio was selected as the metric to demonstrate the 'value for

money' optimum. This was analysed by creating a polynomial regression line from the casualty exchange ratio, as shown in Graph 6-6. Note that the casualty exchange ratio graph is different from that of Graph 6-5 because different Belief and Training cost variables were used to explore different possibilities. Evidently, there is a potential to trade-off the costs of technology against the cost of training, although clearly there are limits to this exercise, beyond which it would be ill-advised to proceed.

Graph 6-6 The Effect of Simultaneously Increasing Missile Cost and Performance while Reducing C² Team Training Costs



Overall, this experiment shows that it is unrealistic to assess the effectiveness of C³I systems without accounting for human performance. It suggests, rather obviously perhaps, that there is a need for a well-trained and experienced C² team. Nonetheless, effectiveness calculations conventionally exclude that team, concentrating exclusively on the technology; this must render such calculations suspect.

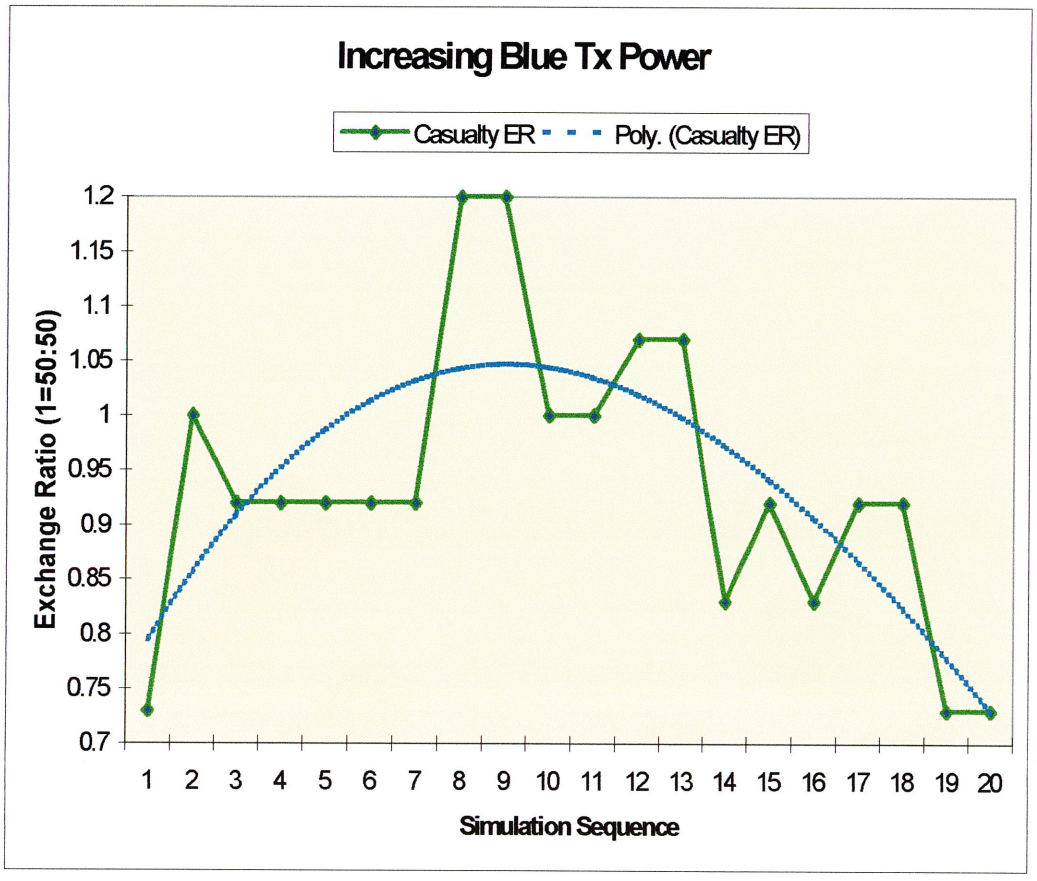
6.5.2 Optimising Individual Performance Experiment

Another type of trade-off experiment was carried out to optimise Blue transmitter power, by identifying the safety region for the radar to operate, in this particular scenario, to avoid early enemy detection. The experiment started by setting the Red Ship to have similar COTS radar to Blue Ship. Blue transmitted power was varied from a low to a large value in a sequence of 20 simulation steps.

Graph 6-7 illustrates the results of this experiment. It shows that the optimum values occurred nearly at the middle of the simulation sequence number, an intermediate setting. Both low and high transmitter power give poorer casualty exchange ratios. Low Blue transmitter power (with respect to Red) enables Red Ship to see Blue Ship first, and to fire first; thereby, putting Blue Ship at risk.

Less obviously, high Blue transmitter power (with respect to Red) enables Red Ship ESM to see Blue Ship first, also putting Blue Ship at risk as Red fires first again. There is, therefore, an optimum Blue transmitter power in this simulated situation.

Graph 6-7 Radar Transmitter Power Trade-off



6.6 Optimising Blue Ship MOEs

It is also possible, using genetic algorithms or hill-climbing routines, to reconfigure the various pieces of technology in Blue Ship so that it is at the peak of effectiveness compared with Red Ship in the given scenario. Additionally, it is possible to vary, for instance, the numbers of damage repair items, the numbers of spares for equipment, etc. Performing this routine for a variety of scenarios, as shown in the trade-off experiments, would provide a scientific approach to establishing the performance, availability and support requirements for each and every piece of technology, seen not as individuals but as members of an integrated C³I system. Part of this process was demonstrated, above, for only one component in the Technology layer. This happened when trading-off decreasing radar transmitter power with increasing radar cost.

It is also evident from the model that discrete measures of performance for individual components cannot sensibly be added together to calculate effectiveness. On the other hand, it seems likely that a full model would allow the reverse process to be undertaken by:

a) varying components to achieve a high, overall C³I effectiveness, and then
b) backtracking to what the various component performances would have to be, to achieve that effectiveness in that configuration and situation.

It is also possible to optimise Blue Ship, and then use it as a reference to optimise Red Ship, and so on, in a cyclic fashion, to obtain maximum optimisation potential.

6.7 Assessment of Modelling Results

The results were all verified, thus providing some confidence in the use of the COEIA white-box C³I modelling technique. At this stage, there is no reason to discount the use of white-box modelling techniques for effectiveness assessment[2]. The model shows that effectiveness is an effect that one system can have upon another. It is, therefore, an emergent property of a complex system: in this case one ship interacting with another. The model also shows that C³I system effectiveness and cost effectiveness, however assessed or measured, are time dependent, and vary with the

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[2] Method of Refutation and the Principle of Falsifiability [Popper, 1959].

experience, training and behaviour of the operators, as well as with the technology used.

Current emphasis on the strong relationship between technology, performance, and C³I effectiveness may be misguided. The evidence from the sensitivity analysis and the model indicates that minor variation in technology performance is discounted by the major effect of human behaviour, particularly in the areas of training, belief, situation assessment and decision making. In operation, all of these human activities continue unabated, even if much of the technology fails to deliver at all.

This work has been able to establish that COTS can have a significant impact on cost, and thus on effectiveness, when measured over a period of time, during which the COTS product is continually upgraded. This compares favourably with the employment of Bespoke systems which initially cost more, and may initially out-perform their COTS counterpart. However, this initial Bespoke advantage is unlikely to evolve as rapidly as COTS and may, therefore, soon be overtaken.

Part of the analysis indicates that similar advantage attaches to COTS in the area of maintenance. For COTS, maintenance is likely to consist of replacing boxes or modules and discarding the faulty items. While seemingly wasteful, discarding repairable COTS items, generally, costs less than maintaining a standing capability in terms of manpower, test facility and spares, which may be considered as needed for a Bespoke system. It is not obvious, either, that Bespoke equipment will be any more reliable than COTS. Indeed, both the complexity and untried technology associated with Bespoke equipment may cause reliability to be reduced. The results of the experiments in this chapter explain the effect of COTS on C³I effectiveness. Some experiments suggest that introducing COTS may benefit one effectiveness measure, but not another. However, costs benefits may be predicted from introducing COTS that is short-lived and replaced in large numbers (i.e. consumables). It is possible, from a procurement point of view, to calculate the optimum mix of COTS/Bespoke, to calculate the optimum maintenance and support, and to calculate the optimum spares holdings.

The significance of these results, together with those of Chapters 3, 4, and 5, are discussed in the following chapter.

Chapter 7: Discussion

7.1 Introduction

This chapter discusses the results of this research project, conveyed in Chapters 3, 4, 5 and 6; assessing their implications and significance in a wider context. It begins by exploring the findings of the research survey associated with the COTS-based procurement of C^3I systems, presented in Chapter 3, to identify issues of potential future significance, and reflect upon the important role of this survey in defining the future direction for this project, in terms of the white-box modelling of C^3I systems for COEIA. The remainder of the chapter then focuses on the results of the COEIA white-box modelling work, presented in Chapters 4, 5 and 6; highlighting and discussing the features, benefits, and limitations of the different stages of the work, and the value added in developing this approach. It also discusses the wider implications of the approach, and identifies some avenues of potential future work. Finally, the chapter provides a brief Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis of the developed COEIA white-box modelling approach.

7.2 Survey of COTS Procurement Issues for C^3I

At the beginning of the project, there was a need for the author, in response to his sponsor's requirements, to establish a sound understanding of current thinking, practice and research in the area of COTS-based procurement of C^3I systems. This led to an initial exploratory survey which was intended to be as broad as possible, and involved visits to industry and DERA, as well as the more conventional literature search.

The initial survey quickly established that the use of COTS for C^3I systems is largely an unexplored academic area. Symptomatic of this are the many definitions of the term 'COTS', which differ in detail. Primarily, there is the need to reconcile whether COTS is literally 'off the shelf', or can embrace modified components (section 3.3.1). Furthermore, there is also the notion of COTS applying to the whole procured system rather than to components within it (section 3.7.2.1).

These definitions attempt to clarify the user's understanding of what is meant by the term 'commercial product' and, as one explores further, additional subtle differences

emerge. For example, [Farrow, 1995] describes COTS procurement from a naval system perspective as "using standard industrial technology in naval systems, instead of developing custom technology", which takes a pure commercial view and would appear to discourage modification of components but not exclude this. This stance on modification concurs with that of NATO, which defines COTS as "Pertaining to a commercial market product which normally is used without modification". However, NATO also includes a further distinction between COTS and 'Government off the Shelf' (GOTS), which it defines as "Pertaining to a product owned by the government of a NATO country and normally used by others without modification." [Matthews, 1996].

In summary, there is a need for a definitive terminology for COTS, which bridges the commercial and government communities. In the absence of this, we can suggest some basic characteristics of COTS which represent a broad 'consensus' view:

(i) Product is cheap compared with a bespoke one.

(ii) Product is readily available commercially.

(iii) Product does the necessary job, preferably without modification.

(iv) There is an expectation of a relatively short lifetime for the product compared with bespoke.

Regardless of the lack of a mature terminology, there is clear evidence that COTS is here to stay, especially for IT-related areas like C^3I, because the global commercial market supports huge Research and Development (R&D) budgets which Defence organisations cannot hope to rival and would wish to exploit (section 3.3.3). Accordingly, there is general acceptance of COTS as the way ahead by the UK MOD and the US DoD, but there are residual and nagging concerns about attendant risks, such as security implications (section 3.3.4). This emphasises the critical need for risk assessment and risk reduction strategies to support the procurement process, which must operate in a defence environment where the inevitable trend will be a reduction in military specific standards (section 3.3.6).

Importantly, from the initial exploratory survey, it was clear that there was no established theory supporting the use of COTS for C^3I systems; it is a topic driven by technology push and customer pull. Therefore, the first hurdle in establishing an

academic basis for this PhD project was to find a means for intellectual structuring of the area (section 3.2) that would add value *inter alia* for the Bahrain Defence Force (BDF) sponsor. This was achieved by postulating a simple COTS-based system development approach, and led to the following areas of focused investigation:

- C^3I Requirements Modelling and Analysis.
- C^3I Architectures and System Modelling.
- Component Technology and Evaluation.
- COTS-based Procurement Processes.

When investigating the first of these areas, it quickly became clear that requirements engineering techniques need to evolve, to reflect COTS-based development (section 3.4.2). This can be achieved by moving away from specifying the system requirements, to specifying capability needed, as is the case for the MOD's recently-introduced Smart Procurement Initiative (SPI) [MOD WWW, 1998]. The potential benefits are exemplified by separating out the User Requirement Document (URD) from the System Requirement Document (SRD) [Stevens, 1998; Dowling, 2000]. Capabilities can be defined if the URD identifies appropriate MOEs by which a potential system can be judged, using operational scenarios. The more the scenarios can relate to the operational need, the better the interaction with the user. Furthermore, there is a requirement to explore the 'business' environment, to understand true need, typically using an Enterprise Modelling technique. A key argument for using such a technique is that, for socio-technical systems such as C^3I, the technical component should not be developed separately from the social or organisational aspects, due to their inherent interrelation [Houghton, 1994]. Ultimately, we need to understand the 'business' process that the system supports. For C^3I systems, this means the Command and Control (C^2) process. Fundamentally, this is a difficult area because it involves people, and it was clear that many behavioural influences are poorly understood; for example, training, beliefs, stereotypes, world models, etc. These shortfalls point to critical areas for potential research, since a better understanding will be necessary to create real progress and mature theories.

Moving on to the next investigation area, C³I Architectures and System Modelling, there was an understandable tendency to advocate the use of open systems architectures and standards, whenever possible (section 3.5.4), to support the inclusion of COTS. A further development in this direction concerns the emergence of Open Source Software [Comerford, 1999]. This is a new model of software development and distribution, which results in the 'open' publication of the source code for software products, and their maintenance by the software community, in general. It has become of interest to some military organisations because of the potential for software cost reductions, and removing reliance on proprietary products. Notable developments in this area are the 'Linux' operating system and the 'Star Office' office applications suite (word processing, etc.), for the PC and other computing platforms. However, it is interesting to note the potential conflict of this approach with that identified for the COE, which is oriented around proprietary software such as Windows NT (section 3.3.9.2).

Continuing with the investigation into C³I Architectures and System Modelling, it was evident that the potential risk of procuring a COTS-based system could be mitigated by the adoption of sound system design approaches. For example, attention must be paid to preventing the effect of combining different kinds of COTS components on the overall behaviour of the system, and on the system qualities such as reliability, security and performance. Section 3.3.8 illustrated this, by the role of 'wrapper' and 'glue' technologies to limit the risk of unwanted side effects from introducing a COTS component into a system. We can reason forward that reliability can also be improved by employing redundancy and fault tolerance techniques; for example, such an approach is regularly used to achieve high reliability from commercial technologies in the avionics industry, such as in AIRBUS aircraft [Voges, 1988]. Similarly, we can postulate that security may be improved using multiple commercial security approaches, as an alternative to developing 'special' Bespoke devices that will be expensive and soon become outdated. Finally, it is likely that future systems will include COTS services [Moulding, 2000], such as communications channels, as well as COTS components, and system design techniques will need to evolve to accommodate this; perhaps, by reducing reliance on any one service provider by employing redundant services from separate suppliers.

Moving on to the next investigation area, Component Technology and Evaluation, it was apparent that this is a critical area for defence organisations, which could have a major effect on operational capability. C^3I is a potential force multiplier, but enemies have access to the same global market for COTS (section 3.3.2). Therefore, friendly forces must continually evaluate the suitability of COTS developments for their C^3I systems, otherwise they will face potential disadvantages by operating outdated equipment compared to their enemies. Evidence of the importance of this, in the UK, is provided by the establishment of reference test centres, by the MOD, such as the Land Systems Reference Centre (LSRC) located at Blandford Camp [Syntegra WWW, 2000]. The purpose of this centre is to reduce risks substantially through all stages of specifying, developing and using military CIS systems. Importantly, in order to support such centres, a defence database of COTS information should be set up; for example, to capture experience of using COTS products, such as risks and problems encountered. This is a good example of how knowledge management techniques can assist in assessing the risk of COTS in procurement.

The final investigation area was COTS-based Procurement Processes, and it was clear that current processes must be upgraded to maximise the use of COTS; for example, using planned technology insertion, rather than having a few, large refits. The SPI appears to be moving in the right direction but its timescales still seem too large to accommodate COTS (section 3.7.2.4). Meanwhile, incremental acquisition seems to hold the key to success over traditional acquisition models [Henderson, 1998]. Finally, risk modelling techniques are urgently needed to support COTS-based procurement decisions, and service-level COTS should also be accommodated, especially for future C^3I systems.

Overall, the research survey, of Chapter 3, proved extremely useful in understanding current developments and issues, and providing a framework for analysing what is being done and where additional work is needed. The initial exploratory survey provided the context for the focused survey, which revealed a number of potential research directions (section 3.8). In fact, the COEIA white-box modelling approach, which was finally selected for the deepening phase of this PhD, was one of many avenues that were identified. It was chosen because of the critical need that it would serve within the procurement process for COTS-based C^3I systems, and its suitability

for academic investigation. Interestingly, the proposal (section 3.8) encompassed a number of the areas of investigation:

- Procurement (COEIA)
- Requirements (MOEs, MOPs, C^2 Process)
- Architecture and Modelling (LVM and GRM)

That this proposal proved successful during the subsequent modelling investigations, as discussed below, confirms the utility of the research survey that spawned it.

7.3 Implementation of the COEIA White Box Modelling Proposal

The COEIA white-box modelling concept, proposed in section 3.8, was based upon the following underlying assumptions:

(i) A white-box model of a C^3I system could be produced using a combination of the LVM and GRM, which allowed representation of the technology, human and process elements of a C^3I system, together with their interactions.

(ii) A COEIA white-box simulation model could be produced, which embeds competing white-box C^3I system models in a dynamic conflict scenario, with which C^3I system effectiveness could be measured.

(iii) The resultant COEIA white-box simulation model would offer benefits over existing black-box parametric approaches to COEIA, particularly with regard to assessing the effect of COTS on C^3I system effectiveness.

In essence, the modelling work of this project, presented in Chapters 4, 5 and 6, provided an opportunity to investigate the validity of these assumptions through the experimental implementation of the proposed COEIA white-box modelling concept. This is discussed in the sub-sections, below.

7.3.1 White Box Modelling of a C^3I System: Developing the LGRM

The starting point for this work was the LVM, with layers representing technology, people and process. Importantly, people were to be seen as part of the C^3I system, not as simply making use of that system. Such a view may not appear uncommon [Sovereign, 1988]. However, including people need not imply including human behaviour; for example, many models represent humans as time delays in making predictable decisions, only. Clearly, this would be inadequate in the research of this

thesis; it would be important to recognise human behaviour, since this evidently has a significant impact on C³I system effectiveness, which could potentially mask any affect that introducing COTS might have.

When attempting to employ the GRM to provide semantics to the layers of the LVM, the resultant mapping was required to be:

- Generic, since the eventual model might be applied to a wide variety of situations and systems.
- Complete, since otherwise it would never be clear if the model were finished; a not uncommon situation in some approaches to modelling.
- Abstracted to a level which was still meaningful, but which would allow practical instantiation. Abstraction promised control of detail.

The use of the GRM, itself, would encourage a generic solution, and the intended inclusion of human behaviour would do much to ensure completeness of the resultant C³I system model. Abstraction, as always, was a difficult issue, and would dictate the way that the GRM was employed within the LVM.

Initial ideas of using the GRM to model individual systems within each of the three layers of the LVM were quickly discounted because of the complexity, and lack of abstraction, that this would produce (section 4.4). Even reducing this to one GRM per layer proved unsatisfactory, and the eventual mapping of individual aspects of the GRM on to the three LVM layers provided the most abstract solution; thus, resulting in the basic LGRM defined in Figure 4-5.

Although the basic LGRM provided an abstract representation of a C³I system, its precise formulation was not trivial. Building upon the notion that one LGRM could represent one C³I system, the three central layers were necessarily mapped as Form, Behaviour and Mission Management. Viability Management and Resource Management became services, supporting all three of the central layers. Finally, in making the logical connections between layers, it became clear that upward connections, from Form to Behaviour, to Mission Management, were insufficient.

There would need to be continual interplay between Behaviour and Mission Management layers, in both directions. Any information entering the overall system was subject to the cognition and interpretation processes in Behaviour, prior to being employed in the Mission Management process. Further, deductions and decisions formed in the processes of Mission Management would necessarily entail beliefs, training, doctrine, ethics, etc., all of which are part of Behaviour. Hence, these two top layers were intimately connected in both directions as shown in Figure 4-6.

There also had to be downward connections from the top layer, Mission Management, to the bottom layer, Form, to represent control information pathways. Without such pathways, Mission Management would not be able to control its own physical structure and activity.

The whole structure of the LGRM took on the form of a layered model, with multiple internal loops, lending itself to subsequent dynamic simulation. It was evident, however, that the LGRM, although capable through these control loops of operating, adapting and maintaining itself within its resource limits, was still disconnected from the outside world. It could neither receive information and resources, nor affect other systems. The LGRM, like the GRM, described only the internals of a system. The LGRM had, however, gained an essential level of abstraction, 'direction of causality' and 'dynamic' from its LVM host, which the GRM, alone, lacked.

At this point, it was clear that:

- It was possible to use the LGRM to represent any socio-technical system explicitly, including architecture, sub-systems, processes, human behaviour, etc.
- It was important to test the suitability of the LGRM for representing C^3I systems, by the process of instantiation.

To test the LGRM, it was used as a template to map out the architecture of a naval C^3I system as shown in Figure 5-4. The instantiation placed technology in the Form layer; technology represented only part of Form as defined in the GRM, but was sufficient for the end-purpose of comparing COTS versus Bespoke equipment.

Mission Management was instantiated as the C^2 Decision-Making Process, with two archetypes of decision-making: naïve and Recognition Primed. This accounted for contemporary research in that discipline area [Klein, 1989]. In the process of instantiation, it became clear that there were potential difficulties in bounding the C^3I system, particularly with respect to the Technology/Form layer. It has never been entirely clear from the literature as to whether sensors and effectors are part of C^3I, or form separate systems. Our initial view was that they should form part of the C^3I system, and instantiating the LGRM as a naval C^3I system supported this. C^3I, at least in the context of this research, would include all sensors and effectors within the control loop passing through the C^2 decision-making process. The instantiation suggested that system bounding is best viewed, not as including/excluding parts or subsystems, but as the perimeter formed by a closed loop of causality. Such loops provide both tangible and psychological closure.

The success of the instantiation process underwrote the acceptability of the LGRM as a way of representing a socio-technical system, and of a C^3I system, in particular. Even then, limitations were considered to exist.

The LGRM, like the GRM from which it is in part derived, is deductive. This is particularly evident in the Behaviour Model, which is based on Jungian psychology [Campbell, 1977]. Furthermore, the Behaviour Model does not predict behaviour, *per se*. Instead, it presents a set of mechanisms and data banks that, together, enable the selection of a suitable behaviour in response to a stimulus. Such a model is not provable in a mathematical or logical sense. Instead, it has to stand up to scrutiny using Popper's Method of Refutation and the Principle of Falsifiability [Popper, 1959].

Notwithstanding the above concern, the work conducted in this phase of the project clearly revealed that the LVM and GRM could be combined in a synergistic way, in the form of the LGRM, to provide a white-box model of a C^3I system. This supported the initial assumption upon which the COEIA white-box modelling approach was proposed, and provided a sound basis for continuing the investigation.

7.3.2 COEIA White Box Simulation Model

With the role of the LGRM established as the basis of a white-box C^3I system model, attention moved to developing the COEIA white-box simulation model that would be used to measure C^3I system effectiveness. The assumption was that this would involve:

(i) Deriving a static COEIA white-box model, using two competing LGRMs (as the simplest case) each representing the C^3I system of an individual Ship (Red and Blue).

(ii) Translating the static model, above, into a (dynamic) COEIA white-box simulation model (using STELLA™), which would provide a simulated scenario within which C^3I system effectiveness could be measured.

Before embarking upon (i), above, it seemed sensible to test the underlying assumption that such an approach was necessary. In particular, could effectiveness be derived directly from the LGRM-based white-box model? Careful examining of this white-box C^3I system model quickly confirmed that it was, indeed, insufficient to measure C^3I effectiveness. As an internal view of the C^3I system, the single LGRM is essentially isolated from the environment, sensible inflows and outflows, and from the effect that C^2 decisions (and weapons) may have on an opponent or situation. For example, the single LGRM is unable to:

- Sense the environment (there is none represented).
- Apply weapons, since it 'knows of' no targets.
- Sustain inflicted damage.
- Assess situations.
- Formulate sensible, ethical, doctrinally-sound decisions.
- Navigate.
- Exercise the internal pathways connecting its various parts.

Accordingly, the static COEIA white-box model was formulated, one half of which is illustrated in Figure 5-4. At this stage, it was pertinent to consider whether this static model would be sufficient, in itself, to assess C^3I system effectiveness, thus obviating the need for step (ii), above. Consideration of the meaning of 'effectiveness' led firmly to the conclusion that this would not be possible.

Adopting the view that "The justification for C^3 systems must be based on the combat or mission outcome" [Girard, 1989], confirmed that system 'effectiveness' must be considered as the effect that one system has on another. Consequently, it becomes evident that effectiveness is unlikely to be a static, single measure even in a stable situation. As one system affects another, particularly in a combat sense, the affected system will change; for example, it may be damaged. In so doing, it is likely to be affected in a different way, to a different degree, or at a different rate. All of this suggests that effectiveness will have a dynamic property that will unfold over time. Hence, the need was re-affirmed for a dynamic simulation to unravel C^3I effectiveness.

Dynamic simulation was also thought necessary to aggregate the separate, yet simultaneous, effects of the various subsystems and mutual interchanges within the white-box C^3I system model. Changes potentially reflect and reverberate throughout a C^3I system, and it was impractical to infer this complex behaviour pattern from the static view of the LGRM [Roberts, 1983].

As a result of these considerations, the (dynamic) COEIA white-box simulation model was constructed, as planned in (ii), above. A key feature of this simulation is the way that the two interacting LGRMs were coupled, so that the outflows of one became the inflows of the other, and *vice versa*. The flows were mediated by the environment and driven by a scenario. Coupling two LGRMs, interactively, creates: information flow, and handling mechanisms, upwards and downwards; logical connections horizontally between corresponding layers; and mutual interaction which elaborates over time, impacting upon all of the systems so represented. This coupling of two LGRMs also creates a formal model, and the basis of a generic scientific methodology; that is, a means of exploring the dynamic interactions between, and within, systems [Forrester, 1972].

Two identical LGRMs were chosen for the COEIA white-box simulation model. The reasons for this choice were as follows:

(a) C^3I effectiveness is determined, not only by attack, but also by defence. To measure effectiveness, then, it is necessary to exercise such capabilities as resistance to jamming, damage repair, etc. If the second LGRM represented the

same ship, then the interchange between the two would reveal the balance between offence and defence for the one ship.

(b) Setting the two LGRMs to be identical creates a null balance. Over any simulation period, within the same environment and scenario, their respective outflows and inflows should be the same; hence, any measures of effectiveness, applied to either LGRM/ship, should be the same, too. This balance allows the introduction of individual changes to one of the LGRMs, while holding the other constant as an interactive, dynamic reference model. Any change to overall C^3I system effectiveness would then be observed as a move away from the null balance, and would be exclusively attributable to the introduced change.

(c) By making the LGRMs/ships identical, the represented ship is interacting with itself. No extraneous factors are introduced, as they would be if some other platform were the opponent. This leads to a 'purity' of result, since only data about the one C^3I system has been used.

(d) Making both LGRMs/ships identical eliminates much of the extraneous detail, since identical factors on both sides tend to cancel each other out. This helps to maintain the high level of abstraction, and allows unforeseen factors which may be relevant, to be introduced on both sides. If, following investigation, these are found to be irrelevant, they can then be deleted.

(e) Dynamic simulation becomes necessary as each LGRM/ship affects the other, changing their respective opponent's transfer function, architectures, resources, etc. C^3I system effectiveness thus emerges, not as a static, single number, but as a profile that unfolds over time. System Dynamics methods (via STELLA™) were chosen, since these emphasise the dynamics and de-emphasise the static structure. Identical simulation models inflict and incur identical damage, keeping the simulation 'pure', as before.

(f) Finally, and philosophically, there is a sense of psychological closure in making both representations identical. This closure is expressed in the Zen koan: "*Fundamentally, the marksman aims at himself*" [Schiller, 1994].

The characteristics of the resultant STELLA™ simulation that was developed, as presented in Chapter 5, provided confidence in the feasibility and utility of the COEIA white-box simulation model. This clearly supports the second assumption upon which the COEIA white-box modelling approach was proposed, and encouraged

the experimental use of the simulation model for effectiveness studies, as presented in Chapter 6.

7.3.3 Comparison of White Box and Black Box Approaches for COEIA

Having completed the development of the COEIA white-box simulation model, and employed it for C³I system effectiveness studies, it is appropriate to re-consider its potential utility, with respect to black-box parametric approaches for COEIA; in particular, that being developed by DERA Portsdown [Young, 1998].

It will be recalled, from Chapter 3, that the DERA approach collects MOPs for various functions of a C³I system, and combines them in a weighted sum, using an MCDA technique, to obtain an overall figure of merit for a particular C³I system. This can be contrasted with the COEIA white-box simulation model, which provides two white-box C³I system models (Red and Blue), competing in a dynamic conflict scenario. Each white-box C³I system model is represented as a LGRM, and effectiveness is measured dynamically by the effect that one C³I system has on the other.

When reviewing the characteristics of these two approaches, the COEIA white-box simulation model appears to provide a number of distinct advantages:

(i) **Model Visibility**. Unlike the DERA black-box approach, the COEIA white-box simulation model, via its incorporated LGRMs, exhibits architecture, interchanges between parts, processes for decision-making, human behaviour as it affected the C² process, and closed control loops for managing sensors, weapons, navigation, engines, damage repair, etc. Importantly, the LGRMs maintain a high level of abstraction, since they are concerned primarily with causal change and dynamics, as opposed to representing static C³I system structure, and this is a significant aid to improving visibility and removing unwanted complexity. This means that it is possible to reason about the effectiveness outcomes which the COEIA white-box simulation model produces; for example, to explain counter-intuitive results, as was the case in Chapter 6. The use of MCDA to understand the effect of black-box weight

selections on C^3I system merit figures, for example, offers less opportunity for such insight and understanding.

(ii) **Human Behaviour Representation**. The COEIA white-box simulation model exhibits purposeful behaviour, through the dynamic interactions of its LGRMs. Whereas a black-box model gives the same response to the same stimulus, each LGRM within the white-box simulation model, with its representation of human behaviour, changes its response as it learns from experience; for example, it changes its behaviour as it receives an increasing number of enemy hits. Clearly, C^3I system effectiveness must address human decision-making performance and behaviour; for example, the ability to learn and adapt. Importantly, under adverse conditions, C^2 decision-making will continue with little or no technology. It is difficult to see how a black-box approach can accommodate these issues, particularly when human decision-making performance is considered non-linear [Klein, 1989]. A natural reaction to this difficulty is to consider people to be outside of the system, and assign MOPs to the human-computer interface. This is clearly of limited utility.

(iii) **Scenario Derived Effectiveness**. The COEIA white-box simulation model measures effectiveness as the effect that one LGRM has on the other, in a dynamic conflict scenario. In the black-box approach, MCDA seeks to amalgamate MOPs for various C^3I system functions. These MOPs must imply some reference environment and or/scenario, and would tend, therefore, not to address a wide range of situations. MCDA should also recognise the interrelationships and synergies between associated elements of architecture (e.g. sensors and weapons). However, since many of these interrelationships behave non-linearly under increasing workload, and neither architecture nor workload is explicit in the black-box approach, there is clearly a difficulty here.

These observations serve both to confirm and extend the potential advantages of the COEIA white-box modelling approach, which were originally envisaged when it was proposed (section 3.8).

7.4 Simulation Model Development Issues

The process of developing the COEIA white-box simulation model was a substantial undertaking, involving the careful implementing and configuring of the incorporated LGRM-based models, and requiring appropriate effectiveness measures to be selected. These issues are discussed in the sub-sections, below, together with an assessment of the STELLA™ tool, which was used to implement this dynamic simulation.

7.4.1 Implementing and Configuring the Simulation Model

First, one LGRM-based C³I model was created in STELLA™, and tested by turning its own outputs back upon itself as inputs. Each module of the model was created in isolation, tested, and then integrated. So, the radar transmitter signal was passed through an inverse fourth power filter, set to represent the attenuation that would result from a signal travelling 50 nautical miles (nm), and the result was fed into the radar receiver. The receiver also received noise from a (chaotic) Lorenz weather simulation, and from ship's own jammer, diminished in this case by an inverse square law filter. The receiver was set with a threshold allowing it just to distinguish signals through a nominal signal-to-noise ratio. Similar conditions were set up for other features, including the firing of weapons and the consequent hit/miss performance and hit-damage distributions. Weapons were allocated a nominal probability of hit (Ph) that could subsequently be altered. Typical damage distributions were matched by damage repair capabilities, in the form of damage repair teams. These teams each comprised 15 members, who were deemed vulnerable to casualties when in action.

The resources module of the simulation was set up to represent storage and repair of technology. Since the specific objective was to measure the impact of COTS on C³I effectiveness, each item of technology was represented as both bespoke and as COTS. Selecting one or the other chose, not only the prime equipment in use, but also the number and type of spares, the maintenance and support facilities, and the costs of the technology and its support.

Implementing the Behaviour Layer required caution. Several factors had to be omitted either because of difficulties of understanding and/or representation [Pew, 1998]. Ethics and morals proved impractical to represent dynamically, so it was

assumed that they did not change over the period of the two-hour simulation. Experience, on the other hand, would accrue over that period, so the simulation accumulated experience as the number of enemy hits received, and used this accumulation to operate within a framework of doctrinal rules. One such rule was: 'if the number of enemy hits exceeds x, then reverse course and disengage'. This rule took the doctrinal view that it was better to retreat than to stand and take a beating.

Training was instantiated as part of the Belief System. Here, the effects of training were considered beneficial in two spheres: recognition of situation and threat; and formulating decisions and orders to fire, navigate, etc. The world view expressed was that training improves speed and ability, along with experience.

The cost model was developed to be comprehensive. Costs were allocated to personnel as casualties. The costs, and effects, of training were represented so that (simplistically, perhaps) a better-trained crew would recognise situations and targets more quickly, and would make decisions about what to do to those targets in less time. Logistics curves were employed, using Fechner's Law, such that more training was better than less, but even more training offered diminishing returns [de Neufville, 1974]. Once the single C^3I model simulation had been tested using its own outputs as inputs, the model was duplicated and cross connected so that outflows from one C^3I model crossed to inflows to the other. The two C^3I models/ship models gave identical cost effectiveness profiles at the first test.

7.4.2 Measures of Effectiveness

Additional measures of effectiveness were now feasible. Three were trialled:

1) Cost exchange ratio, in which the relative combat costs of Blue ship versus Red ship were calculated. Equal costs gave a ratio of 1:1.
2) Casualty exchange ratio, where the numbers of Red and Blue ship casualties were calculated and arranged so that equal casualties gave a ratio of 1:1.
3) Return on Capital Employed (ROCE), in which combat costs to Red were seen as Profit, combat costs to Blue were seen as Loss, and Capital was seen as the overall cost of the ship and its trained complement.

None of these measures would have been sensible without the essence of the LGRM and, most importantly, two identical, interacting LGRMs representing two identical ships.

The other measure used was conventional cost effectiveness. Blue cost effectiveness was defined as:

(Blue Capital Cost-Blue Combat Costs) ÷ Blue Capital Cost*100 [7.1]

An equivalent measure was established for Red Cost Effectiveness. This measure was set up to be consistent with Sun Tzu's dictum: *greatest effectiveness arises where there is no fighting, where the enemy surrenders or runs away without fighting* [Griffiths, 1982]. Cost Effectiveness was 100% when there was no combat. Combat Costs included both the cost of weapons, and the cost of losses and damage:

Crew Costs + Damage Expenses + Maintenance Costs + Weapons Costs [7.2]

Even in this measure, then, it is necessary to have two interacting ships, since the measure considers not only expenses of firing and maintaining, but also those of incurring casualties and damage.

7.4.3 Pros and Cons of the STELLA™ Simulation Tool

The resulting STELLA™ model was simple to use and gave sensible verifiable results. Results were often counter-intuitive. This arose because the simulation model was complex; it comprised a very large number of loops, giving rise to complex behaviour such as is evidenced in real C^3I systems. In every case, it proved possible to determine the source of the apparent anomaly, and to justify the counter-intuitive result; this gave confidence in the model and the results. Ideally, time-elaborated profiles of effectiveness should be the measure of effectiveness. Pragmatically, it is difficult to compare profiles, so the effectiveness figures at the end of engagements were frequently used. The whole simulation was kept within bounds of simplicity by limiting combat time to two hours only. This negated any need for logistic re-supply, for instance, and allowed the two interacting LGRMs to be sensibly considered as the whole system.

In a more practical situation, combat might occur only after many hours at sea, and combat might occur spasmodically over an extended period. STELLA™, being a continuous event simulation, could represent such situations, but the program would

run for hours with nothing much happening. This irksome delay can be addressed either by employing a discrete event simulation program, or by coupling together a number of STELLA™ models, some addressing these long periods of relative inactivity and providing starting conditions for the more active combat models.

Considering one ship in combat with one ship is also unrealistic. It is more likely that a battle group or surface action group would be formed. A battle group might comprise several ships, aircraft and submarines. Each of these could, in principle, be represented by one or more LGRMs, with the whole set interacting. As before, the best way to establish objective effectiveness measures would be to pit the group against itself. Such a simulation would be much more complex than that developed so far. Until recently, it would have been prudent to suggest that STELLA™ might be unable to accommodate such complexity and processing demand. The advent of gigaflop desktop machines (such as the Apple G4) suggests that the limitation may no longer be relevant. Overall, the advantages that STELLA™ offers, including its active icon representations, and its three levels of representation, make it difficult to match for this application.

7.5 Application of the COEIA White Box Model

This section describes some alternative uses of the existing COEIA white-box model, and makes recommendations for improving and expanding the current concept within the naval domain.

7.5.1 Using the COEIA White Box Model

The COEIA white-box model can be considered as looking down on the interaction between two identical systems, as shown in Figure 7-1. The figure shows both systems interacting, within a common operating environment. As a result of their mutual interactions, effectiveness of either system can be observed as the impact it has on the other. This measure will change over time as each system also changes the other. With both systems being identical, changes in both systems' MOEs become relevant.

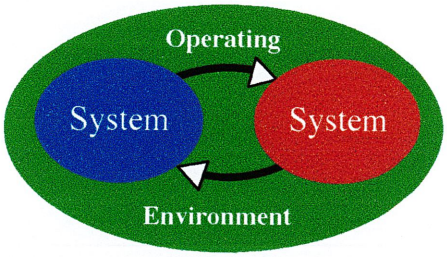


Figure 7-1 Two Interacting Systems

Elaboration opens up the two systems, as shown in Figure 7-2. This view is essentially the white-box view, with measurements of effectiveness being made as the two LGRM-based ships interact.

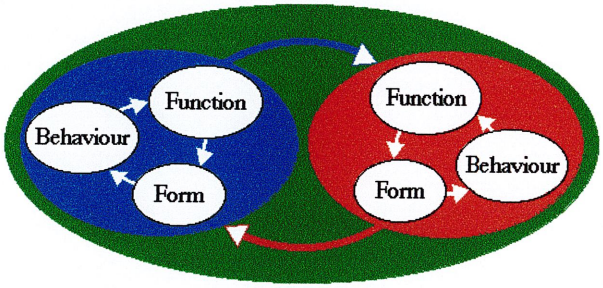


Figure 7-2 Two Interacting LGRMs

Figure 7-2 is a view of the COEIA white-box simulation model, at its highest level, which has been developed, simulated, tested, and used to establish proof of principle. The COEIA white-box model is proposed as a suitable medium to predict and measure effectiveness. In particular, it has been used in this research to explore the impact of introducing COTS on C³I effectiveness. As many of the figures for costs, failure rates, powers, etc., were notional only, and as the intent of the research was to establish proof of principle for the COEIA white-box approach, it would be imprudent to read too much into the actual results from the simulations undertaken so far. However, some broad deductions seem possible. First, it is difficult to define the characteristics of COTS components. They may perform as well, or better, than their bespoke counterparts. They may be as reliable, or more so. In fact, it is difficult to find any single, technical characteristic that clearly distinguishes COTS. One feature that seemed reasonable to choose was initial price. It seemed reasonable to expect a COTS item to cost less than its bespoke counterpart; otherwise, why would defence procurers want to buy it?

A second reasonable characteristic was a shorter intended operational lifetime. It seemed reasonable to suppose that COTS equipment would be subjected to update and upgrade, or even simple redundancy, in less time than bespoke. This reduced lifecycle presents both a cost and an opportunity to the procurer and the operator. The continual upgrade will incur cost, and may incur organisational disturbance; it also presents opportunities for continual performance improvement.

Within these constraints, the proposed COEIA white-box model was able to show that COTS is most likely to offer benefit where it is treated by the users as a consumable. So, all other things being equal, weapons clearly would benefit, since they are consumable by definition. Firing a lot of cheaper weapons saves a lot of money, provided they are as effective as their bespoke equivalent. Less obviously, perhaps, most information handling systems and components could also be viewed as consumables; that is, bought with the *intention* of discarding them after a period. This is not the current attitude of defence procurers, nor is the military organisation set up to deal with this high turnover in consumable products. It is routine commercial practice, however, where everything from company cars to management information systems is treated as consumable.

The COEIA white-box model also offered potential to undertake trades-off in such an unconventional area as command team training costs versus weapon performance. The idea was that a weapon with greatly enhanced capability may take the pressure off the command team to recognise and react to threats so quickly. The results from that experiment were inconclusive.

7.5.2 Alternative Uses for the COEIA White Box Model

So far the COEIA white-box model has been employed with identical competing systems. Within this bounding condition, it is possible to examine a limitless variety of scenarios and environmental conditions. It would be necessary to consider a variety of scenarios before establishing an overall effectiveness measure for a C^3I system.

It could be possible to use the COEIA white-box model to optimise the C^3I system, using cumulative selection or hill-climbing techniques (section 6.6). This enables the

COEIA white-box model user to identify the performance characteristics of individual technological equipments that enable them to contribute optimally to overall C³I effectiveness. So, instead of supplying measures of performance into a black-box model, the white-box approach derives measures of performance from the optimisation process. This approach establishes the performance characteristics of the various equipments, not individually, but as a set of synergistic contributors to overall C³I effectiveness.

It might also be possible to test this optimum (Blue Ship) C³I configuration by replacing Red Ship with a representation of an entirely different ship; one which might be confronted as an enemy in the future. Optimised Blue Ship's C³I effectiveness may now be measured against this hostile Red Ship.

Using this revised COEIA white-box model, the potential then exists to hold one ship model constant, as a reference, while the other is optimised. The positions would then be switched. The second ship is held constant while the first is optimised, and so on, in a cyclic fashion. This would enable Blue Ship C³I design to be optimised against a variety of enemy Red Ships, and would also enable Blue Ship design to leapfrog, by anticipating upgrades to enemy ships.

7.6 A Systems Approach to Procurement

This section discusses the wider implications of this research work and how it can lead to the wider application of COEIA, an understanding of emergence, and a new scientific way to conduct systems engineering.

7.6.1 Wider Application to Support COEIA

The COEIA white-box model enables measures of effectiveness, expenditures and costs. It seems ideally suited to support COEIA. However, as Figure 7-3 shows, it is possible to go further. The Blue LGRM has been elaborated further, revealing both Resource Management and Viability Management. Connected to Form, is an external Procurement System, and Resource Management is connected to an external Logistic System. Each of these two external systems interacts with Defence Suppliers. Similar external systems and connections could be attached to Red System.

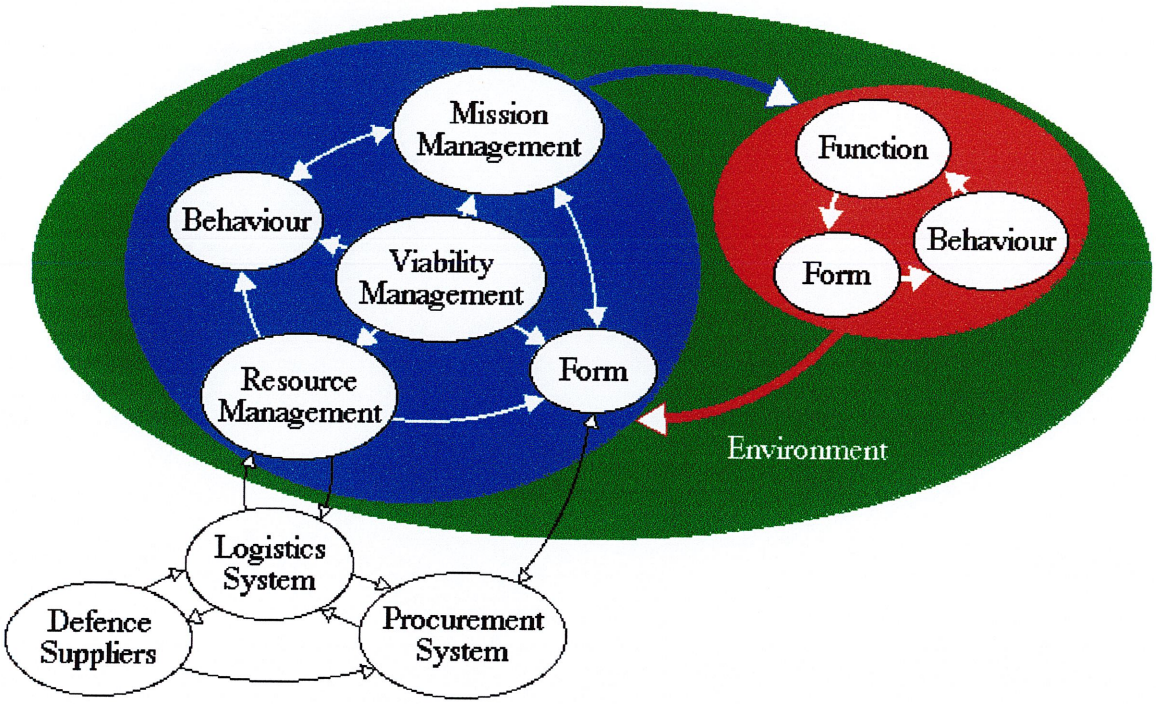


Figure 7-3 Elaborated Systems Interaction Model

Using this arrangement, the simulated combat between Red and Blue Ships can be supported by simulated procurement and logistic systems. The expanded COEIA white-box model would operate in the same way as before. Once the model has been set up to represent, say, current logistic and procurement methods, then C^3I effectiveness should be identical for Red and Blue systems. Changing an element in, say, Blue Logistics would create an imbalance, and would affect the null balance between the two competing ships. It would then be feasible to experiment with Blue System design, for example, and optimise the complete system (suppliers, logistics, procurement and force).

7.6.2 Understanding Emergence

In the course of the research, complex representations of systems interacted mutually, and frequently produced counter-intuitive results. It was often the case that, in unravelling these situations, several causes were found to have contributed to a counter-intuitive result. It seems reasonable to assert that the complex interacting system representations are exhibiting emergent properties, capabilities and behaviours (PCBs). This assertion is in keeping with the definition of emergence: properties of

the whole that cannot be exclusively attributed to any of the parts. There is, for example, a most definite irreducibility about C^3I effectiveness.

In the COEIA white-box model, and because (particularly) of the representation of complex interactions within the internal causal loops, changes in any of the parts impacted on the other parts. Changes to any one part, or process, affected many others, and it was the combination of all these changes that affected C^3I effectiveness, *inter alia*. In fact, the COEIA white-box model generates emergent PCBs, of which C^3I effectiveness is only one.

As a result of the nature of the representation, the COEIA white-box model exhibits only a small proportion of the full range of PCBs that real ships would exhibit. For instance, all up weight, centre of mass, top speed, and many other features do not emerge. Nonetheless, within the limits of the represented features, dynamic behaviour does emerge from the white-box model, in the form of decisions to navigate, to withdraw, to engage, to cease firing, etc. All of these decisions are acted upon, and modified in the light of experience, provided that the ship is still capable.

It is tempting to believe, in generating simulated emergent behaviour, that it is now fully understood. That would be unrealistic. The STELLA™ program comprises a set of inter-linked differential equations which generate emergent behaviour, but that falls short of understanding.

However, the mechanisms of emergence are becoming clearer. Each processing and translating element in the complex system has some form of transfer or transmission function. The elements are also transitive; that is, an external influence is passed through and beyond the element, so that all elements are connected either directly or indirectly. The various elements are inter-connected and intra-connected into webs of interactions; feedback occurs in the process, both as positive reinforcing, and as negative control feedback.

As a result of this complex web of interactions, 'pools of stability' are established within the overall system; that is, areas of relative dynamic stability. These are

observed/labelled as functional sub-systems, and they may result from negative feedback or from multiple positive feedback loops.

In principle, it may be possible to produce a mathematics, or calculus, for emergence, to describe the elemental functions and the web of interactions. If so, it seems likely that the resulting mathematical structure would prove difficult to solve for any but the simplest cases; if only because of the overtly non-linear behaviour of the elements and the feedback mechanisms. However, a world view of emergence seems possible:

- Many PCBs emerge from a complex system.
- Some PCBs emerge as a result of interactions with other systems and/or the environment.
- Each PCB emerges, *inter alia*, as a result of features within the system, and as a result of interrelationships and interactions between some or all of those features.
- Different PCBs may derive from different parts and different interactions, but since all PCBs may emerge simultaneously and continuously, it follows that the sum of PCBs emerges from the sum of all parts and all interactions and interrelationships.
- This is the nature of the irreducibility, and explains why reductionist methods of systems analysis must inevitably be limited.

Given such a world view, it may seem more practical to pursue an understanding of emergence along lines similar to those used to create the COEIA white-box model, but omitting any instantiation; that is, retaining a generic, whole-system view.

7.7 Scientific Systems Engineering Method

At a more practical level, the research suggests that there may be a scientifically supportable way to conduct systems engineering. Instead of starting with a system design already in mind, it would be straightforward to create an initial design using an LGRM template, to ensure appropriateness and completeness. An overall system design could be built up from subsystems, with (at least) one LGRM per subsystem, and different teams, using the same LGRM template, could design different subsystems, perhaps in different locations.

Connecting the subsystems constitutes the creation of system architecture, and the capacity of the intra-connecting 'pipes' can be modelled, too, to represent the potential for interface constrictions, bandwidth limitations, etc.

Once the overall system design has been achieved, it can be tested against itself in representative environments, using a COEIA white-box model approach, then evolved and optimised using cumulative selection. This process leads to ideal system and subsystem specifications; these being chosen, not individually, but to ensure that the overall solution exhibited the required whole-system emergent PCBs. All of this could be achieved, if necessary, using a distributed white-box model, with subsystem representations mutually remote but connected via data links.

The overall model would then act as a template to guide development of the system. If parts or subsystems, as developed, were not as specified, then the likely effects of differences could be explored using the model. Other subsystems or intra-connections might be adjusted to restore the requisite emergent PCBs of the whole.

In essence, such a white-box model would enable system designers and developers to see how the design works, how the parts and their intra-actions contribute to the whole, and how to balance those parts and intra-actions to create the requisite, optimum emergent PCBs.

7.8 SWOT Analysis

The following SWOT analysis examines the essence of the COEIA white-box modelling concept, to outline its perceived strengths and weaknesses, the opportunities that it may afford in the future, and any possible threats that must be considered for its successful continuation.

7.8.1 Strengths

The principal strengths of the COEIA white-box modelling approach are:

- Scientifically based.
- Uniquely, exhibits emergent Properties, Capabilities and Behaviours.
- Open, verifiable, falsifiable.
- Generic, so widely applicable.
- Points to important areas for research, especially in areas of human behaviour.
- Soundly based on systems principles.
- Represents a total system, bounded within a causal loop.
- Subsystem interactions explicitly represented.
- Represents/generates linear and non-linear patterns of behaviour, including chaotic, if appropriate.
- Generates requisite measures of equipment(s) performances as a consistent set needed to optimise system effectiveness
- Represents the impact of contained human behaviour on a system's emergent PCBs.

7.8.2 Weaknesses

The major weaknesses of the COEIA white-box modelling approach are:

- More complicated to create than a black-box model, since the white-box model invokes explicit representations of architecture and inter-connection.
- More difficult to analyse than the static black-box model, since the white-box presumes dynamic behaviour; changing with time, situation and scenario.
- Difficult to instantiate completely, especially for Behaviour, about which insufficient is known.
- For some systems (e.g. international forces comprising many different ethnic and cultural groups) a significant number of LGRMs might be needed to

provide reasonable representation for the whole. Cross connecting these various LGRMs to create a COEIA white-box model may well result in unacceptable complexity.

- Alternatively, reducing the number of LGRMs to control complexity necessitates assumptions about social homogeneity that may be unreasonable.

7.8.3 Opportunities

Opportunities presented by the COEIA white-box modelling approach include:

- Significantly improved COEIA.
- Expanding the application of COEIA to cover defence capabilities.
- Extending the application of COEIA to encompass life cycle logistics, procurement and defence contractor relationships.
- Developing an understanding of the phenomenon of emergence and, hence, applying that knowledge to social as well as technical issues, within defence, but also on a wider social front. For example:
  - policing, both at the international level (peacekeeping) and at the local level.
  - digitisation of the battlefield.
  - crime and punishment.
- Creating a much needed scientific approach to systems engineering, both for defence and more general application.

7.8.4 Threats

Threats to the acceptance of the COEIA white-box modelling approach include:

- Approach requires broad understanding across many disciplines to apply it, and is probably best suited to team creation.
- Distrust of simulations and models, even open white-box models.
- Adherence to traditional methods; resistance to change.
- Reluctance to fund the white-box approach.
- Misapplication/misunderstanding of the white-box approach by introducing unnecessary, reductionist detail.
- Disregard for System Dynamics methods which have been denigrated in the past.

- Poor understanding of causal loop modelling and causal loop system bounding, as opposed to (superficially-similar) influence diagramming.

7.9 Summary

This chapter commenced by discussing significant issues arising form the research results of Chapters 3, 4, 5 and 6, under the following main areas:

- Survey of COTS procurement for C^3I systems.
- Implementation of the COEIA white-box modelling concept.
- Development of the COEIA white-box simulation model.
- Application of the COEIA white-box simulation model.

Additionally, on a much broader front, the chapter has discussed and proposed how the COEIA white-box modelling approach may be used to address:

- Extension of COEIA to include defence logistics and procurement.
- Understanding emergence from complex systems.
- A scientific method for systems engineering.

Finally, it has provided an outline SWOT analysis for the COEIA white-box modelling approach.

Chapter 8: Conclusions

8.1 Introduction

This chapter presents the overall conclusions from this PhD project. It does this by drawing upon the research results and discussion of Chapters 3, 4, 5, 6 and 7, to address the research objectives and hypotheses defined in Chapter 2.

8.2 Achievements against Objectives and Hypotheses

The objectives that this thesis is intended to meet are divided into two separate sets. The first set was derived to address an initial 'exploratory' hypothesis; the second set was formed to address a central hypothesis, which resulted from achievements against the first set. The following two sections (8.2.1 & 8.2.2) identify how the achievements of the project addressed the initial and central hypotheses, via their associated two sets of objectives.

8.2.1 Initial Objectives

Three initial objectives are described in Chapter 2. The following three sub-sections (8.2.1.1 - 8.2.1.3) describe the project's achievements against these objectives.

8.2.1.1 To Uncover Current Thinking, Issues of Importance, and Trends in COTS-based Procurement for Military C³I Systems

This objective was addressed by the initial exploratory phase of the research survey, presented in section 3.3. Issues covered included: the perceived advantages and disadvantages of COTS-based procurements, the probable effect of COTS on military standards, relevant trends, and outstanding issues to resolve. Many of the reported COTS developments related to UK activities, but some US initiatives were also considered. The survey established that the use of COTS for C³I systems is a relatively recent initiative, with varying published definitions, and no established theory supporting it. However, there is general acceptance in military organisations that defence budgets cannot hope to rival global, commercial developments in information technologies and, thus, COTS-based procurement is vitally important for C³I systems. Nevertheless, there are residual concerns about the attendant development and procurement risks, which are exacerbated by the lack of academic

definition and understanding. Therefore, this field requires careful scientific structuring, which is addressed in the next objective.

In conclusion, the work provided a sound foundation upon which to tackle a more focused survey. Accordingly, this objective is considered to have been achieved, within the context of this project.

8.2.1.2 To Identify and Explore Specific Areas of Central Importance to Achieving an Effective COTS-based Development and Procurement Approach for Military C³I Systems

Using a simple model of COTS-based development, four key areas were identified to address this objective: C³I Requirements Modelling and Analysis, C³I Architectures and System Modelling, Component Technology and Evaluation, and COTS-based Procurement Processes. Collectively, these provided a structuring of the research domain for the COTS-based procurement of C³I systems, and a focused research survey in each of these areas was conducted. The results of this are presented in sections 3.4 – 3.7, and discussed in section 7.2. This focused investigation proved extremely useful for understanding current developments and issues, and for providing a framework for analysing what is being done and where additional research could usefully be undertaken.

Although the focused research survey was necessarily constrained by project timescales, it was possible to identify opportunities for deepening research, from its results, to address the following objective. Accordingly, it is considered to have fully met its objective, and provides a basis for further investigations and research structuring in this field.

8.2.1.3 To Identify a Specific Issue of Significance to the COTS-based Procurement for Military C³I Systems, which Would Benefit from a Formal Scientific Approach

From the focused research survey above, a number of potential research topics were revealed, where formal scientific/engineering research could support the COTS-based procurement of C³I systems. These are identified in section 3.8 and discussed in section 7.2. They are each associated with one of the areas of the focused research

survey: requirements engineering using Enterprise Modelling techniques; exploitation and assessment of commercial security mechanisms; wrapper technology for dealing with legacy systems/components; procurement risk modelling; and procurement process modelling for incremental acquisition.

In addition, one further issue was identified, which resulted from considerations across the areas. This was concerned with perceived limitations in 'black-box' parametric techniques employed in support of the Combined Operational Effectiveness and Investment Appraisal (COEIA) process (section 3.4.4). Section 3.8 defines a proposal for addressing these limitations, based upon the idea of developing a 'white-box' model of a C³I system, using a combination of a Layered Virtual Machine (LVM) and Generic Reference Model (GRM) (sections 3.5.2 & 3.5.3), which would represent technology, people and process within a C³I system, and would be open, explicit, verifiable and scientifically sound. These white-box C³I system models would then be employed in a COEIA white-box simulation model, within a dynamic combat scenario, to allow C³I system effectiveness to be measured as a function of COTS equipment selection, for example.

In defining the COEIA white-box modelling proposal, the final objective for this initial stage of the project is considered to have been fully achieved, and a sound basis for the central hypothesis of the thesis to have been established.

8.2.2 Initial Hypothesis

The previous section describes how the initial research stage of the project has made a significant impact on the achievement of the initial objectives. Ultimately, a number of potential research topics have been identified, which could improve the formal scientific and engineering basis for procuring COTS-based C³I systems. One of these, the COEIA white-box modelling proposal, has been selected as the basis for the central hypothesis of the thesis. Therefore, it is concluded that the results of this initial stage of the project strongly support the notion propounded in the initial hypothesis that: *Formal scientific techniques have an important role to play in improving the procurement of COTS-based C³I systems.*

8.2.3 Objectives Relating to the Central Hypothesis

Three further objectives, relating to the central hypothesis, are defined in Chapter 2. The following three sub-sections (8.2.3.1 - 8.2.3.3) address the project's achievements against this second set of objectives.

8.2.3.1 To Devise a Suitable White Box Model to Represent a C³I System

The Layered Generic Reference Model (LGRM), presented in Chapter 4, was developed to address this objective. This was achieved by integrating the LVM and GRM, as originally intended, but the precise arrangement was critically governed by the need to provide a high level of abstraction, sufficient to capture appropriate C³I characteristics whilst enabling reasoning about the behaviour of the model. The LGRM was designed to represent C³I systems explicitly, including architecture, sub-systems, processes and human behaviour, in keeping with the original white-box concept. Importantly, weapons and sensors were considered to be part of the C³I system. The LGRM was subsequently instantiated as a way of representing a naval shipborne C³I system. This provided confidence in its ability to represent socio-technical systems, and enabled it to be used to address the next objective.

In conclusion, the instantiated LGRM is considered to have fully met this objective.

8.2.3.2 To Develop a COEIA White Box Simulation Model, to Support C³I System Effectiveness Measurements

The research results associated with this objective are presented in Chapter 5. Initially, a static COEIA white-box model was developed. This comprised two LGRMs each representing the C³I system of one ship (Red and Blue), coupled for the purpose of engaging each other in conflict. One half of this arrangement is illustrated in Figure 5-4. This static model facilitated the implementation of the (dynamic) COEIA white-box simulation model, constructed primarily using STELLA™ as a convenient simulation tool. In addition, cost models were built, Measures of Effectiveness (MOEs) were defined, and operational scenarios were used. The dynamic COEIA white-box simulation model was necessary to aggregate the separate, yet simultaneous, effects of the various subsystems and mutual interactions within the white-box C³I system model. The simulation model was subjected to

appropriate Verification and Validation (V&V) checks, and proved to be a suitable medium to predict and measure effectiveness. This is addressed in the next objective.

In conclusion, the COEIA white-box simulation model, which was developed in STELLA™, is considered to have fully met this objective.

8.2.3.3 To Assess the Potential Utility of the COEIA White Box Simulation Model, through Experimentation

The COEIA white-box simulation model, developed in response to the previous objective, was used to explore the impact of introducing COTS on C³I system effectiveness. Several experiments were conducted for this purpose and are described in Chapter 6. MOEs employed were Blue (Ship) Cost Effectiveness, Cost Exchange Ratio and Casualty Exchange Ratio. The experimental configuration was to set up both ships initially with identical characteristics, then to change one whilst holding the other constant as a dynamic reference. Experiments included the effect of reducing (COTS) equipment costs, technology ageing, technology updating, and C³I system design trades-off.

Results from these experiments revealed that the COEIA white-box simulation model provided a valuable scientific way to determine C³I system effectiveness, establish performance requirements to achieve that effectiveness, and to calculate maintenance and logistic needs to support that effectiveness. Furthermore, the results were all verifiable, thus providing some confidence in the use of the COEIA white-box C³I modelling technique. Moreover, the white-box nature of the model permitted counter-intuitive outcomes to be explained. Overall, these results indicate that the COEIA white-box C³I modelling approach is a viable way forward.

Within the constraints of project timescales, the experiments performed on the COEIA white-box simulation model are considered to provide an adequate 'proof of principle' for this approach. Accordingly, it is concluded that this objective has been achieved.

8.2.4 Central Hypothesis

The previous sub-sections indicate the project's experimental approach and execution have made substantial achievements against the second set of objectives. The results of the experiments suggest confirmation of the central hypothesis that: *It is possible to build a white (or glass) box model of a C³I system with all parts and parameters both visible and adjustable, to assess the impact of COTS selection on overall C³I effectiveness, in order to improve the Combined Operational Effectiveness and Investment Appraisal (COEIA) associated with the procurement of C³I systems.*

Chapter 9: Future Work

There are several ways in which the research work described in this thesis could be built upon. Areas for future work include, but are not limited to, those outlined below.

9.1 Other Directions from the Research Survey

The research survey of Chapter 3 identified a number of potential research directions, which were considered as potential ways of improving the development and procurement of COTS-based C³I systems. Only one of these, the COEIA white-box modelling approach, was elaborated and then adopted for the deepening stage of this PhD project. The others are enumerated in section 3.8 and feature in the discussion of section 7.2. They comprise: requirements engineering using Enterprise Modelling techniques; exploitation and assessment of commercial security mechanisms; wrapper technology for dealing with legacy systems/components; procurement risk modelling; and procurement process modelling for incremental acquisition. Each of these would provide an interesting avenue to explore for future research investigations, within the context of C³I systems.

9.2 Improving the C³I System and COEIA Simulation Models

The current LGRM model, for a C³I system, exhibits purposeful behaviour, but several factors had to be omitted either because of difficulties of understanding and/or representation. These shortfalls point to areas for potential research, since understanding will be necessary to create richer models, especially in the representation of Behaviour; this may necessitate research focused on aspects of human behaviour and decision making, especially under stress, to create real progress and mature theories. In addition, the COEIA simulation model uses a comprehensive cost model, evaluating capital and operating costs, including the cost of damage and repair. However, it would be necessary to feed real cost data to the model, together with naval domain expertise, to take the simulation forward to produce more concrete results.

9.3 Extending the Simulation Model and Combat Scenarios

The COEIA simulation model has demonstrated an engagement between two ships, Blue and Red. This was sufficient to establish 'proof of principle', which was the objective in this first instance. Clearly, the model could be extended, as necessary, to represent more ships, or a Surface Action Group (SAG). It would be necessary to consider a variety of scenarios before establishing an overall effectiveness measure for a C^3I system. For this, the work should be extended to the mission characteristic and mission type level outlined in section 5.3.1, in order to consider properly the impact of the various inter-relationships on overall C^3I system effectiveness. Specifically, the inclusion of the supporting capabilities, particularly communications and interoperability, should be considered further with other mission scenarios.

9.4 Expanding the Usage of the COEIA Simulation Model

The present model has looked at the impact of the LGRM Technology layer on C^3I effectiveness. It is also possible to explore much further. For instance, it is possible to add the performance specifications in greater detail for each component in the Technology layer, associated with the performance cost profile, in order to calculate individual performances, capabilities and behaviours necessary to achieve peak effectiveness.

The present model does not explore the effect of external support and enabling systems on overall C^3I system effectiveness. This area requires further investigation to expand the COEIA simulation model usage, as described in section 7.6. It should be possible to determine the overall value of COTS versus Bespoke on a scientific basis. Using this scientific method, it should be possible, not only to measure and optimise C^3I system effectiveness, but also to measure and optimise:

- The supporting logistic system, which is intended to maintain that level of effectiveness.
- The procurement system, which is intended, not only to supply equipments to the requisite performance standards, but also to supply continual/periodical upgrades throughout the life of the C^3I system.

9.5 Applying the COEIA Simulation Model Concept to other Areas

The potential use of the COEIA simulation model concept, using two small forces competing with each other, seems to be both eminently practicable and a reasonable way ahead to evaluate future systems. This potential should be explored for other application areas. The idea is that pre-developmental research is essential in both military and non-military domains. Although the COEIA white-box simulation model was designed specifically for this project, using a naval C^3I system context, the approach could equally well be applied in other areas where problems exist in defining requirements for socio-technical systems; for example, police force systems at both international and local levels.

GLOSSARY OF ABBREVIATIONS

ABIS	Advanced Battlespace Information System
API	Application Program Interface
BCE	Blue Cost Effectiveness
BDF	Bahrain Defence Force
C^2	Command and Control
C^3I	Command, Control, Communications, and Intelligence
CER	Cost Exchange Ratio
CIS	Command Information System
CISE	Computing Information Systems Engineering
COE	Common Operating Environment
COEIA	Combined Operational Effectiveness and Investment Appraisal
COTS	Commercial off the Shelf
DERA	Defence Evaluation and Research Agency
DII	US Defence Information Infrastructure
EAC	Equipment Approval Committee
EPM	Electronic Protective Measures
ESM	Electronic Support Measures
EW	Electronic Warfare
FAR	Federal Acquisition Regulation
FASM	Future Attach Submarine
FSM	Formal System Model
GRM	Generic Reference Model
GOTS	Government off the Shelf
HAS	Human Activity System

IPT	Integrated Project Team
ISO	International Standards Organisation
IT	Information Technology
JOCS	Joint Operations Command System
JTF	Joint Task Force
JV2010	Joint Vision 2010
JWARS	Joint Warfare System
LGRM	Layered Generic Reference Model
LRU	Line Replaceable Unit
LSRC	Land Systems Reference Centre
LVM	Layered Virtual Machine
MCDA	Multiple Criteria Decision Analysis
MOD	Ministry of Defence
MOFE	Measure of Force Effectiveness
MOE	Measure of Effectiveness
MOP	Measure of Performance
NATO	North Atlantic Treaty Organisation
OEA	Operational Effectiveness Assessment
OMG	Object Management Group
OSI	Open Systems Interconnection
PCBs	Properties, Capabilities and Behaviours
PC	Personal Computer
PGP	Pretty Good Privacy
Ph	Probability of hit
PhD	Doctor of Philosophy

R&D	Research and Development
RMCS	Royal Military College of Science
ROCE	Return on Capital Employed
RPD	Recognition Primed Decision-making
SAG	Surface Action Group
SBA	Simulation Based Acquisition
SDR	Strategic Defence Review
SE	Systems Engineering
SEI	Software Engineering Institute
SME	Subject Matter Expert
SNR	Signal to Noise Ratio
SPI	Smart Procurement Initiative
SRD	System Requirement Document
SSM	Soft System Methodology
STELLA	Systems Thinking Environment and Learning Laboratory Approach
SWOT	Strengths, Weaknesses, Opportunities, and Threats
UK	United Kingdom
URD	User Requirement Document
US	United States
V&V	Verification and Validation
VFM	Value for Money
VM	Virtual Machine
VSM	Viable System Model
WARCON	War Consumables

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Appendix A: Theory and Tools to Support the COEIA White Box Modelling Approach

A.1 Introduction

This appendix reviews current theory and tools relevant to supporting the COEIA white-box modelling approach, which is proposed in Chapter 3 and developed in Chapters 4 & 5. The appendix also presents different kinds of Measures of Effectiveness (MOEs), some of which will be used to conduct simulation experiments to predict C^3I system effectiveness, in Chapter 6.

A.2 Measuring Effectiveness

Although, MOEs have been employed in Systems Engineering (SE) for many years, there appears to be no universally-accepted standard, or definition, for the term. For instance, the interim standard, EIA/IS-632, included MOEs as part of the 'Process Input' to the Systems Engineering Process Model. While most of the other inputs appear to be self-explanatory, no explanation or definition of MOEs is offered by the interim standard. There is also a tendency to confuse other terms such as Measure of Performance (MOP) with MOE (see Chapter 3, section 3.4.3).

A.2.1 General Concept of Effectiveness

To understand the behaviour and performance of a command and control system, it is necessary to provide it with some task to perform, in some representative environment.

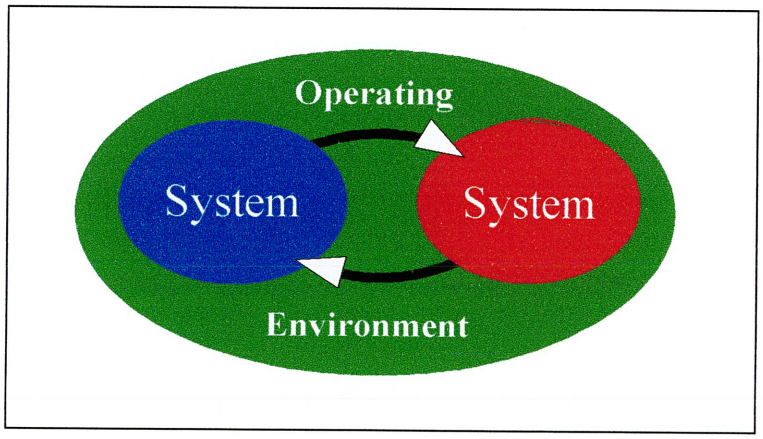


Figure A-1 Effectiveness Concept

Similarly, it is necessary in examining the behaviour, or measuring the effectiveness, of any system to view it as interacting dynamically with other systems in a containing environment, or system. In the above figure, there are two systems. Blue acts on Red and Red acts on Blue, simultaneously. As Blue acts on Red, Red is changed; Red acts on Blue, therefore, Blue changes, too; and the cycle progresses. To 'measure' Blue, then, is to measure dynamic emergent behaviour - which emerges only when Blue and Red are interacting in specific ways in a specific environment. Therefore, it is possible to determine the effectiveness of Blue only in the context of its effect on Red, and *vice versa*, in the particular Green operating environment; and, even then, only when doing particular things.

A.2.2 Different Kinds of MOEs

One way to calculate effectiveness is by using weighting and scoring methods. The selection of weights and scores may prove difficult, and may contain elements of subjectivity. Such an approach may show one solution marginally better than another but with no degree of confidence. Others prefer to use ranking methods; these have the advantage of being potentially less subjective [Hitchins, 1992].

The implication of effectiveness is that it must somehow be judged by the impact (effect) on something else. Effectiveness is an external measure of what the system does, rather than what the system is. This concept can be used to evaluate the impact of COTS on C³I system effectiveness. The process of evaluating the impact of introducing COTS on C³I system effectiveness can, thus, be seen as comprising three parts:

(i) Establish a model of two C³I systems in conflict representing Blue and Red platforms within an operational environment.

(ii) Within each C³I system (Blue and Red) create the facility to include either COTS or Bespoke equipment.

(iii) Conduct a simulated combat to observe effectiveness in conflict with either COTS or Bespoke equipment.

Given such a model, overall effectiveness deals with a change in situation brought about by the environment and the dynamic interaction between the two systems. In such a dynamic, interactive situation it is possible to observe, say, Blue C³I system's

emergent properties, capabilities and behaviours (PCBs). As Blue acts on Red through the environment, Red is affected and changes. This change is a measure of Blue effectiveness; but, Red also acts on Blue, so Blue is changed.

Thus, once Red and Blue start to interact, each changes and is changed by the other. This results in a dynamic situation, in which the emergent PCBs and effectiveness of both Blue and Red unfold over time. Thus, effectiveness is not some fixed, arbitrary figure, and is not really capable of being specified *a priori*. Instead, it is an emergent property of the interaction of a system of interest (e.g. Blue) with other systems in some operating environment.

Effectiveness can be measured in a number of ways including the following:

a) Mission Effectiveness

Mission effectiveness is the degree to which a C³I system is able to achieve its designated mission. It is considered at the operational level and may be known as Measure of Force Effectiveness (MOFE). MOFE is a measure of the degree of mission success, and is scenario and enemy dependent.

b) Cost Exchange Ratio (CER)

Cost exchange ratio is widely used in the strategic context, and in wars of attrition. It is calculated as the ratio of respective Blue and Red combat costs. It is considered at the technical and the operational levels, and is scenario dependent.

c) Casualty Exchange Ratio

Casualty exchange ratio is the ratio of respective Blue and Red casualties. It is considered at the operational level and is scenario dependent.

d) Return on Capital Employed (ROCE)

A fourth way to measure effectiveness is to perceive the capital cost of, say, a Blue C³I system as an investment; Red C³I system combat losses represent the profit, and Blue C³I system combat costs are losses. It is considered at the procurement level and is scenario dependent.

e) Cost Effectiveness

Cost effectiveness is generally used to choose between options. Cost is generally not a MOE *per se*. Cost is appropriately considered when choosing the most cost-effective system; that would be the system with the greatest effectiveness for the least cost. This equates broadly to best Value for Money (VFM).

Cost effectiveness seeks to maximise VFM by maximising the ratio of effectiveness to cost. Therefore, it is considered at the procurement and operational levels. Using cost effectiveness as a ratio to be maximised in choosing between options may be inadequate, however. An option may be relatively ineffective yet be so cheap that the effectiveness/cost ratio is nonetheless high. It is reasonable to assume that cost effectiveness, on its own, is inadequate as a MOE.

A.2.3 Criteria for Choosing MOEs

The impact of COTS on overall C³I system effectiveness may arise in different ways. Measures of effectiveness can be chosen such that they capture these different impacts. So, COTS may be upgraded more frequently than Bespoke equipments. Maintenance of COTS and, hence, the costs of spares, test facilities, training and technicians, may differ from Bespoke. The choice of particular MOEs must sensibly capture such difference between COTS and Bespoke. Additionally, MOEs are conventionally, and sensibly, concerned with exchange ratios; notably cost and casualty exchange ratios.

Measures of effectiveness should be as few as possible, in order to simplify the comparison between options. They should also be as high level as possible, partly to keep them few in number, and partly so they reflect military objectives as directly as possible.

A.2.4 MOE Characteristics

There has been relatively little work concerned with modelling the effect of COTS products on C³I system effectiveness. Ideally, this should relate COTS to MOPs and MOEs. One way of achieving this is to identify differences between Bespoke and COTS-based systems, simulating identical situations alternatively with each, then

observing any differences in MOEs. As a result, there are two options, COTS versus Bespoke.

To assess the relative values of COTS and Bespoke, it was necessary to develop a clear-yet-comprehensive system for measuring C^3I system effectiveness. The system has to address the meaning of 'value' of effectiveness and even of what is encompassed within C^2. 'Value' is a difficult concept. It is to be seen in context as a contributing factor to the whole system.

C^3I systems comprise people and machines. The effectiveness of these systems depends on many factors, including the interactions between people and machines, as well as the interactions between the two C^3I systems in their environment.

An interval scale is appropriate for such measurements. Two scales were considered useful in the current context:

(i) **Ruler scale**: the option that performs the best for a given attribute is given a value of 100, the worst a value of 0, as a 'pseudo-percentage'. This scale was appropriate for cost effectiveness and ROCE.

(ii) **Ratio scale**: this essentially 50:50 ratio can be multiplied by 0.02 to render the mean value of unity. Values above unity are in one system's favour, while values below unity are against that system. This scale was appropriate for exchange ratios.

A.3 Layered Virtual Machine (LVM)

The Layered Virtual Machine (LVM) is a widely established technique for managing the complexity of software and hardware interactions that take place in a computer system [Allworth, 1981]. A simple example of this is illustrated in Figure A-2. Typically, at the lowest level, one might represent the computer hardware as a layer upon which an operating (software) system executes. This operating system will manage the hardware resources, and may provide common services, such as communications and data management, to the application software that resides in higher-level layers.

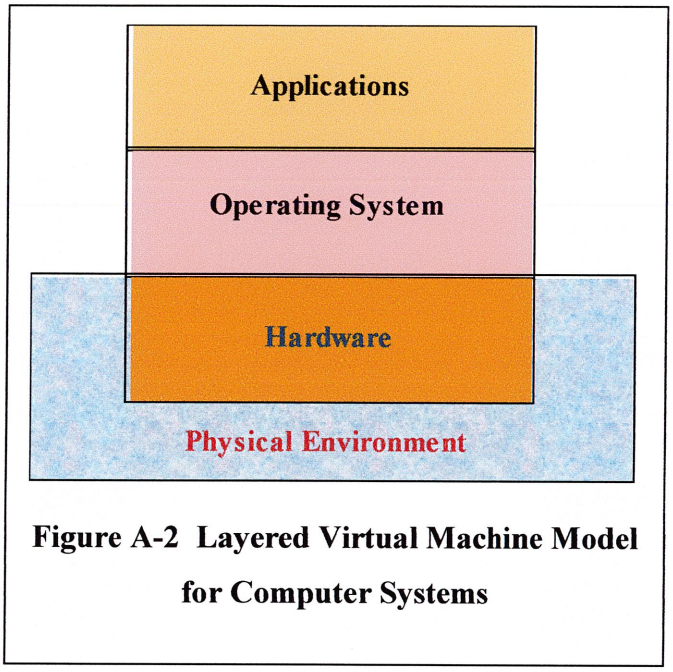


Figure A-2 Layered Virtual Machine Model for Computer Systems

In principle, any number of layers is possible and, above the hardware layer, each software layer can be considered to use the services of the layer below, to provide services to the layer above. In essence, each layer adds to the layers below to create a 'virtual machine' upon which the software in the layer immediately above can execute.

The LVM approach has several desirable properties. First, it supports design based on increasing levels of abstraction, which allows partitioning of a complex problem into a sequence of incremental steps. It also supports enhancement, since each layer interacts with two layers: the layer below and the layer above. Changes to the function of one layer, therefore, affects, at most, two others layers.

Third, it supports reuse, because different implementations of the same layer can be used interchangeably, provided they support the same interfaces to their adjacent layer. Finally, LVMs can provide much richer forms of interaction, since each layer allows much closer interaction between layers, and permits two-way transmission of information.

The LVM approach also has disadvantages. Not all systems are easily structured in a layered fashion. Additionally, it can be quite difficult to find the right levels of abstraction. This is particularly true for standardised layered models.

A.4 System Models

System models allow us to reason about the characteristics of a system, using appropriate abstractions. Three archetypal candidates are given, below, to identify one suitable modelling approach to populate the three individual layers (technology, people, C^2 process) of a C^3I system (see Chapter 3, section 3.8).

A.4.1 The Formal System Model (FSM)

This model has been invented and developed by Professor Peter Checkland for the express purpose of helping the building of conceptual models, and testing and validating them, in stage 4 of the 'Soft Systems Methodology'. He had been in industry for a number of years, working with a number of hard system methodologies, and was dissatisfied with their ability to analyse 'soft' systems, or Human Activity Systems (HASs) [Checkland, 1989]. The FSM consists of a set of conditions, which a particular system must fulfil to qualify as a complete system. The components of the model are as follows.

S is a 'formal system' if, and only if, all the following conditions are satisfied:

- S must have some mission.
- S must have a decision making process.
- S must have components that interact with each other such that the effects and actions are transmitted through the system.
- S must be part of a wider system with which it interacts.
- S must be bounded from the wider system, based on the area where its decision making process has power to enforce an action.
- S must have resources at the disposal of its decision making process.
- S must either have long term stability, or the ability to recover in the event of a disturbance.
- Components of S must be systems having all the properties of S (subsystem).

The FSM appears to be generally useful, and was applied during the white-box modelling of a C^3I system, presented in Chapter 4, to test the LGRM, shown in Figure

4-5, in its proposed dual-interacting configuration for COEIA white-box modelling. The test results are show in Table 4-1 of Chapter 4.

A.4.2 The Viable System Model (VSM)

Professor Sir Stafford Beer created this model over twenty years ago. It has been used as a conceptual tool for understanding organisations, redesigning them, and supporting the management of change. Despite its successful application within a large number of private and public sector organisations, however, the VSM is not yet widely known among the general management population.

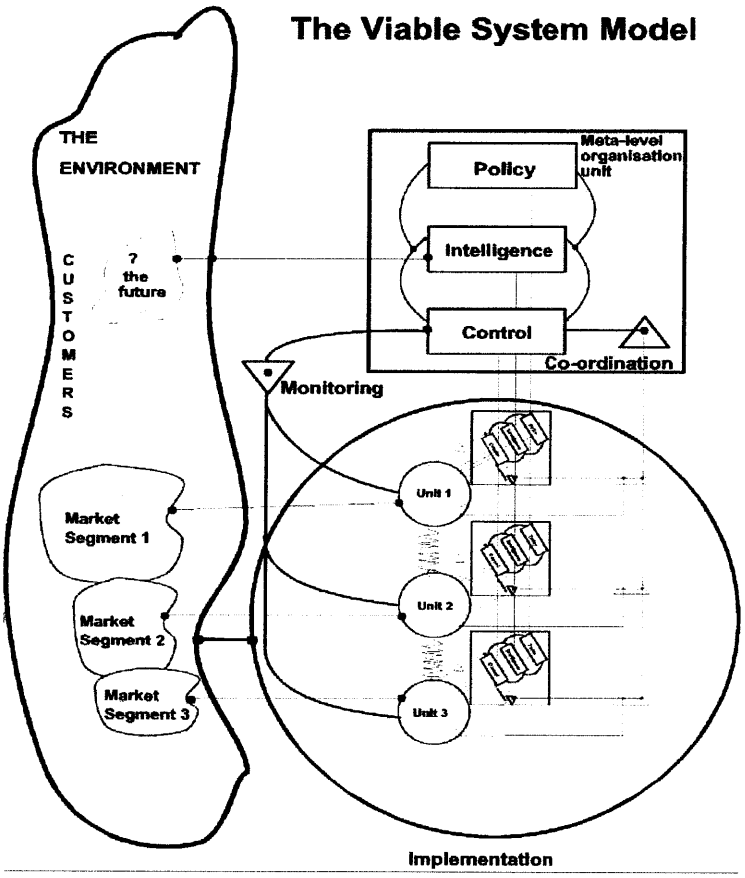


Figure A-3 The Viable System Model

According to the model, a viable system needs to have five key elements in place if it is to operate effectively in its environment, as shown in Figure A-3. These are Implementation, Co-ordination, Control, Intelligence and Policy [Espejo, 1989]. The VSM is a useful tool in helping organisational members to take a systematic view of their communication process. A shared understanding of the organisation as an integrated whole is a powerful platform for various kinds of change. The modelling

tools define an underlying structure for communications in support of viability, whilst providing a viable template for both structural organisational design and the mapping of the Information Technology (IT) architecture.

Although the VSM was initially attractive as a modelling approach because it claimed to have a mathematical structure, it was not clear how it could be used to represent behaviour within the LVM structure. The Generic Reference Model, below, was considered a better match to this requirement.

A.4.3 The Generic Reference Model (GRM)

This model has been invented and developed by Professor Derek K. Hitchins as a reference for any system to assist systems engineers in designing, checking, and evaluating their systems for completeness. It is type independent and scale independent. The model consists of three intimately related parts. The Generic Reference (Function) Model, describes the 'doing' of any system, that in turn comprises three parts: Mission Management, Resource Management, and Viability Management. The second part is the Generic Reference (Form) Model. It also consists of three parts: Structure, Influence, and Potential. The final part is the Generic Reference (Behaviour) Model, which proposes how behaviour might be selected, and it is the most complex of the three first-level models [Hitchins, 1997], comprising Cognition, Behaviour Selection, Stimulation and Belief elements.

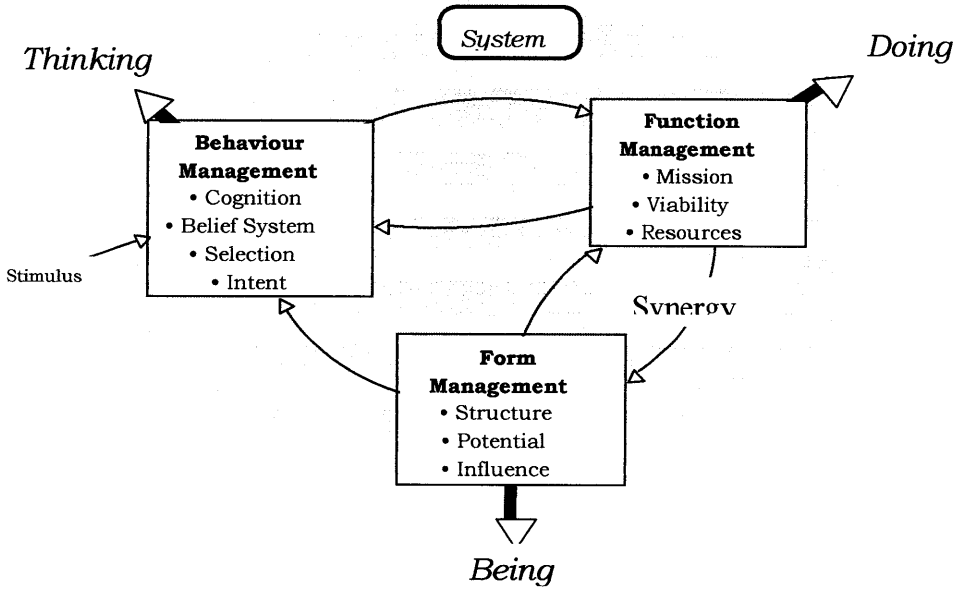


Figure A-4 Generic Reference Model - Level 0

The Generic Reference Model describes the 'inside' of *any* system, i.e. subsystems and their mutual interactions, as the source of emergence and effectiveness. The model at its top level is shown in Figure A-4. At its simplest, a system has being, or just exists without function or behaviour. The solar system, it seems, just *is*. It has structure, sources of energy, gravitational influences, etc., but nonetheless just *is*.

Some systems not only exist, but do things, too. Plants and simple animals fit this description, but so too do manufacturing systems, tanks, ships and places - these have function, although they may not work without operators. Yet again, some complex systems exist, do things, and think. Humans fit into this category, but so do C³I systems, and tanks, ships and planes when they have their operators and decision-makers installed and active. So, the GRM can represent any system by choosing which of the three parts to invoke. All systems exist, some function as well and, of these, some think, too. Figure A-4 also shows internal structure, which will be expanded briefly below.

A.4.3.1 Mission Management

Figure A-5 shows the first level of elaboration for Mission Management. The sequence of activities is the simplest set, and they can be seen deriving information from some operational environment and then acting into that environment. This figure could represent an earthworm seeking refuge, NASA putting Neil Armstrong on the Moon, or a C³I decision-making process. Note that energy is needed to maintain the circular process.

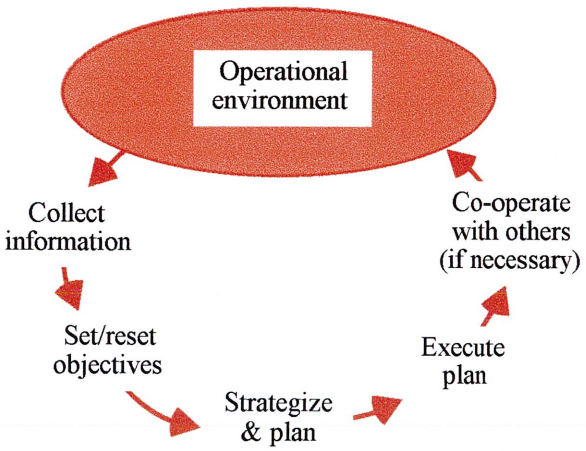


Figure A-5 GRM-Mission Managemet

A.4.3.2 Resource Management

Figure A-6 shows a similar figure representing the process of resource management. Resources are acquired from some resource environment and excess/waste (even product) is returned to the resource environment. Note, as before, that energy is needed to maintain the rotation.

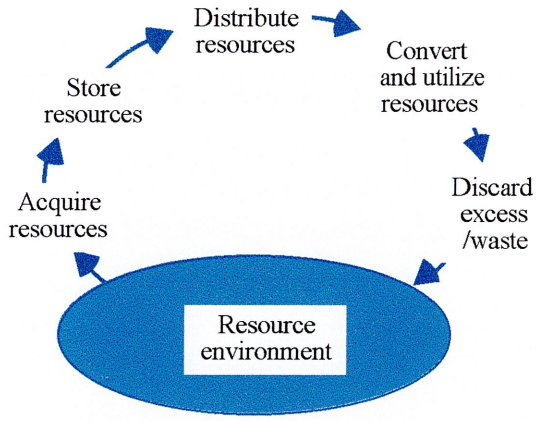


Figure A-6 GRM Resource Managemet

A.4.3.3 Viability Management

Figure A-7 shows Viability Management. The idea of the division of Function Management into Mission, Resources and Viability was suggested by a similar division used for a US tactical fighter. There, the split was Mission, Resources and Platform. Platform management included all the resources needed to maintain the integrity of the platform as it undertook its various missions.

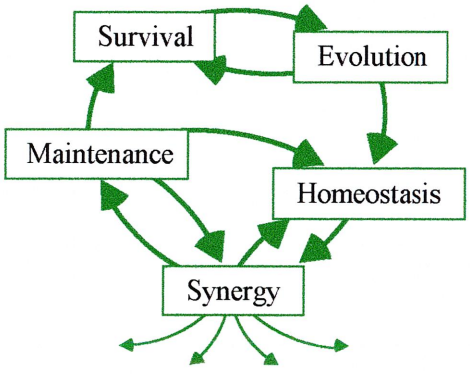


Figure A-7 GRM - Viability Management
Note: Read arrows as 'enhances/enables'

Viability management employs the same idea, but in generic form, i.e. applicable to any system. In the figure:

- The whole forms a self-sustaining set
- Homeostasis maintains internal environment for all other internals
- Synergy co-ordinates all internal parts
- Maintenance detects, locates, replaces, disposes
- Survival protects from externals
- Evolution adapts, improves…
- Together = Viable System

Synergy is 'co-operation and co-ordination of internal parts to produce some desired external effect'.

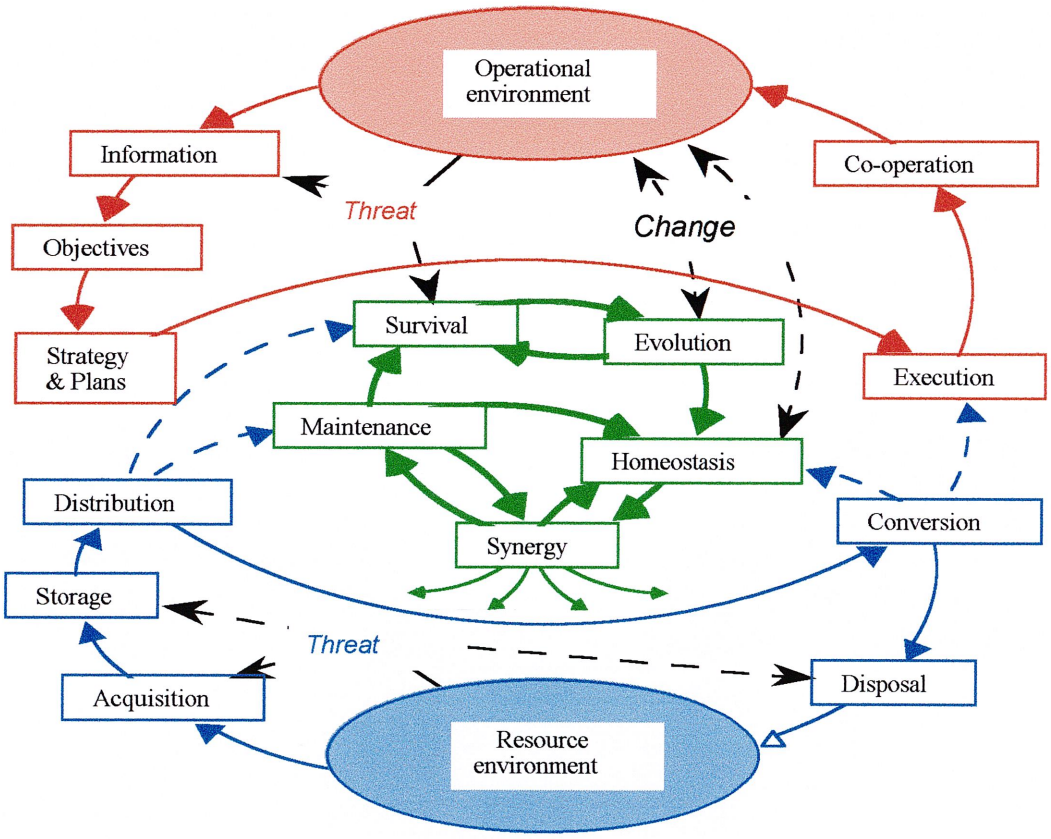


Figure A-8 Full Function Model with Inter-connections

Figure A-8 illustrates the function model with its environment. In the above figure elements are seen in respective 'environments'. Viability provides a platform for mission management. Resources provide energy and materials for viability and internal operations. Threats to mission management change resource management, and challenge homeostasis (resist) and evolution (adapt).

A.4.3.4 Generic Reference (Form) Model

Figure A-9 shows the first level of elaboration for the GRM Form Model. As with the other parts of the GRM, it is erroneous to view these various elements as existing separately from each other. All aspects coexist. For instance, Viability Management is integral to Form, and Function requires Form to give effect.

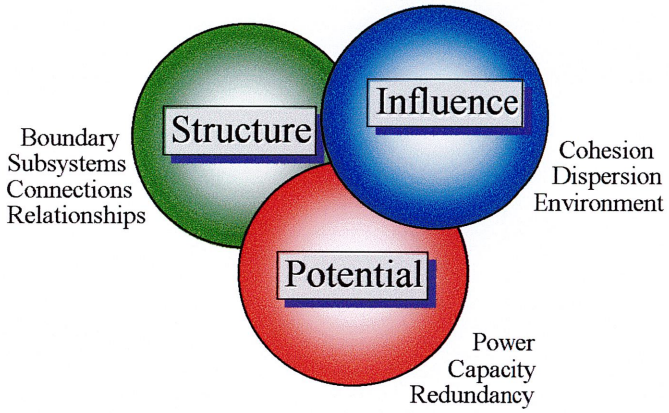


Figure A-9 Form Model - Level 1

The Form model consists of three parts: Structure, Influence, and Potential. Structure describes the evident features of a system, Influence identifies those features which hold that structure together in a static or a dynamic balance. Potential describes those features held in the structural web which enable the system, which characterise it as big or small, powerful or weak, and with or without redundancy.

A.4.3.5 GRM - Behaviour Management

The Behaviour Model, Figure A-10, proposes how Behaviour might be selected generically - it does not identify which particular behaviour results from a given stimulus. That is beyond current capability.

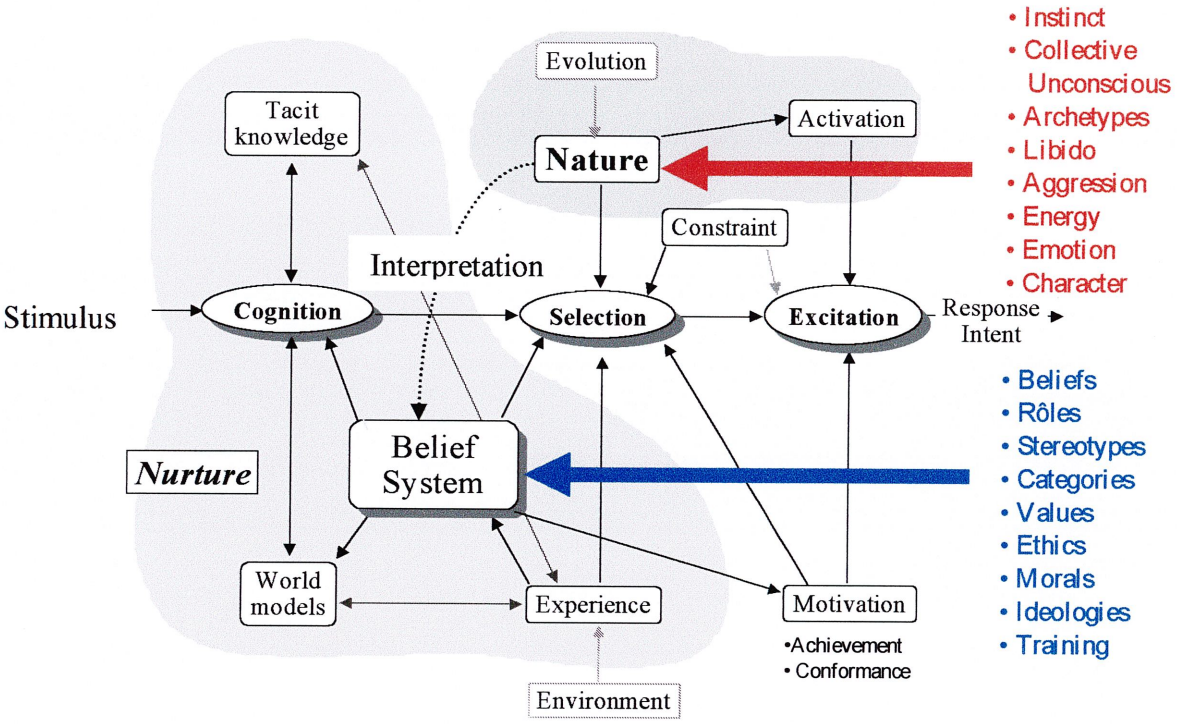


Figure A-10 GRM - Behaviour Management - Level 1

Of three first-level models, Behaviour is the most complex and subtle. It is based on a variety of psychological models and proposes ways in which both instinctive and sentient entities respond to stimulus. It is appropriate for individuals and groups. It recognizes essential nature-nurture conflict. The Behaviour Model is a classic Stimulus-Response model, based on the tension between Nature and Nurture. So, stimulus enters at the left and is interpreted in the cognition process, in the light of Tactit Knowledge, World Models and Beliefs. The interpretation triggers the selection of consequent behaviour. The particular behaviour response is chosen by some trade-off process which accounts for Nature (e.g. 'knee-jerk' reactions), Nurture, or learned behaviour, experience and beliefs. Finally, the chosen Behavioural Response excites the Function and Form elements to elicit an overall Behaviour.

A.5 The Psychology of Decision Making

A decision is defined as a choice between options. If there are no options, or no choice, then there is no need for a decision. Decision-making is the process of choosing between alternatives, selecting and rejecting from available options. Traditionally, decision theory is divided into two major topics. One is concerned mainly with choice among competing actions, while the other is concerned with modification of beliefs based on incoming evidence [Pew, 1998].

Recent work at the Royal Military College of Science (RMCS), concerned with defining the training process for Army Command and Control (C^2) applications, has investigated the military decision-making process [Hone, 2000]. All military commanders have some limit to their authority and choice of action. At the highest level these limits are defined by the State, and at the lowest by a higher level commander. Current military thinking is that the key differences between command levels include:

- Time available over which action must be planned
- Size and scope of available physical assets
- Sensor availability and other tactical information
- Scope of any decision making

In essence, the function of any commander is to assess the available information and to make decisions based on that information. The knowledge required by a commander at any level will relate to:

- The mission
- The enemy forces
- Own troops
- The terrain
- Constraints

The matching skills will be those defined, below.

(i) **Situational Awareness** is a concept that has been taken from sports psychology, and the term indicates a mental model of the current and near-term disposition of both friendly and opposing forces as related to each other, and to

the terrain that they share. Perhaps the best definition is the one offered by Endsley [Endsley, 1988]:

"Situation Awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future".

Situational awareness is, therefore, a state of knowledge.

(ii) **Situational Assessment** is the process by which that state is achieved. Generally speaking, any army will have established doctrine and procedures (e.g. planning methods) that enable an assessment of the current situation and of probable and possible near-future developments

(iii) **Decision-making** translates situational awareness into a set of orders, effectively creating a blueprint for near-future action. There are three fundamental decision -making techniques:

a) **Rule-based reasoning** is constructed from rules of the 'IF x, THEN y' type; otherwise, known as 'production rules'. These rules are often very complex in nature, with multiple clauses, and internal dependency structure. The application of a large rules-set can be very time-consuming, but can produce solutions that are very near to optimal.

b) **Case-based reasoning** is generally similar to rule-based reasoning, but draws on a limited set of exemplars. These exemplars can be regarded as abstractions over a number of sub-sets of production rules, but which are grounded in previous experience. Case-based reasoning will usually produce solutions in a shorter time.

c) **Heuristic reasoning** can be viewed as the use of a set of 'rules-of-thumb'. The rule-set is generally very simple (and usually incomplete), and solutions are generated in a short time.

(iv) **Group Awareness** is also referred to as crew awareness, distributed cognition, shared mental models, or 'having a common frame of reference'. Initially this area was studied with regard to the C^2 functions on board a warship [Hutchins, 1990]. There is now a more general view that a cohesive team (say a

battlegroup or company/squadron command) will have some group cognition of operations that does not reside solely in the Commander's mind.

From the above, it can be seen that there is a hierarchy of decision-making strategies. Full rule-based reasoning will deliver a near-optimal solution, but if any of the underlying information is incomplete or inaccurate, or if any assumptions on which the decision may rest are violated, then the decision will not be robust. Conversely, heuristic reasoning seldom gives optimal solutions, but those generated will be very robust across changes in the underlying information. There is, therefore, an inverse relationship between the time available for a decision and the robustness of that decision, but a positive relationship between time and optimality. These two relationships also relate to the level of command, with the higher levels having more time for decisions (and equally having to look forward to a greater degree).

Accordingly, this research work proposes two types of decision-making. Specifically, the LGRM white-box model for a naval C^3I system, instantiated in Chapter 5, includes, in the C^2 process layer, both the naive decision making model and Klein's Recognition-Primed, or naturalistic, decision-making. These have been described in Chapter 3, section 3.4.1.2. The model switches from one to the other when decision time becomes so short that the naive approach would take too long.

A.6 Effectiveness Modelling Schemes

A.6.1 Black Box (Parametric) Modelling

Multiple Criteria Decision Analysis MCDA is a field which has seen a considerable development during the last ten years. It is an umbrella term for a number of formal methodologies for decision support, which seek to take explicit account of multiple conflicting criteria [Belton, 1990].

Researchers are aware of the presence of multiple criteria in real-life problems of management and decision, whatever their natures. As its name indicates, multiple criteria decision analysis aims to give the decision-maker some tools in order to enable him to advance in solving a decision problem where several, often contradictory, points of view must be taken into account.

In MCDA the notion of a weight is commonly used. Often, a decision-maker spontaneously considers one criterion as being more important than another, and represents this perception by weighting scores for the preferred criteria, to give them more impact. This phenomenon is an example of modelling.

This black-box approach is currently being researched for the effectiveness assessment of Naval command and control systems [Robson, 1998]. It is a parametric modelling approach in which various elements are scored for performance, the scores are weighted according to their perceived contribution to a system's effectiveness, and the sum of the weighted scores is considered to provide an overall effectiveness measure.

The advantages of such an approach are:

- It is simple, mathematical, and straightforward.
- The weightings may be derived by experts from the relevant operational environment who know from experience which parameters are more important than others.
- Similarly, scoring may be undertaken by experienced experts, so instilling some practical knowledge into the process.

The limitations of such an approach are:

- Both weighting and scoring are subjective.
- Using experience is only helpful where such experience is current and relevant - often not the case when addressing warfare.
- Weighting and scoring essentially ignores synergy between the various parameters, treating each as separate. For C^3I systems this may be inappropriate, since the whole comprises integrated subsystems.
- Black-box modelling omits interactions and relationships, obviating any experimentation with their effects.
- Black-box modelling tends to overlook dynamic interactions with an opponent/competitor and/or environment. It, therefore, lacks the potential to elaborate the dynamics of effectiveness as the measure changes with time.

The black-box method is, for the case of C³I systems, illustrated in Figure A-11. Operators (etc.) provide expert knowledge, from which capability metrics are derived, relating to C³I system functions. These are combined in a weighting and scoring scheme to establish that the various command function choices (e.g. using particular equipments) can, when provided together, achieve the requisite score and, hence, 'be effective'.

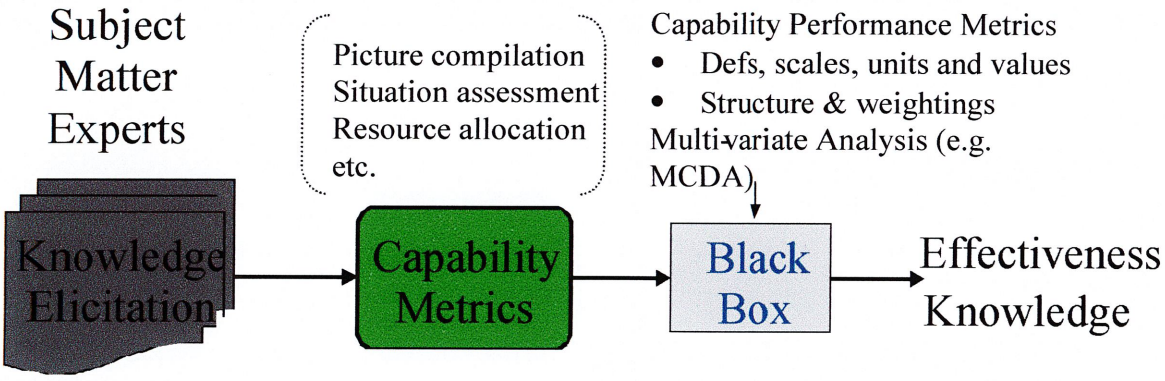


Figure A-11 Black-box Model to 'Measure' Effectiveness

A.6.2 White Box Modelling

White-box modelling is proposed as a scientific approach, which provides insight into how key features of any system can affect overall effectiveness. It includes, in a suitably abstracted form, influences of human behaviour, system component performances, system architecture, and their processes. The white-box method works quite differently from the black-box approach, as shown in Figure A-12. In this case, using a C³I system example, a dynamic representation of the whole system is constructed, with all parts and parameters visible and adjustable (hence, 'white-box', implying open and visible). Interactions between the various parts are included, together with representations of operators and decision-makers. The parts and interactions are adjusted so that the emergent PCBs of the whole coincides with the real world.

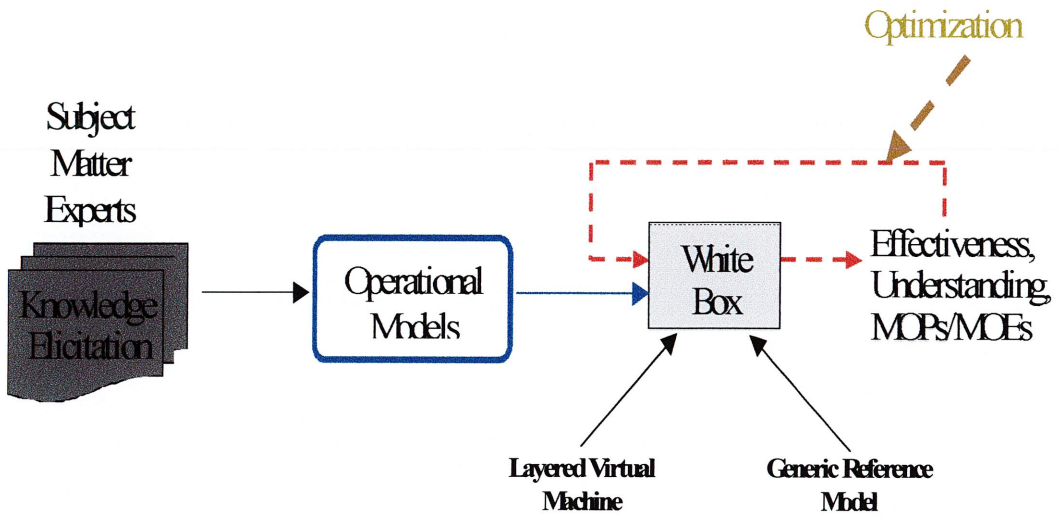


Figure A-12 White-box Model to 'Measure' Effectiveness

A major benefit of this scientific white-box modelling approach is that, by experimenting with a model, we are able to refine its properties in a way which extends the theoretical understanding of the associated problem domain. Adjusting the weights of a parametric black-box model is unlikely to yield the same degree of theoretical insight. Also, by using the white-box model, it is possible to observe what MOPs of individual equipment correspond to overall system effectiveness. It is even possible to adjust the various technology parameters to maximise overall system effectiveness, and so to determine the optimum MOPs for each equipment as part of the set, rather than in isolation.

The white-box approach requires a comprehensive representation of the C³I system at its heart, including the technological systems, the human operators and decision-makers, their various resources, and the interactions and intra-actions to which they are subject. This requires a novel approach, which is proposed in Chapter 3 (section 3.8), and is progressed in Chapters 4 & 5.

A.7 The STELLA™ System Dynamics Tool

The STELLA™ software was first introduced in 1985, and is now supplied by High Performance Systems[1]. It is a dynamic modelling tool that has a variety of applications. It is a powerful and flexible package for building and simulating models of dynamic systems and processes. Using a simple set of building block icons, the modeller can construct a map of a process or issue of any kind. Output can be viewed as graphs, tables, diagram animation or QuickTime movies. Multi-run sensitivity analysis allows modellers to explore a variety of 'what-if' scenarios as the modeller explores the interdependencies of the system under scrutiny. It uses distance and time, and other variables, to model problem domains [HPS-INC WWW, 2000].

Essentially, STELLA™ is a graphical System Dynamics simulator. Its software solves initial value problems in sets of ordinary differential equations. The user draws (with the mouse) relationships between components in a dynamic system; specifically, the flow of information between components. The software then uses the graphical description to generate and integrate the appropriate differential equations, providing numeric, graphical and animation output. Using this program, the emphasis is placed on broad viewpoints, or the 'big picture' view, so that interrelationships and interconnectivity are the focus rather than a collection of complex variables. Several other simulation modelling tools are available but, with regards to our research, STELLA™ seems to be the one which is best suited to the purpose of our study. Similar modelling tools, such as Vensim, Powersim, offer the same functionality, but STELLA™, Research version 5.1.1, was selected because it is object-oriented and, therefore, offers a very direct, one-for-one correspondence with the LGRM entities. Conveniently, it also runs on both PC and Macintosh platforms.

A.8 Summary

This appendix has presented:

- A sound basis for viewing system effectiveness.
- A set of complementary MOEs.
- The Layered Virtual Machine.

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[1] High Perfomance Systems, Inc., 45 Lyme Road, Suite 200, Hanover, NH 03755 USA.

- Candidate System Reference Models.
- The Psychology of (C^3I) decision- making.
- Black-box modelling and MCDA, for assessing system effectiveness
- White-box modelling, for assessing system effectiveness.
- A simulation tool, STELLA™, to facilitate experimentation.

Web: www.hps-inc.com

Appendix B: Simulation Concept, Design and Development

B.1 Conceptual Model

The main aim of the simulation was to construct a dynamic representation of the static COEIA white-box model, to carry out overall C³I effectiveness measurements for a defined scenario within the naval domain; hence, to determine the impact of introducing Commercial off the Shelf (COTS) equipment on C³I system effectiveness. For this, STELLA™ was used as a convenient modelling medium.

The approach was to enable comparisons between Bespoke equipment and COTS equipment, in terms of their relative contributions to Command and Control effectiveness. It was decided to simulate a naval engagement between two ships that would stress command and control sufficiently to present a worthwhile evaluation.



Figure B-1 Type 23 Frigate - HMS Iron Duke

The simulation model represents two generic fighting ships, broadly - but not specifically - of the type shown in Figure B-1. Further, by representing two such ships in conflict, minor omissions or errors would tend to balance and cancel each other out: this would be true only provided results from simulations were used to show trends and behaviours, rather than produce absolute figures.

Figure B-2 shows the non-specific fighting ship schematically. On deck are shown:

(a) A weapon delivery system (hard kill).

(b) A radar head (primary sensor).

(c) Jammer (soft kill).

(d) Electronic Surveillance Measures (ESM) (secondary sensor).

(e) (Part of) the protected Citadel in which the command/combat team operate, providing Command and Control (C^2).

Below decks are the various sensor, processing and, control systems, etc. The basic task starts with some searching activities, perhaps for a threat. The received signal is presented on a display where it is interpreted by an operator, one of several who together conduct the command process, i.e. make command decisions. Those decisions are implemented via the various controls, so fulfilling both the command and the control functions.

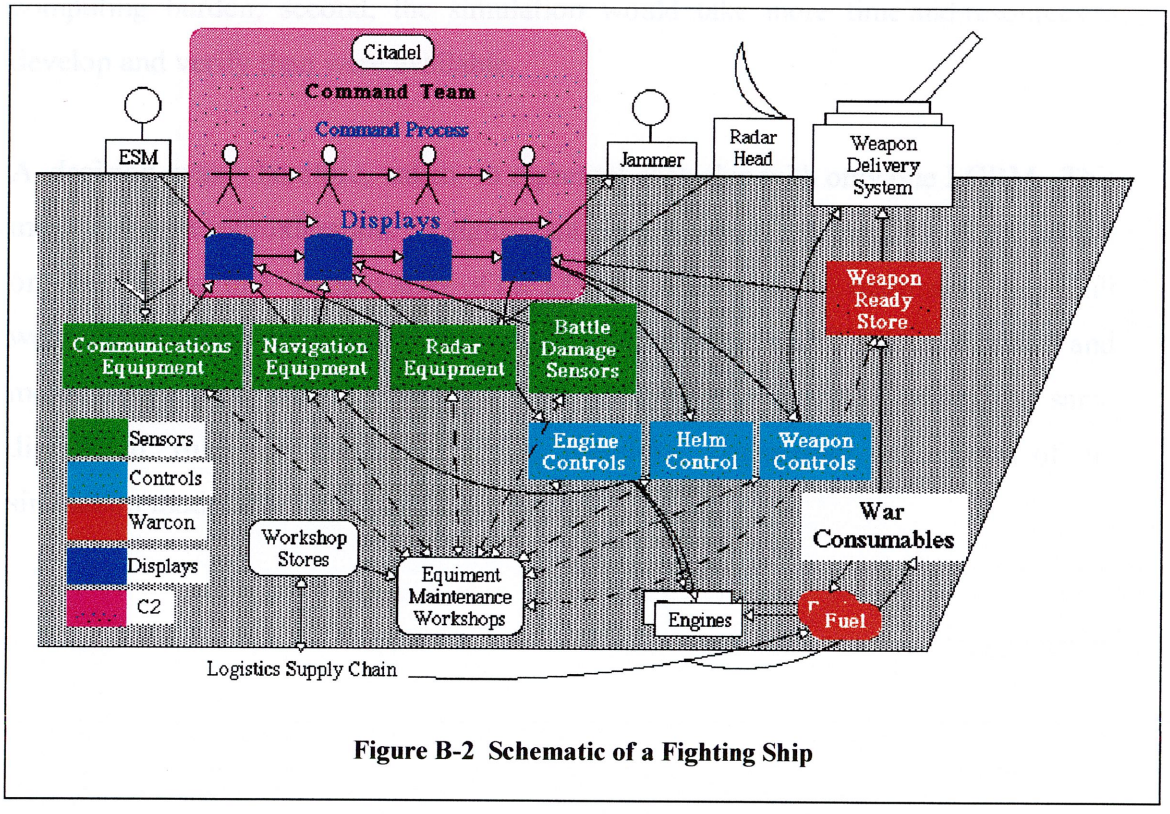


Figure B-2 Schematic of a Fighting Ship

B.2 Simulation Model Design Strategy

In order to represent two identical ships interacting, the simulation model design strategy was as follows:

- Represent the environment within which both ship models will operate.
- Represent one ship, Blue, operating within that environment.
- Incorporate within Blue Ship both Bespoke technology and COTS technology, together with the ability to select any equipment, its spares, and its maintenance system, as either COTS or Bespoke. This would allow Blue Ship to be all COTS, all Bespoke, or any combination of COTS and Bespoke equipment.
- Turn the outputs from Blue Ship, initially, into inputs to that same ship, after accounting for environmental interference, supposed signal fall off with range, etc.
- Hence, establish Blue Ship operating successfully against itself.
- Create a comprehensive Blue Ship cost model, accounting for COTS and Bespoke equipment and their support systems.
- Duplicate Blue Ship to create Red Ship; break Blue's self-interactions and replace them with cross-links to Red Ship (e.g. disconnect Blue jammer from Blue ESM, replace Blue jammer with Red jammer - and vice versa).
- Check that Blue Ship operates as previously, and that Red and Blue operate identically.
- Introduce disparities into Blue Ship while keeping Red Ship constant - check sense of results.
- Develop a variety of measures for C^3I effectiveness, observe how each varies dynamically throughout simulated engagements, and with the introduction of disparities.
- Hence, establish and verify the simulation model.

B.2.1 Representing the Environment and the Equipment

Figure B-3 shows the LGRM Form Model containing technology, with the operational environment below. The equivalent layer within the Simulation is the Technology Layer.

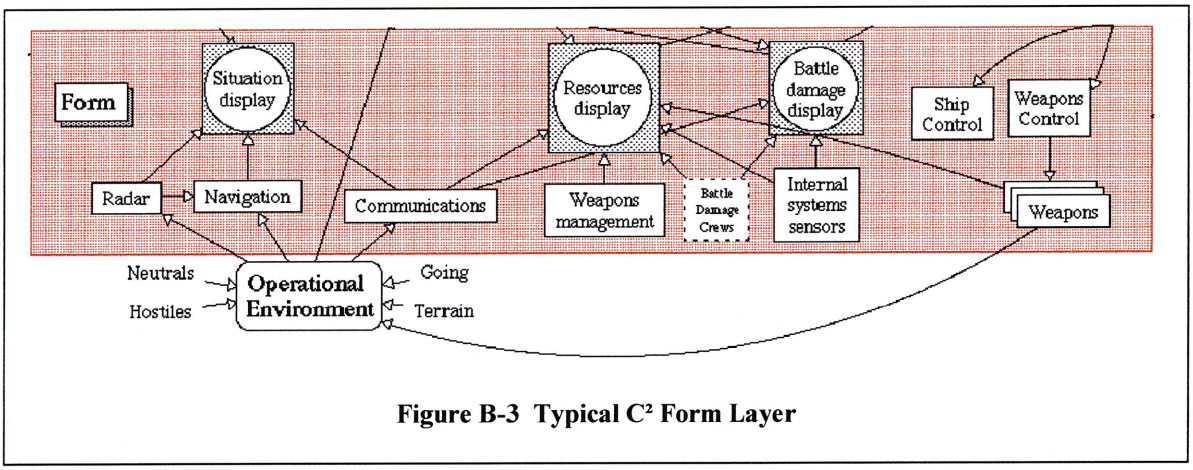


Figure B-3 Typical C² Form Layer

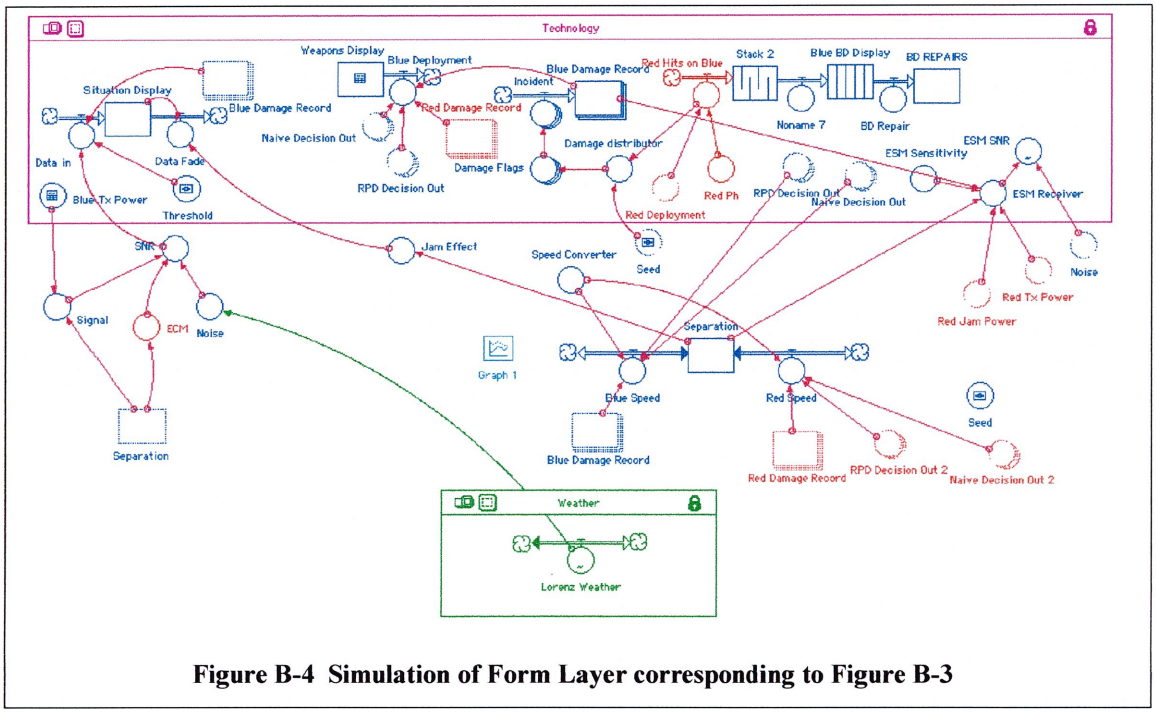
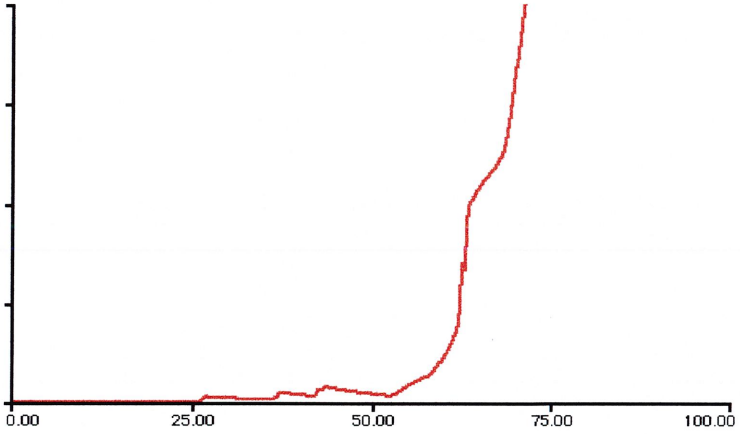


Figure B-4 Simulation of Form Layer corresponding to Figure B-3

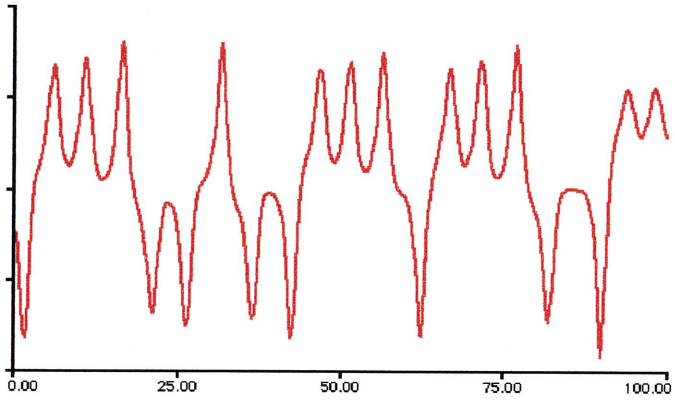
Figure B-4 shows the corresponding simulation to the part model of Figure B-3, using the STELLA™ notation. There is a general one-to-one correspondence in layout.



Graph B-1 Situation Display Signal - y-axis - against elapsed simulation time, and as separation between ships reduces

Top left is the Blue Situation Display receiving signal plus noise (Graph B-1) against time (as the separation between ships reduces) from Blue Radar transmitter, Red ECM (Jammer) and Noise from a Lorenz Weather Source, providing simulated 'windows' in the weather at range. (This weather source was developed in a separate simulation using Edward Lorenz's original climate equations with which he discovered what is now referred to as deterministic chaos - see Graph B-2.). The Situation Display presents data only when the Signal to Noise Ratio (SNR in the figure) exceeds a pre-set Threshold.

At centre are the Blue Resource Displays showing Weapons and Damage. Weapons Display shows the number of Weapons in the Weapons Ready Store (Figure B-2). This store counts down from a starting number of weapons as decisions to fire (RPD Decision Out and Naïve Decision Out) are implemented as Blue Deployment - see Graph B-3.

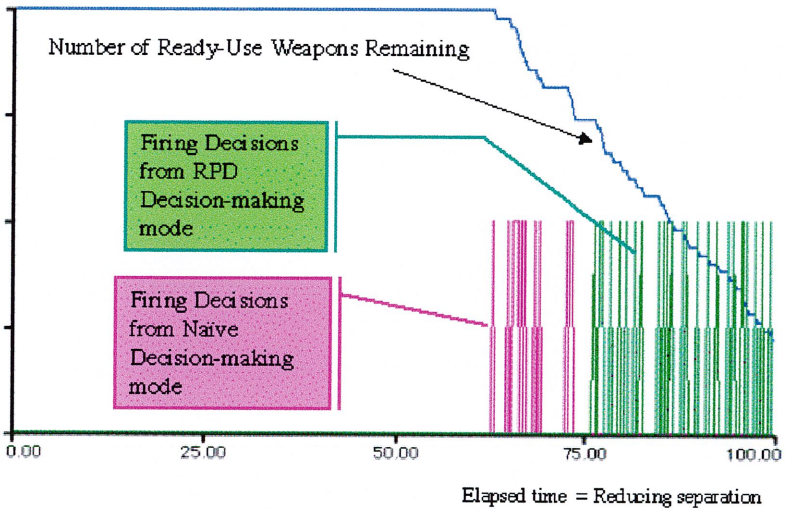


Graph B-2 Lorenz Weather. Climate Variation as Predicted by Edward Lorenz's Equations

Top right is the recorded damage caused by Red hits on Blue. Red Deployments are the firing of Red Weapons, which hit Blue Ship with a Hit Probability, (Red) Ph.

These hits trigger repairs, top right, and the damage distributor, top centre. The damage distributor generates a random number between 1 and 100, inclusive. The random number stream is passed to a Damage Flags array, with one array cell for each of: radar, ESM, jammer, weapon, engines and 'ship sunk'. Each damage flag is set to 1 using the following logic (in this case for damage to Blue weapons). 'IF Damage distributor > 66 AND Damage distributor < 71 THEN 1 ELSE 0'. There is, therefore, a 4 in 100 chance that a Red weapon, having hit Blue Ship, will damage Blue weapons. The overall result of this arrangement is that those weapons that hit Blue Ship (with a probability of hit, Ph) will have their effects distributed randomly across Blue Ship, causing damage to different equipment with different probability. Many will have no effect. Occasionally, Blue Ship will lose its engines, or its radar, etc., or it may be sunk. The link to ESM is shown middle right in the figure.

Centre bottom is shown the Separation reservoir. This simply determines the relative separation of the two ships. The simple scenario starts with a separation of 100nm and each ship closing on the other at 25 knots (i.e. 50 knots relative speed.) The simulation thus represents an elapsed time of about two hours. Decisions to close, hold or withdraw are received as control signals from the Process Layer - see below. Note that Damage Records are applied - if a ship's engines are damaged, its ability to move is inhibited.



Graph B-3 Count down of available weapons with Naïve and RPD Fire Decisions. Note Naïve Decision-mode firing first, followed by rapid RPD Decision-mode firing as separation reduces, and with it the time available to make decisions.

B.2.2 Representing the People/Behaviour Management Layer

Figure B-5 repeats the People Layer that, largely, houses the Behaviour Management portion of the LGRM. It contains a variety of features which are either difficult, or perhaps unnecessary, to represent in a dynamic simulation representing a two hour naval engagement. World Models and Tacit Knowledge are implicit in the organisation of the simulation, the creation of a scenario, and in the decision-making process; moreover, they are unlikely to change during the short engagement, so they would make no varying contribution. Simple elements of doctrine are contained in the rules that cause the ships to engage and, perhaps, withdraw when out-gunned. Ethics and Morals may be important in decision-making, but would be unlikely to change within a two-hour engagement.

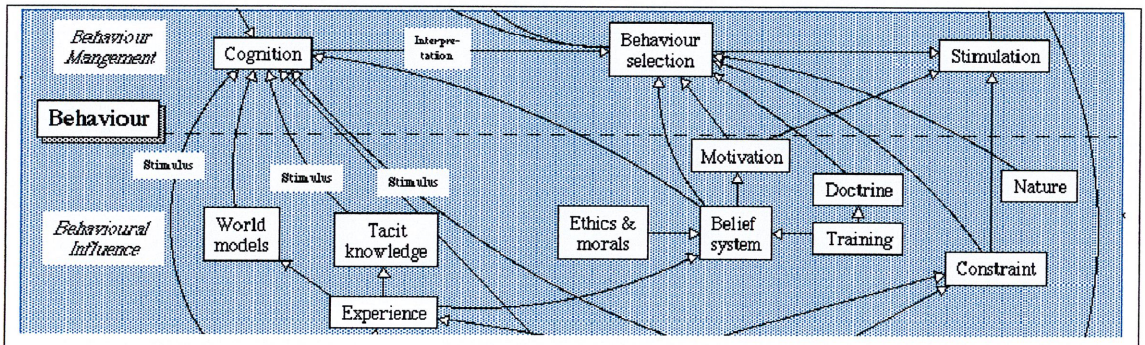


Figure B-5 Behaviour Management - the People Layer

Figure B-6 shows the representation. On the left is Cognition, as in Figure B-5. It receives information from the Situation Display, see Figure B-4. This is normalised, so that other factors may be associated with it; these include Belief & Training, and Experience. At extreme right are the Rules of Engagement, selectable to Engage (Close), Discretion (Hold) or Disengage (Withdraw). Also on the right are the Battle Damage Crews who, in the simulation, are considered most at risk as they attempt to repair damage, control fires, etc. They are the principle source of casualties from Red Hits on Blue.

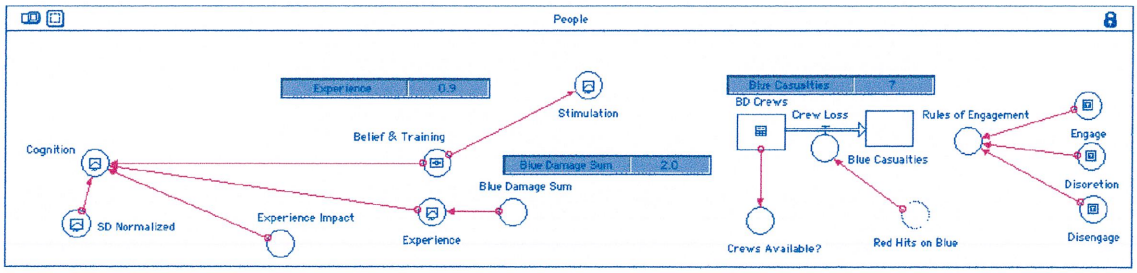


Figure B-6 The People Layer Representation

As in Figure B-5, the simulation of Figure B-6 contains a process for learning from Experience, and modifying consequent Behaviour. As the number of hits received by Blue rises, it increases a level emerging from Experience which, in turn, impinges on Cognition. The overall effect is to improve Blue Cognition, i.e. to make Blue Ship personnel recognise their situation more quickly.

Belief and Training are treated as one in the simulation, because a well-trained and disciplined crew might behave as though they shared the same beliefs. Belief & Training influence Cognition, reasonably, in that a better trained crew will recognise situations from the Situation Display by virtue of training as well as by virtue of Experience. Belief & Training also feed Stimulation, which in turn will influence the C^2 Process at Layer three. See Figure B-7 and Figure B-8 below.

Doctrine is not shown explicitly, apart from Rules of Engagement. Elementary Doctrine is, however, embedded in the Decision-making Process (see following) and appears as a number of conditional logic statements (the values of the numbers used are unimportant):

- Engage–Close Logic. IF Crews Available? >= 0 AND Rules of Engagement = 0 AND Experience <= 0.85 and Weapons Display> 0 AND Separation > 3 AND Situation Assessment > 0 THEN PULSE(1,0,0.5) ELSE 0
- Discretion–Hold Logic. IF Crews Available? < 0 OR Rules of Engagement = 1 OR (Experience > 0.85 AND Experience < 0.9) OR Weapons Display < 5 OR Separation < 0 OR Situation Assessment < 0 THEN PULSE(1,0,0.5) ELSE 0

- Disengage–Withdraw Logic. IF Rules of Engagement = 2 OR Experience >= 0.9 OR Crews Available? < 0 OR Weapons Display <= 0 OR Separation < 2 OR Situation Assessment < 0 THEN PULSE(1,0,0.5) ELSE 0

From the above logic statements, it can be seen that, for example, a ship will Close on the enemy provided:

- Rules of Engagement permit it.
- Experience is less than or equal to 0.85 (indicating that the ship has not received excessive hits).
- At least one weapon is available.
- Separation is greater than 3nm and Situation Assessment is sufficient to show the presence and location of the target.

(The Pulse statement represents the initiation of a process of decision-making, which will traverse the decision-making chain, emerging at the far end as a control pulse. See following section.)

The sum effect is doctrinal, in that it determines C² and ship behaviour according to a set of rules based on experience, practice and common sense. Moreover, a ship will change its behaviour within a simulation run if circumstances and those same rules dictate.

B.2.3 Representing the C² Process/Mission Management Layer

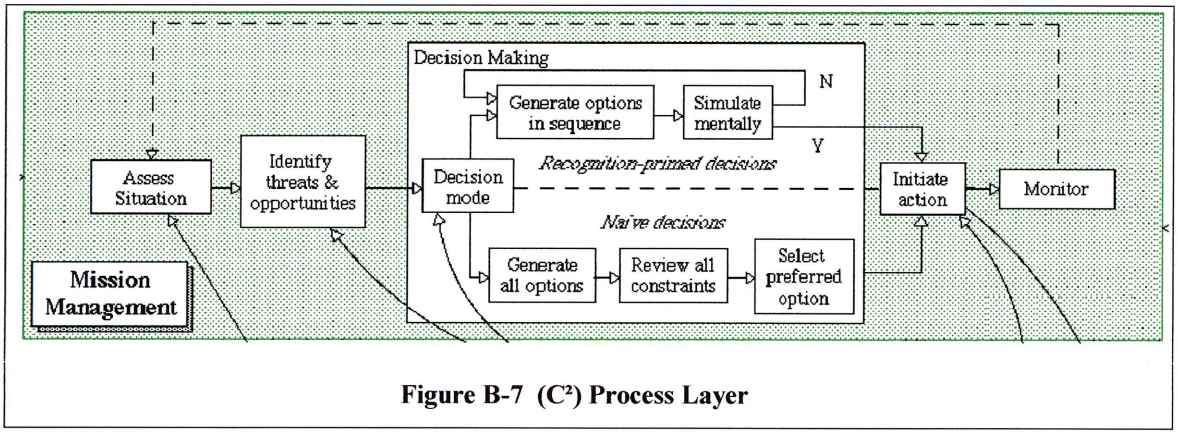


Figure B-7 (C²) Process Layer

Figure B-7 shows the C² Process Layer, taken from the LGRM. Its corresponding simulation is shown in Figure B-8. Figure B-7 shows Assess Situation on the left, followed by Identify Threats & Opportunities, followed by a decision-making block,

then Initiate Action and Monitor, which feeds back to Assess Situation as both own and enemy action alter circumstances. This is the standard C² process, except perhaps for the Decision-Making block. Two distinct decision-making modes are envisaged. One, the so-called naïve approach, follows the lower arm in the block. It is the standard: Generate all options; Review all constraints; Select preferred option. The upper arm exhibits Gary Klein's so-called Recognition-Primed Decision-Making (RPD) mode. This mode would be invoked by an expert decision-maker under time pressure. Essentially, the expert decision-maker uses experience to identify similar situations from memory and uses that experience to go straight to a decision. RPD, then, is experience-based and fast.

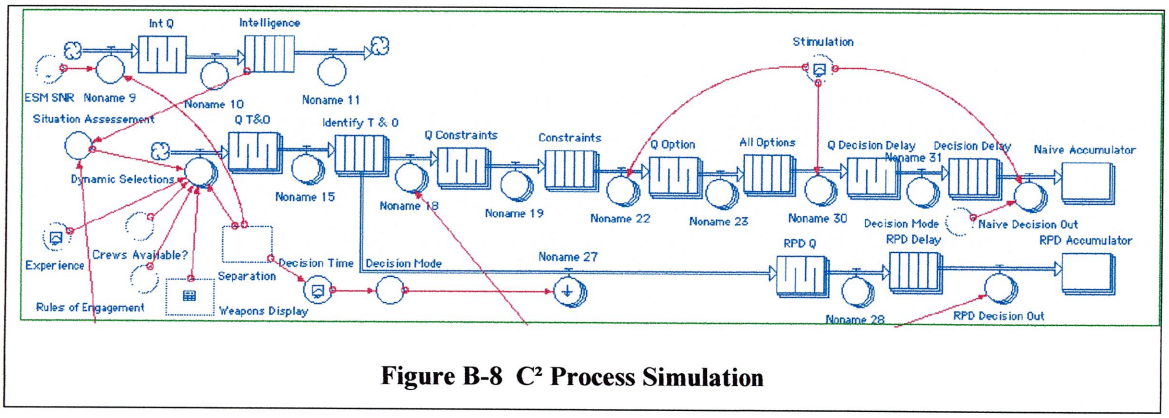


Figure B-8 C² Process Simulation

The C² Process is simulated in Figure B-8. The two branches for the two decision-making modes are in evidence, although they have been inverted so that RPD is at the bottom. On the left, as in Figure B-7, is Situation Assessment, which derives inputs from Cognition (Figure B-6) and from Intelligence. The simulation assumes that Intelligence is derived from ESM when the ESM Signal to Noise Ratio (SNR) rises above a sensitivity threshold, and the ships are separated by more than the primary radar range. Intelligence from ESM is passed through a conveyer and then dissipated, representing the volatility of Intelligence.

Dynamic Selection is the input flow to the decision-making chain, or C² Process. In addition to Situation Assessment, it has inputs from: Weapons Display; Rules of Engagement; Experience; Crews Available; and Separation. These various inputs form the basis of the conditional logic statements, constituting Doctrine, shown in the previous section. Decision impulses pass along the chain, dividing at Identify T & O (Threats and Opportunities) into the two decision-making modes. The choice of

decision-modes is determined by the Separation between Blue and Red Ships: when Separation goes below an adjustable threshold, the time necessary to complete the full naïve decision-making process is too long, and decisions switch to the lower, RPD arm - which takes less time to traverse. Additionally, Stimulation from the People/Behaviour Management Layer acts on both decision-mode chains to reduce the overall decision-delay: this represents the effects of training in improving speed in co-operative human decision-making.

Finally, the outputs from the two decision-mode chains, RPD Decision Out and Naïve Decision Out, are copied into the Technology Layer (Figure B-4) where they exert control over weapon firing, navigation, helm, etc.

B.3 Maintenance

Figure B-9 shows the schemes in the simulation for representing COTS and Bespoke equipment maintenance. Each simulation run starts with COTS Spares Stock, top left, being filled to the level set by COTS Spares Scaling. The Spares Stock is then used up as Equipment fails during the course of the simulated engagement. Each piece of equipment has its own spares scaling, its own stock and its own failure rate.

For COTS, it is presumed that both primary equipment and spares are less expensive than for Bespoke. In consequence, COTS equipment is repaired by replacement and the faulty items discarded. This is shown in the figure, where each icon is an array, so that costs are calculated separately for weapon, radar, ESM, jammer and displays.

Bespoke equipment is presumed expensive by comparison with COTS and, in consequence, repairs are executed by module replacement. Defective modules are then repaired, if possible, while the restored equipment is returned ready for reuse. (Bespoke LRU Stock - where LRU is Line Replaceable Unit).

For Bespoke equipment, a more extensive suite of test facilities is therefore necessary and technicians have to be trained to a higher level - both invoking extra costs. These extra costs appear in the cost model, see below.

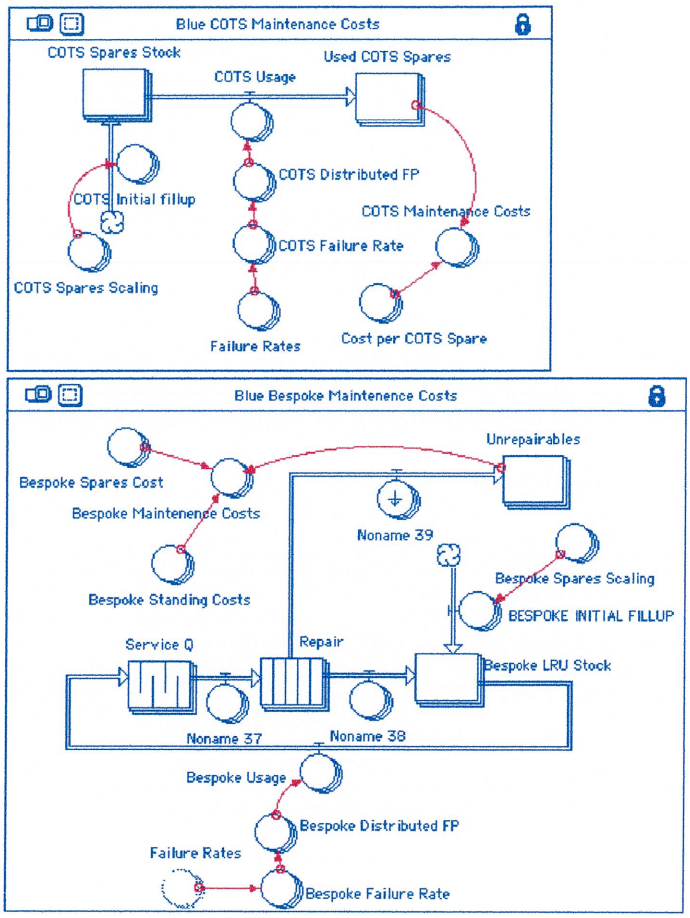


Figure B-9 Bespoke and COTS Maintenance Schemes

B.4 The Three Layers Interconnected

Figure B-10 shows the three layers interconnected. Note that, while some interconnections are evident (e.g. Situation Display to SD Normalised, to Cognition, to Situation Assessment), others are effected by creating 'ghosts'; this avoids unnecessary, untidy links. For example, Stimulation, top right of the C² Process layer, is a ghost of Stimulation in the People Layer. Ghosts are evident by their dotted outlines, but otherwise behave exactly as their alter egos. Other interlayer connections include:

- Blue Damage Record (a matrix of different damage inflicted) leading to Experience via Blue Damage Sum, which sums the different damage effects.
- Blue Battle Damage Display leading to Crews Available? This connection is used to establish whether there are crews available to repair damage. A ghost of 'Crews Available?' can be seen at top left influencing Dynamic Selections. If there are no crews available, then the ship will attempt to withdraw

- RPD Decision Out and Naïve Decision Out, as ghosts in the bottom layer, firing weapons as Blue Deployment. A cross connection from Red Ship, Red Damage Record, is used to inhibit Blue Weapons in the event of their being hit by Red Ship.
- Another cross-connection, Red Deployment (as a ghost) indicates a Red weapon firing. Red Ph is combined with Red Deployment to record a Red Hit on Blue, using a random number generator and a threshold as previously described.

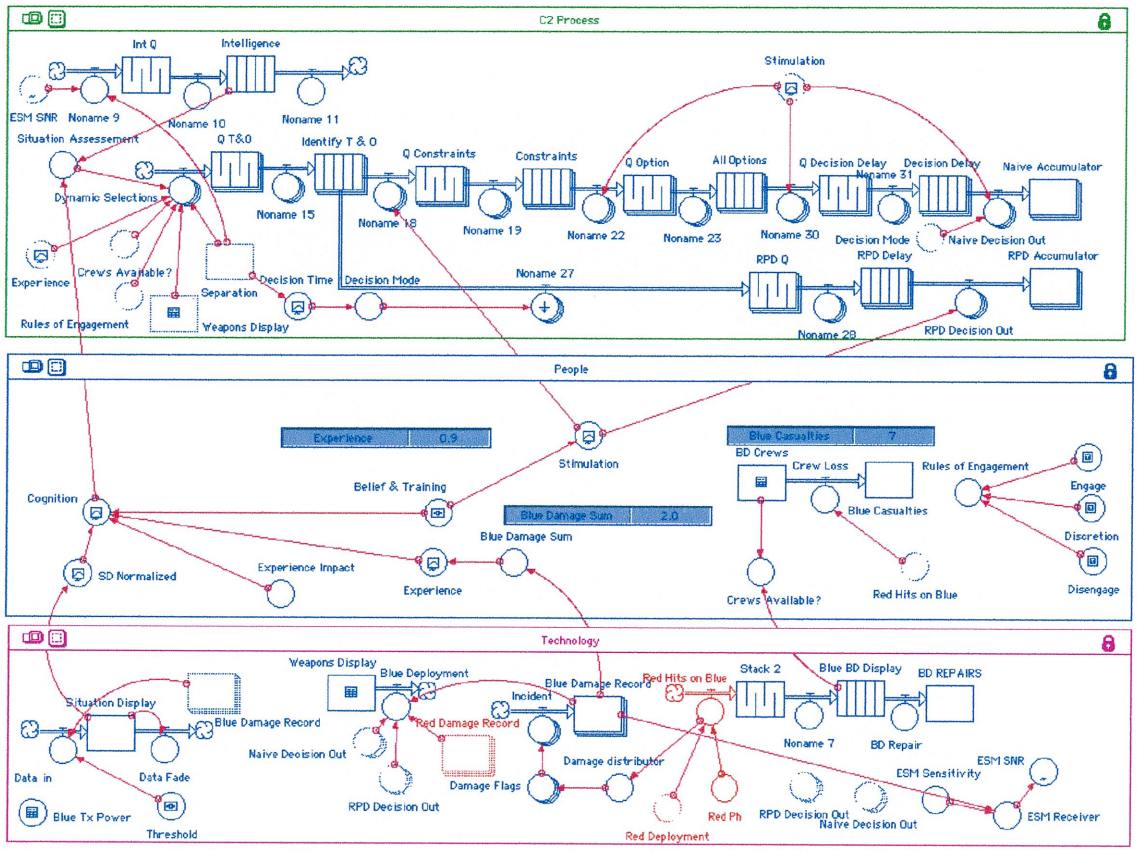


Figure B-10 Three Simulation Layers, showing Interconnections

Note that the symbols that appear as superimposed icons, such as all of those in the Process Layer Decision-making chains, represent arrays, and that the model is effectively many similar models superimposed on each other. In that particular instance, the array allows several different decisions to be passed down the chain coherently. The decisions are: fire weapon; activate jammer; close (engage the enemy); hold (position); withdraw (disengage from the enemy). In the case of Damage Flags, in the Technology layer, the matrix holds measures of damage to: engine, radar, weapons, jammer, ESM and the whole ship (i.e. that it has been sunk).

An alternative view of interconnectivity, showing the complexity of the overall simulation model is given in Figure B-11. This figure, produced by the STELLA™ tool, shows both ships, their support systems, their intra-connections and mutual interconnections, cost models, and exchange ratio calculators. Note that Red Jamming Pattern appears in Blue Ship locale and vice versa, since the effects from one vessel are experienced by the other.

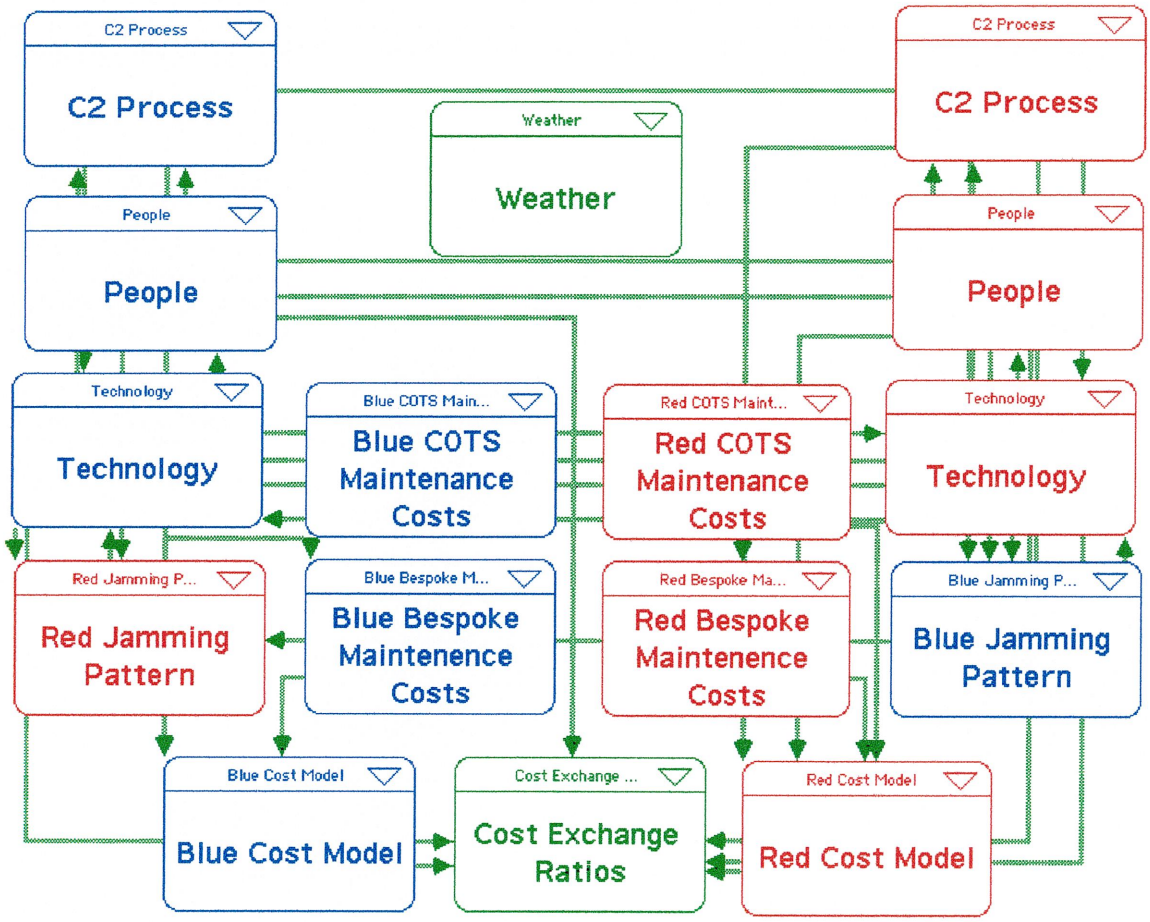


Figure B-11 STELLA™ Simulation Model Block Diagram showing Red and Blue Ships and their Interactions

B.5 Cost Models

Both ships have extensive cost models. Figure B-12 shows that for Blue Ship. The approach is conventional cost build-up, using cost per item multiplied by number of items.

Costs are included for:

- Bespoke and Maintenance, for each equipment.
- Damage.
- Crew losses.
- Equipment.
- Training.
- Bespoke and COTS spares scaling for each equipment.
- Weapons fired.

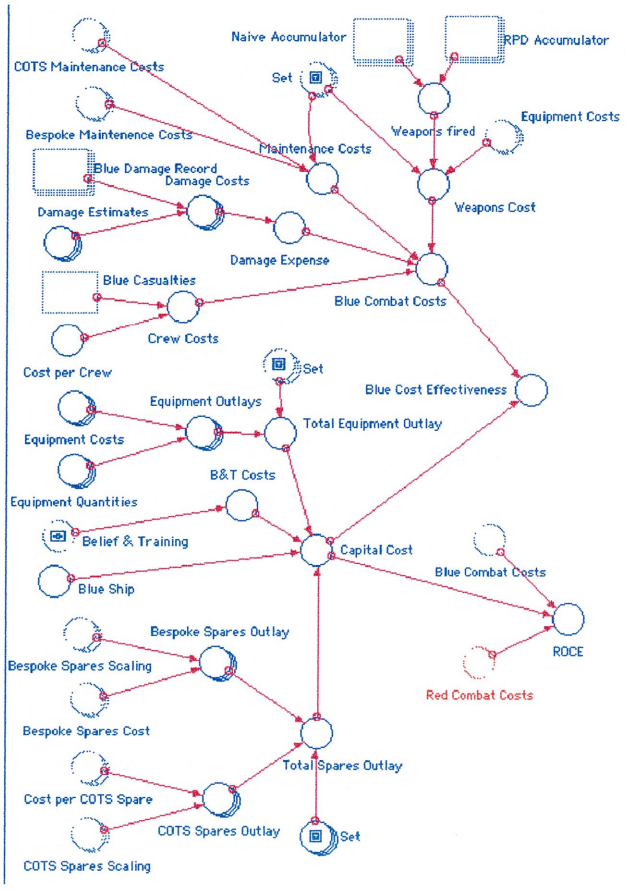


Figure B-12 Blue Cost Model

The various costs are drawn together to form Combat Costs and Capital Costs, which are then formed in turn into several measures of effectiveness, there being no universally accepted single measure.

Blue Cost Effectiveness is calculated in the model as follows:

(Capital Cost - Blue Combat Costs) ÷ Capital Cost x 100 %.

The logic derives from Sun Tzu's observation that the greatest effectiveness arises when one does not even have to fight: merely one's presence deters the enemy. Blue Cost Effectiveness will also be at its maximum with no fighting, since there will be no expenditure on weapons, and no damage will be experienced. Both of these would reduce cost effectiveness.

The formation of an alternative measure of effectiveness, Return on Capital Employed (ROCE) is also shown in the figure. ROCE, by analogy to the accountant's measure, is given by:

(Red Combat Costs - Blue Combat Costs) ÷ Capital Cost x 100%.

In this measure, Red Combat Costs is considered as Revenue, Blue Combat Costs as (e.g.) Cost of Sales, and ship Capital Cost as the investment.

Additionally, Exchange Ratios are calculated by forming the appropriate relationships between Combat Costs and Casualties respectively, to form Cost Exchange Ratio and Casualty Exchange Ratio. Both of these measures follow the same style. For example, Cost Exchange Ratio is given by:

*Red Combat Costs/(Blue Combat Costs + Red Combat Costs)*2.*

The logic is as follows. If Red and Blue are identical, then Red Combat Costs equals Blue Combat Costs, and the ratio becomes 1. Values above 1 indicate advantage to Blue, since this would be caused by Red Combat Costs exceeding Blue Combat Costs. Casualty Exchange Ratio works in the same manner, using Red and Blue Casualties.

B.6 Controlling the Simulation

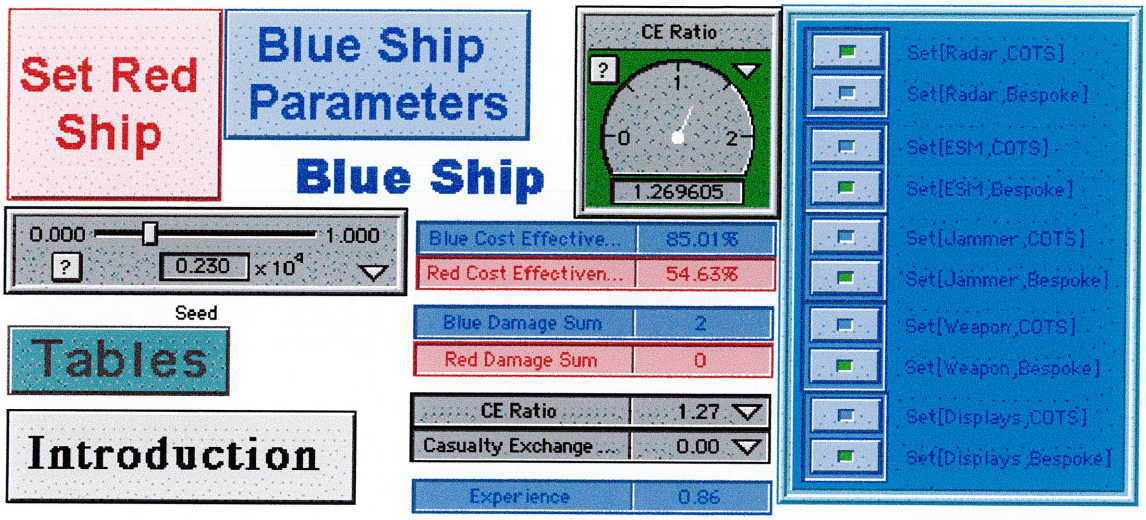


Figure B-13 Blue Ship 'Autopilot'

Figure B-13 shows the main controls for the simulation, sometimes referred to as the auto-pilot. At right are the chained selectors for choosing whether Blue Ship equipment is to be COTS or Bespoke. As shown, only Blue Radar is COTS; all other equipments are Bespoke. Not only does each switch choose the equipment as COTS or Bespoke, it also selects the corresponding maintenance organisation, spares scaling, spares costs, equipment costs, etc. So, although the simulation calculates all factors for all equipment at once in every simulation, only those selected by the controls are put into the various calculations.

The Set Red Ship button presents a similar set of chained selectors to set up Red Ship. Normally, Red Ship would be set to all Bespoke, so that the effects of (in this case) introducing only COTS radar into Blue Ship can be assessed. However, both ships could be set to all COTS, or any combination of COTS and Bespoke. And the two ships could be set up quite differently if desired.

Blue Ship Parameters Button opens a secondary control panel that allows adjustment to other parameters, via graphical and slider interfaces - see Figure B-14. These include Rules of Engagement, starting numbers of weapons, Blue Transmitter power, numbers of Battle Damage Crews, Blue missile hit probability (Ph), etc. Similar controls exist for Red Ship.

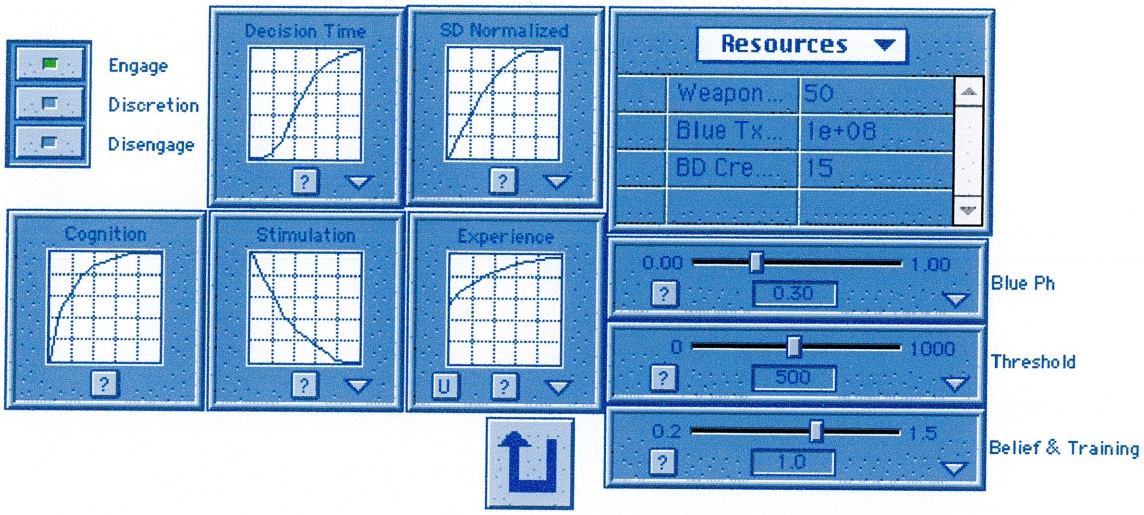


Figure B-14 Secondary Controls

The Tables button of Figure B-13 displays Tables, which spell out the progress of parameters over simulation time. These figures can be transferred to, say, Microsoft Excel for statistical and graphical analysis.

The Seed slider control enables the seed number, which selects the sequence of random numbers that determine where damage is inflicted by an enemy missile, to be changed. For many applications, it is convenient to undertake only single runs, where Blue and Red Ship can be compared. This requires identical performance from both ships; hence, the seed to generate identical sequences for each ship.

However, any one sequence might introduce particular circumstances, so the seed slider is used to see if any counter-intuitive results have arisen simply because of a particular damage sequence. In such an event, full Monte-Carlo simulation would be invoked by eliminating the seed altogether and conducting, typically, a 1000 run analysis to uncover more statistically-acceptable results.

Figure B-13 also shows a Cost Exchange Ratio dial, and several number counters showing Red and Blue Cost Effectiveness, Cost Exchange Ratios, Casualty Exchange Ratios, and Blue Experience level. These are used to observe the progress of a simulation. A graphical display would normally appear with the auto-pilot, showing parameters of interest unfolding as a simulation or sensitivity analysis unfolded.

Finally, the Introduction button reveals a textual introduction explaining the purpose of the simulation.

B.7 Viability Management

Viability Management from the LGRM does not appear explicitly as a separate simulation panel or sector. Instead it is embedded in the simulation, as follows:

- Synergy is inherent in the interconnections which make the various parts of the simulation work together
- Maintenance is explicit, see above
- Evolution is explored by employing the sensitivity function within STELLA™ to represent different levels of performance and cost for selected items over a period of years. So, holding other factors constant, a sensitivity run of 20 cycles might represent 20 years of equipment evolution, with each year introducing a small increase in performance and in cost
- Homeostasis is built into the simulation design, with the simulated ship able to repair enemy damage, and also able to sense excessive danger and withdraw, using the experience function
- Survivability is also built in. Survivability may be considered under 3 headings: avoidance of detection; self-defence; and damage tolerance. Avoidance of detection is addressed in the value set for weapon hit probability. A low value equates to a low visibility target. Self-defence is addressed in the low probability of damage - many hits result in little damage, implying self-protection, or armouring. Damage tolerance similarly implies the ability to be hit without damage affecting capability, and battle damage repair - both addressed in the model.

B.8 Resource Management

The last part of the LGRM to consider is Resource Management. That too is embedded in the simulation. The assumption in the scenario is that both ships are fully stocked at the start of the engagement, and operate throughout on those stocks. Running out of stocks causes the respective equipment to cease functioning.

The distribution of resources and their employment is addressed explicitly in the area of maintenance, while the people resources appear in the people layer, conducting the C^2 process and as Battle Damage Repair crews. This last is expended as casualties.

Appendix C: Testing the Simulation Model

C.1 Introduction

This appendix covers a pilot study. It provides the initial tests results during the verification and the validation process of the simulation model described in Chapter 5. It explores the effects of random variations on three measures of effectiveness (Cost Effectiveness, Cost Exchange Ratio and Casualty Exchange Ratio) for two identical ships. Hence, it determines the number of runs required to achieve precise, stable, statistical data (Mean, Mode and Median) and equal effectiveness for both ships as a start point.

C.2 Test Scenario

The scenario represents an engagement between two ships, Blue and Red. The two ships are set up some 100 nautical miles (nm) apart and closing. Both ships are identical, and with both ships set to Bespoke. The same scenario was applied for all the following experiments with the model.

C.3 Tests

The four tests were carried out to find out the number of runs needed to produce a consistent measures of effectiveness set. Although, Test 1 and Test 2 are the same, 100 separate runs each, they produced substantially different simulation results. Therefore, the number of runs was increased to 500 for Test 3 and Test 4. Having done this, the simulation results show only minor differences in the histogram and table results.

C.3.1 Test 1

This is a sensitivity test of 100 runs. The results of each run were captured in a table. Those results include three parameters:

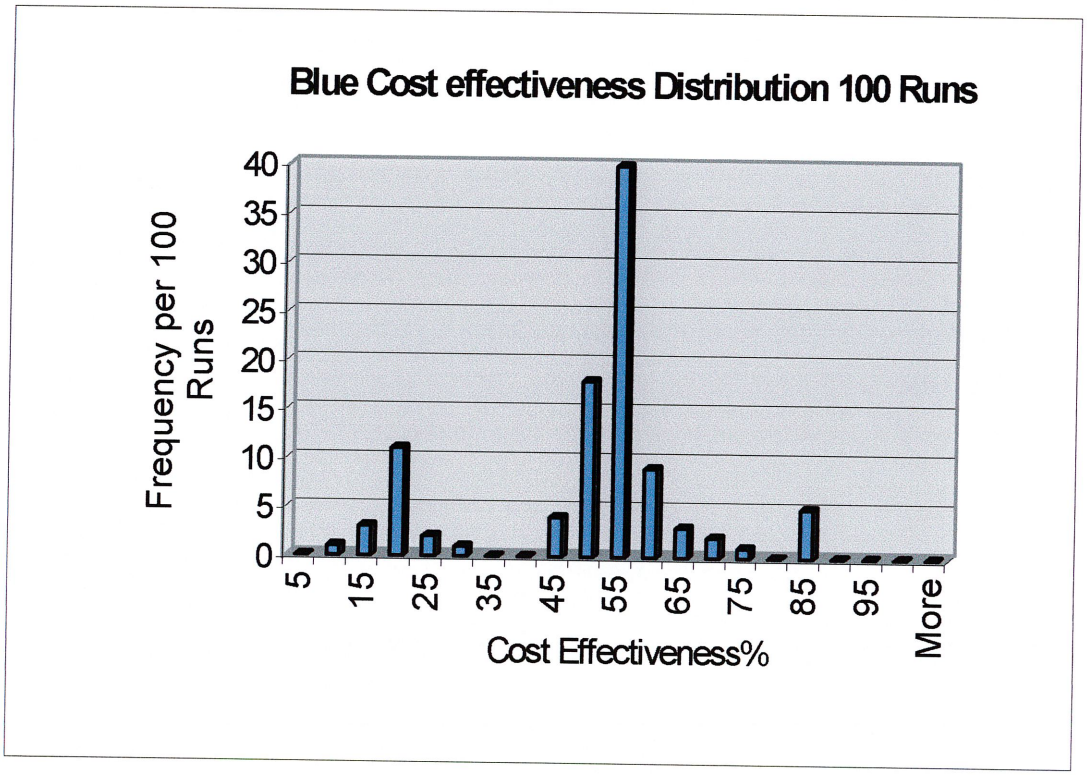
- Blue Cost Effectiveness (same as Red, since both models were set up to be identical). See Graph C-1 and Table C-1.
- Casualty exchange Ratio. See Graph C-2 and Table C-1.
- Cost Exchange Ratio. See Graph C-3 and Table C-1.

The degree of variability, can be seen best when presented in histogram form. Graphs C-1 to C-3 illustrate the histogram results from 100 simulation runs with Blue and Red identical. The general statistics, generated by Microsoft Excel, give precise statistical data, as shown in Table C-1.

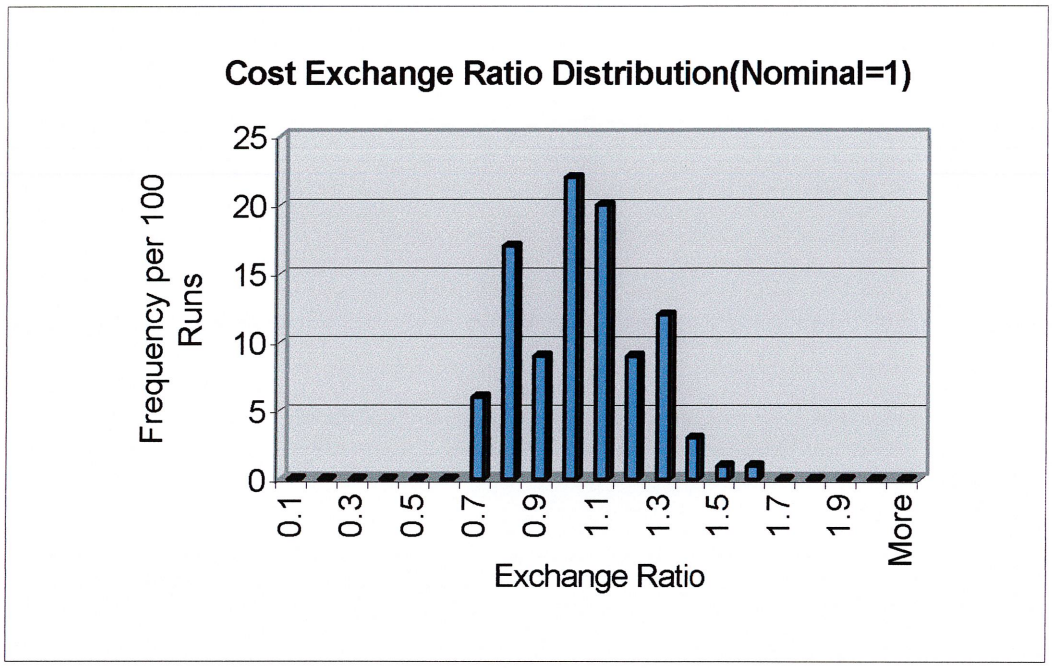
Measures of Effectiveness MoEs	Statistical Summary		
	Mean	Mode	Median
Blue Cost Effectiveness	47.9	54.4	52.8
Cost Exchange Ratio	0.9	0.7	1.0
Casualty Exchange Ratio	1.1	1.0	1.0

Table C-1 First 100 Runs Summary Table - both Ships Bespoke

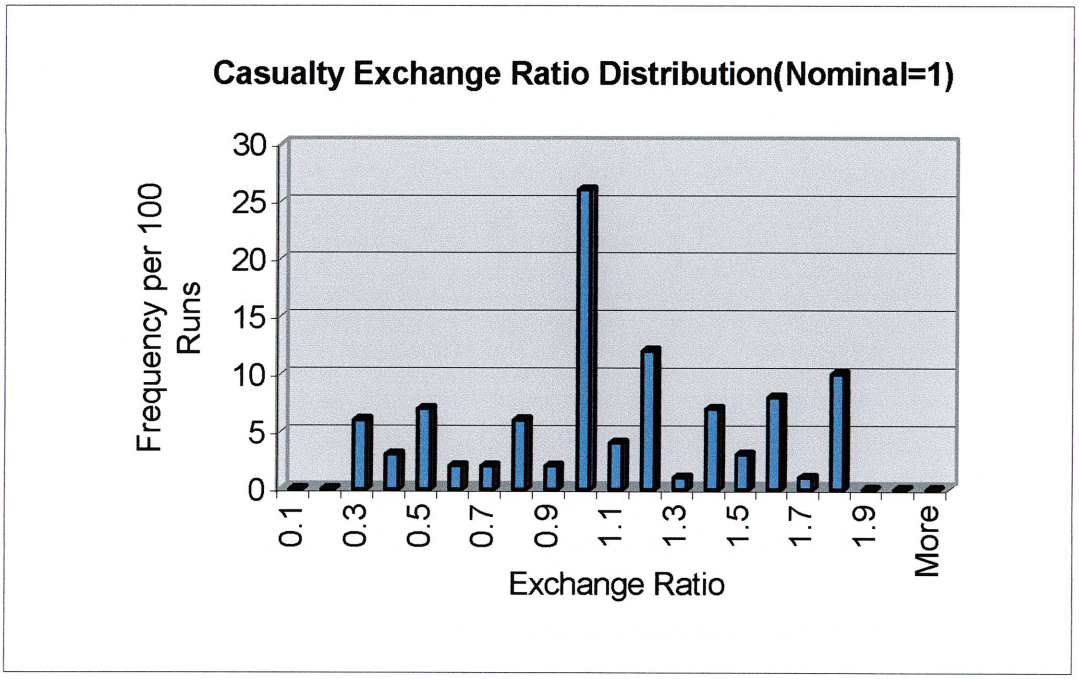
Graph C-1 Blue Cost Effectiveness Variability over 100 Runs



Graph C-2 Cost Exchange Ratio Distribution over 100 Runs



Graph C-3 Casualty Exchange Ratio Distribution over 100 Runs



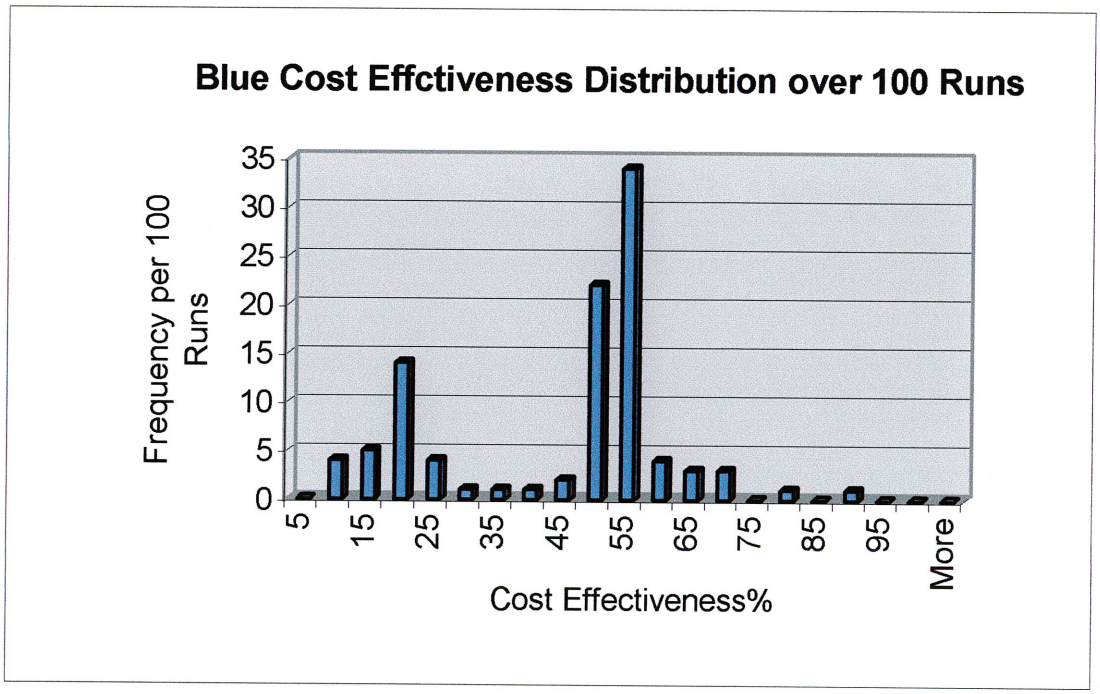
C.3.2 Test 2

This test is exactly the same as Test 1, but with a different 100 runs. By comparing the histogram and the statistic data captured from both Test 1 (Table C-1 & Graphs C-1 to C-3) and Test 2 (Table C-2 & Graphs C-4 to C-6), it can be seen that there are some differences in the effectiveness measures. Therefore, more runs would be required to achieve stability. Graphs C-4 to C-6 illustrate the histogram results obtained in this test from a new 100 runs. The general statistics are also shown in Table C-2.

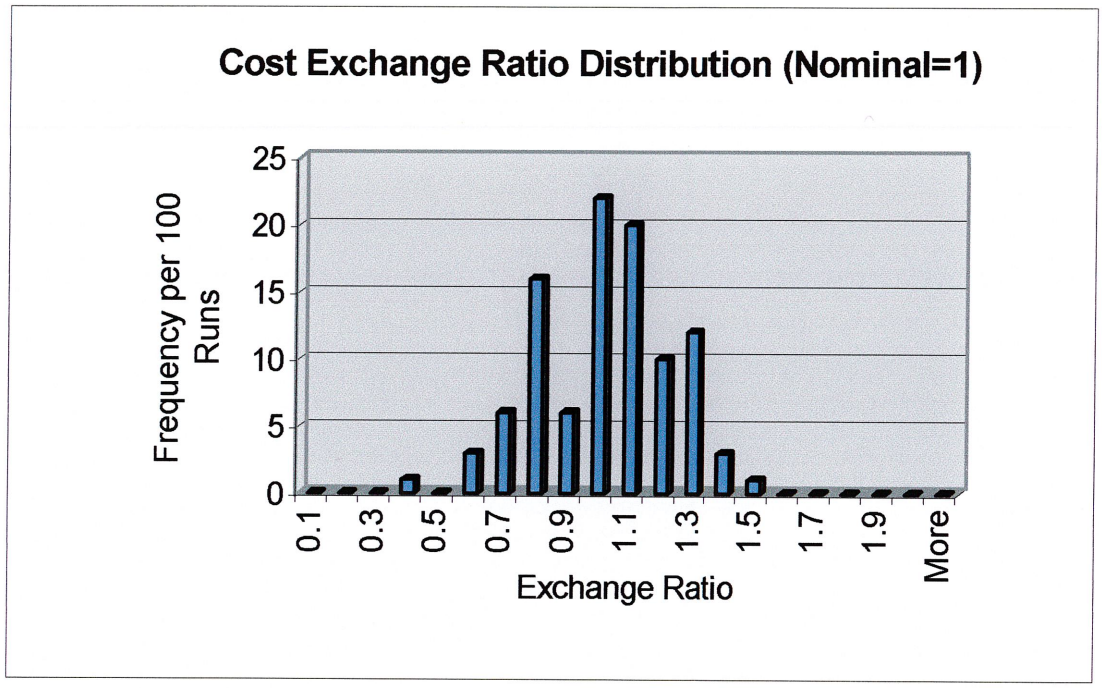
Measures of Effectiveness MoEs	Statistical Summary		
	Mean	Mode	Median
Blue Cost Effectiveness	42.5	54.4	49.5
Cost Exchange Ratio	0.9	1.0	1.0
Casualty Exchange Ratio	1.0	1.0	1.0

Table C-2 Second 100 Runs Summary Table- both Ships Bespoke

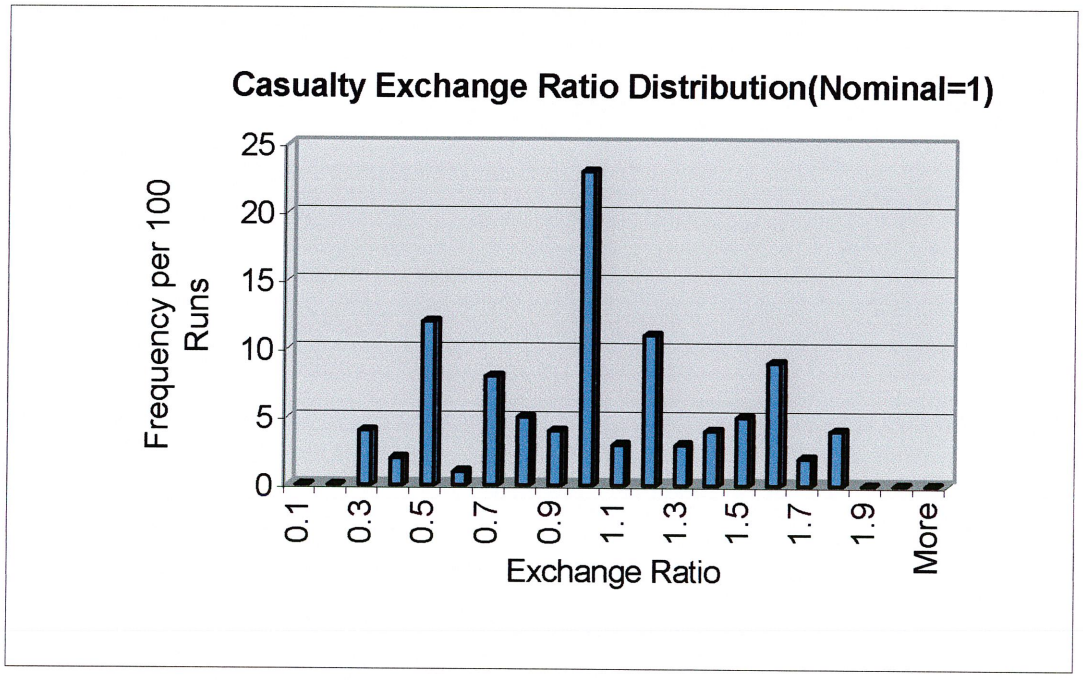
Graph C-4 Blue Cost Effectiveness Variability over Second 100 Runs



Graph C-5 Cost Exchange Ratio Distribution over Second 100 Runs



Graph C-6 Casualty Exchange Ratio Distribution over Second 100 Runs



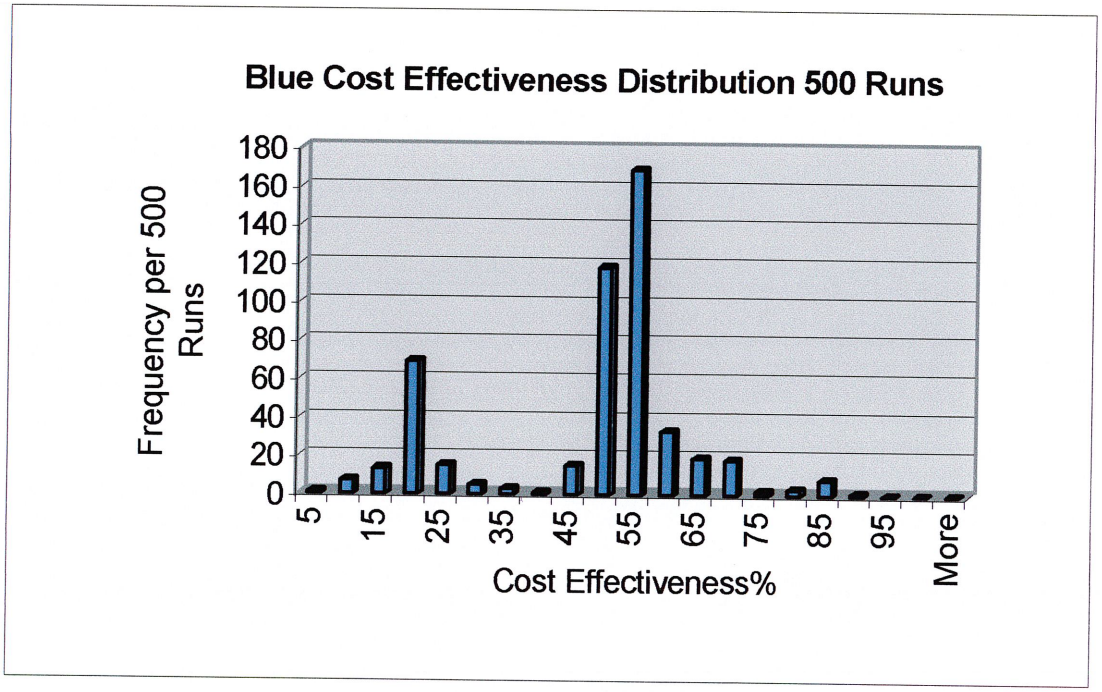
C.3.3 Test 3

It was clear from Tests 1 and 2 that 100 runs were not enough to produce stable results. In this test, the number of runs was increased to 500. Graphs C-7 to C-9 illustrate the histogram results from 500 runs. The general statistics are shown in Table C-3.

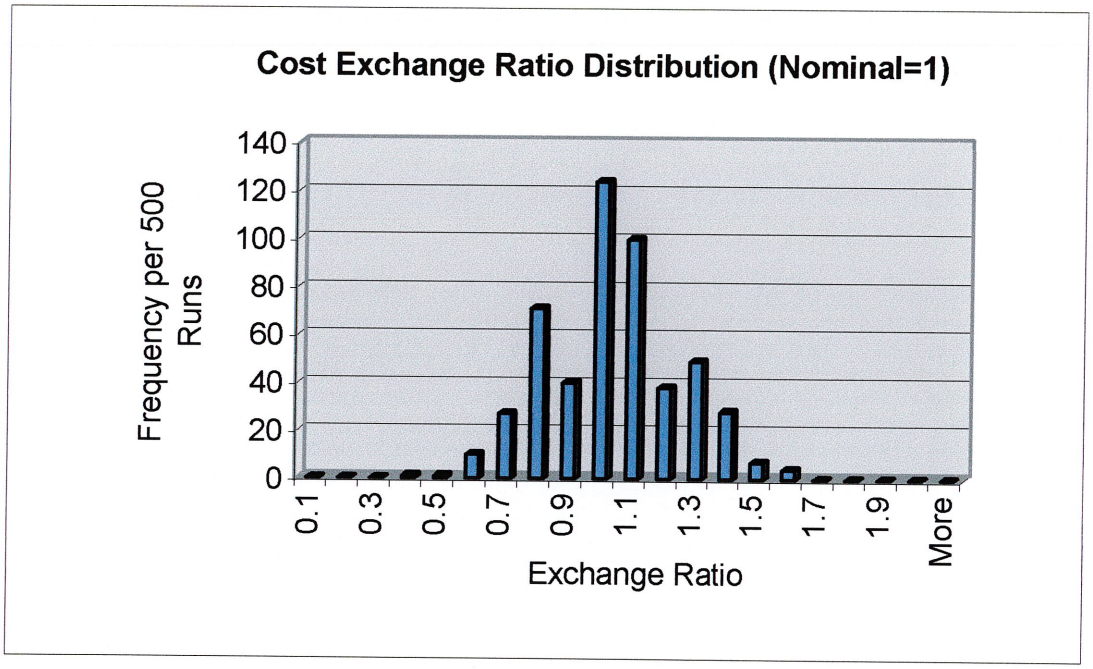
Measures of Effectiveness MoEs	Statistical Summary		
	Mean	Mode	Median
Blue Cost Effectiveness	45.4	54.4	50.0
Cost Exchange Ratio	1.0	1.0	1.0
Casualty Exchange Ratio	1.0	1.0	1.0

Table C-3 First 500 Runs Summary Table - both Ships Bespoke

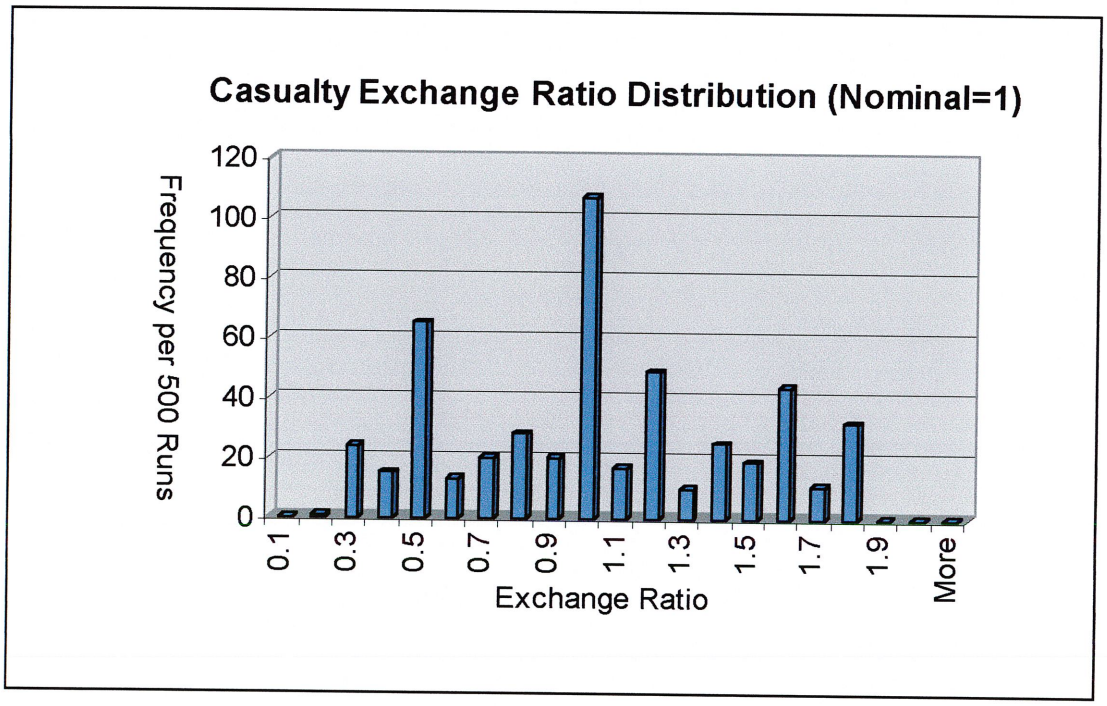
Graph C-7 Blue Cost Effectiveness Variability over 500 Runs



Graph C-8 Cost Exchange Ratio Distribution over 500 Runs



Graph C-9 Casualty Exchange Distribution over 500 Runs



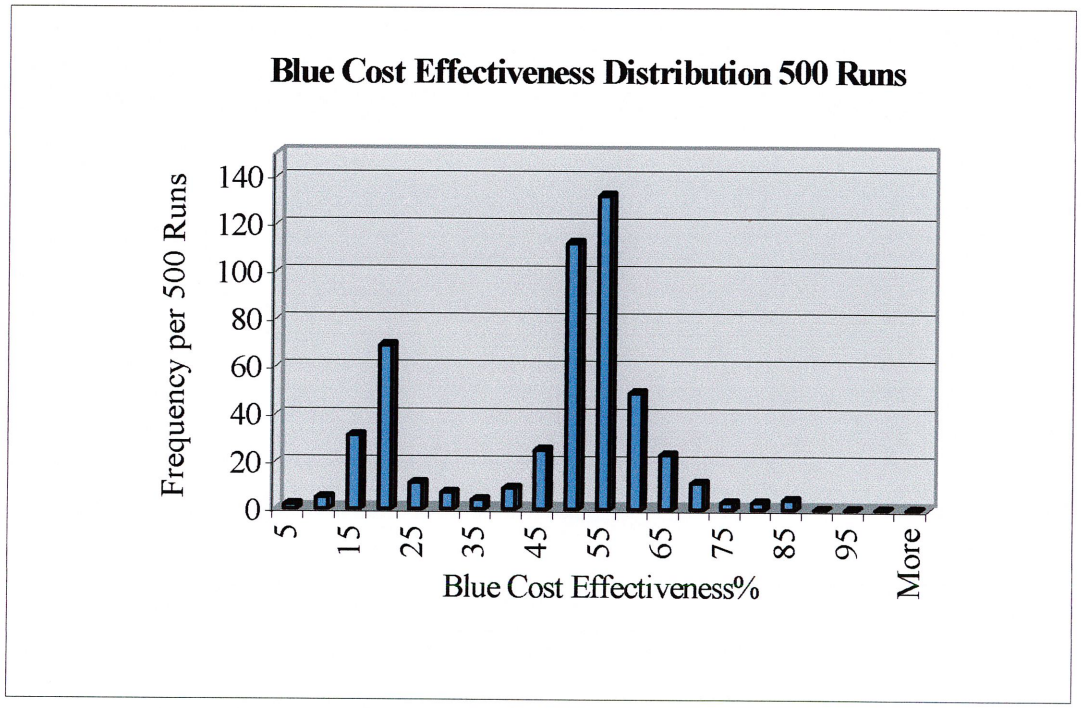
C.3.4 Test 4

This test is exactly the same as Test 3, but with a new 500 runs. By comparing the histogram and the data captured by both Test 3 (Table C-3 & Graphs C-7 to C-9) and Test 4 (Table C-4 & Graphs C-10 to C-12), it can be seen that each effectiveness measure is getting closer to its counterpart. Graphs C-10 to C-12 illustrate the histogram results obtained in this test from fresh 500 runs. The general statistics are shown in Table C-4.

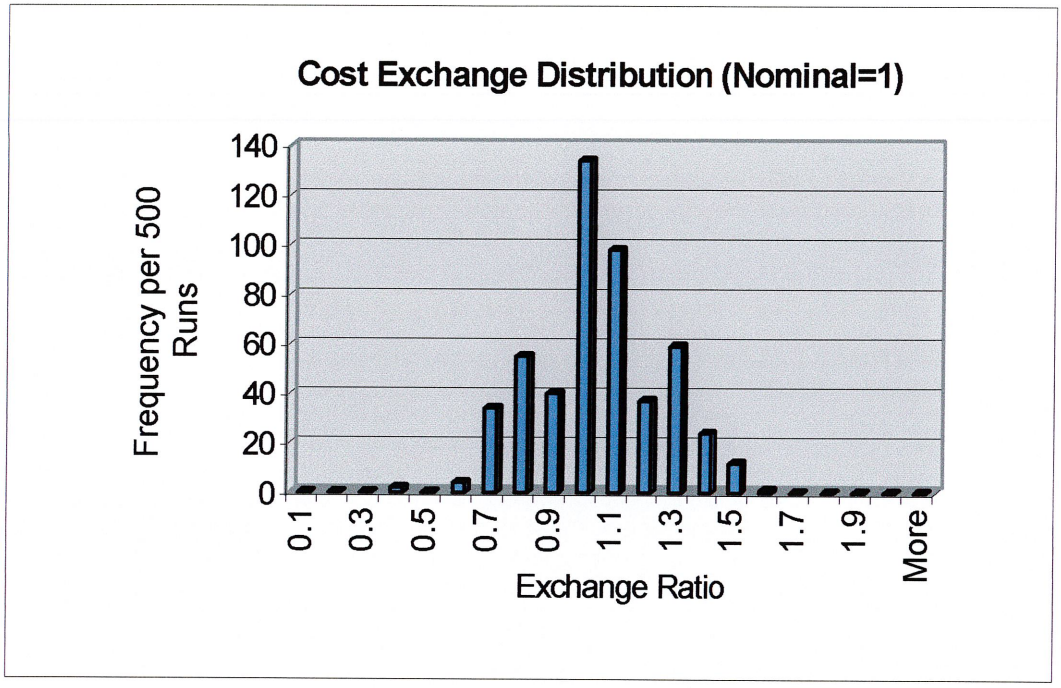
Measures of Effectiveness MoEs	Statistical Summary		
	Mean	Mode	Median
Blue Cost Effectiveness	43.6	54.6	49.5
Cost Exchange Ratio	1.0	1.0	1.0
Casualty Exchange Ratio	1.0	1.0	1.0

Table C-4 Second 500 Runs Summary Table - both Ships Bespoke

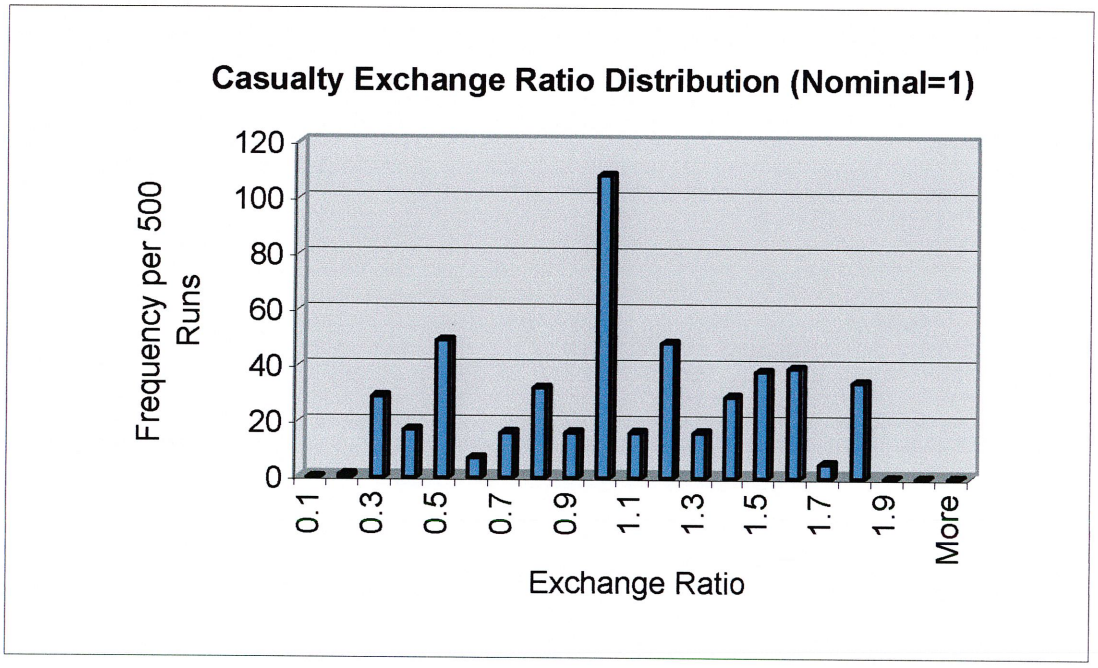
Graph C-10 Blue Cost Effectiveness Variability over Second 500 Runs



Graph C-11 Cost Exchange Ratio Distribution over Second 500 Runs



Graph C-12 Casualty Exchange Ratio Distribution over Second 500 Runs



C.4 Conclusions

After conducting the two 500-run tests, it was considered that the results between two equal ships were almost close enough to proceed to the main tests. In order to be safe, however, 1000 runs were used in Chapter 5, as the basis for measurements.

Appendix D: Simulation Results

D.1 Introduction

The purpose of this appendix is to describe, using a set of tables, all the different simulation input data and measurement outcomes of the supplementary experiments described in Chapter 6. These include several types of modelling measurements on Blue Ship, such as technology ageing, technology update and trades-off studies.

D.2 Weapon Ageing

The purpose of the experiment was to determine the effect of keeping Blue Ship technology unchanged while enhancing Red Ship. The two tables, below, give additional details regarding the experiment carried out in section 6.3.1 of Chapter 6 (Graph 6-1). Table D-1 shows the simulation input data in the form of an improvement in Red Ship weapon performance over 20 years and the associated cost.

	Input Variables	
Run #	Equipment Costs ...	Red Ph
1	1e+06	0.3
2	1.1e+06	0.316
3	1.1e+06	0.332
4	1.2e+06	0.347
5	1.2e+06	0.363
6	1.3e+06	0.379
7	1.3e+06	0.395
8	1.4e+06	0.411
9	1.4e+06	0.426
10	1.5e+06	0.442
11	1.5e+06	0.458
12	1.6e+06	0.474
13	1.6e+06	0.489
14	1.7e+06	0.505
15	1.7e+06	0.521
16	1.8e+06	0.537
17	1.8e+06	0.553
18	1.9e+06	0.568
19	1.9e+06	0.584
20	2e+06	0.6

Table D-1 Upgrading Red Ship Weapon System

Table D-2 illustrates the results of this modelling experiment.

Run #	Cost Exchange Ratio	Casualty Exchange Ratio	Blue Cost Effectiveness
1	1	1	66.09
2	1.02	1	66.09
3	0.88	0.92	54.35
4	0.89	0.92	53.76
5	0.91	0.92	53.76
6	0.92	0.77	53.46
7	0.93	0.77	53.46
8	0.95	0.77	53.46
9	0.96	0.77	53.46
10	0.97	0.77	52.88
11	0.98	0.77	52.88
12	0.99	0.77	52.88
13	0.95	0.71	46.71
14	0.96	0.71	46.71
15	0.97	0.71	46.71
16	0.98	0.71	46.71
17	0.99	0.71	46.71
18	1	0.71	46.71
19	1.02	0.71	46.71
20	0.97	0.71	40.84

Table D-2 Blue Falling Behind Technology Effectiveness

D.3 Sensor Failure

The two tables (Table D-3 and Table D-4) below provide additional details regarding the experiment conducted under section 6.3.2 in Chapter 6 (Graph 6-2). Table D-3 shows the simulation input data in the form of a failure rate values of Blue Ship radar over 10 simulation runs.

	Input Variables
Run #	Failure Rates[Radar,COTS]
1	0.01
2	0.02
3	0.03
4	0.04
5	0.05
6	0.06
7	0.07
8	0.08
9	0.09
10	0.1

Table D-3 Increasing Radar Failure Rate over 10 Runs

The outcome results of this experiment are shown in Table D-4.

Run#	Cost Exchange Ratio	Casualty Exchange Ratio	Blue Cost Effectiveness
1	1	1	49.2
2	1	1	49.19
3	1	1	49.19
4	1	1	49.19
5	1	1	49.19
6	1	1	49.19
7	1.12	0.83	60.41
8	1.12	0.83	60.41
9	1.12	0.83	60.41
10	1.12	0.83	60.41

Table D-4 COTS Radar MTBF Effectivess Measures

D.4 Missile Upgrading

The two tables below (Table D-5 and Table D-6) provide additional details regarding the experiment carried out under section 6.4.1 in Chapter 6 (Graph 6-3). Table D-5 illustrates the simulation real data inputs for upgrading Blue Ship missile in terms of probability of hit (Ph) and the upgrade cost over 20 years, while keeping Red Ship without any upgrade.

Run#	Equipment Costs	Blue Ph
1	1.00E+06	0.3
2	1.20E+06	0.324
3	1.40E+06	0.347
4	1.60E+06	0.371
5	1.80E+06	0.395
6	2.00E+06	0.418
7	2.20E+06	0.442
8	2.40E+06	0.446
9	2.60E+06	0.489
10	2.80E+06	0.513
11	3.00E+06	0.537
12	3.20E+06	0.561
13	3.40E+06	0.584
14	3.60E+06	0.608
15	3.80E+06	0.632
16	4.00E+06	0.655
17	4.20E+06	0.679
18	4.40E+06	0.703
19	4.60E+06	0.726
20	4.80E+06	0.75

Table D-5 Effectiveness Measures Variability

The outcomes of this modelling experiment are shown in Table D-6.

Run#	Cost Exchange Ratio	Casualty Exchange Ratio	Blue Cost Effectiveness
1	1	1	66.09
2	1.06	1	65.22
3	1.11	1.08	64.67
4	1.09	1.08	63.86
5	1.08	1.23	63.35
6	1.06	1.23	62.6
7	1.04	1.23	61.87
8	1.03	1.23	61.17
9	1.01	1.23	60.49
10	1.06	1.29	59.84
11	1.04	1.29	59.2
12	1.03	1.29	58.59
13	1.01	1.29	58
14	1	1.29	57.43
15	1.03	1.29	56.87
16	1.02	1.29	56.33
17	1.01	1.29	55.81
18	1	1.29	55.3
19	1.05	1.5	60.3
20	1.02	1.53	58.8

Table D-6 Missile Upgrade Effectiveness Measures

D.5 Optimum Radar power Density

The two tables below (Table D-7 and Table D-8) provide additional details regarding the experiment carried out under section 6.4.2 in Chapter 6 (Graph 6-4). Table D-6 illustrates the simulation real data inputs for Blue Ship radar performance improvements over 20 years in terms of the radar radiated power and the corresponding costs. Table D-7 shows the outcome of this modelling experiment.

	Input Variables	
Run #	Blue Tx Power	Equipment Costs[R...
1	2e+08	1.6e+07
2	1.9e+08	2.6e+07
3	1.8e+08	3.5e+07
4	1.7e+08	4.5e+07
5	1.6e+08	5.5e+07
6	1.5e+08	6.4e+07
7	1.4e+08	7.4e+07
8	1.3e+08	8.4e+07
9	1.2e+08	9.3e+07
10	1.1e+08	1e+08
11	9.5e+07	1.1e+08
12	8.4e+07	1.2e+08
13	7.4e+07	1.3e+08
14	6.3e+07	1.4e+08
15	5.3e+07	1.5e+08
16	4.2e+07	1.6e+08
17	3.2e+07	1.7e+08
18	2.1e+07	1.8e+08
19	1.1e+07	1.9e+08
20	100000	2e+08

Table D-7 COTS Radar Value for Money

Run #	Cost Exchange Ratio	Casualty Exchange Ratio	Blue Cost Effectiveness
1	0.95	0.73	47.46
2	0.95	0.73	49.21
3	0.96	0.92	50.85
4	0.96	0.92	52.38
5	0.95	0.83	53.82
6	0.97	0.92	56.09
7	0.97	0.83	58.23
8	0.98	1.07	59.39
9	1	1	62.15
10	1	1	63.15
11	1	1	64.09
12	1.1	1.2	66.67
13	1.04	0.92	68.86
14	1.04	0.92	69.6
15	1.04	0.92	70.31
16	1.04	0.92	70.98
17	1.04	0.92	71.63
18	1.07	1	73.59
19	1.15	0.73	78.1
20	1.27	0	85.01

Table D-8 Radar Optimum Performance Effectiveness Measures

D.6 Trades-off

The four tables below (Tables D-9 to D-12) provide additional details regarding the experiment carried out under section 6.5 in Chapter 6. Table D-9 shows the input variables that have been used to obtain the graphical result shown in Graph 6-5, while Table D-10 represents the output results in numerical form. They are the numbers scored for three measures of effectiveness (MOEs) shown in Graph 6-5.

Table D-11 shows the input variables for Graph 6-6, and Table D-12 represents the output results in numerical forms. They are the numbers scored for three measures of effectiveness (MOEs) shown in Graph 6-6.

	Input Variables		
Run #	Equipment Costs[...	Blue Ph	Belief & Training
1	1e+06	0.3	1.20
2	1.1e+06	0.321	1.18
3	1.1e+06	0.342	1.16
4	1.2e+06	0.363	1.14
5	1.3e+06	0.384	1.12
6	1.3e+06	0.405	1.09
7	1.4e+06	0.426	1.07
8	1.5e+06	0.447	1.05
9	1.5e+06	0.468	1.03
10	1.6e+06	0.489	1.01
11	1.7e+06	0.511	0.989
12	1.8e+06	0.532	0.968
13	1.8e+06	0.553	0.947
14	1.9e+06	0.574	0.926
15	2e+06	0.595	0.905
16	2e+06	0.616	0.884
17	2.1e+06	0.637	0.863
18	2.2e+06	0.658	0.842
19	2.2e+06	0.679	0.821
20	2.3e+06	0.7	0.8

Table D-9 Increasing Missile Performance & Costs and Decreasing Training

Run #	Cost Exchange Ratio	Casualty Exchange Ratio	Blue Cost Effectiveness
1	1.39	1.07	65.12
2	1.42	1	65.4
3	1.43	1.08	64.83
4	1.41	1.08	64
5	1.4	1.23	63.47
6	1.39	1.23	62.69
7	1.37	1.23	61.94
8	1.36	1.23	61.22
9	1.34	1.23	60.52
10	1.36	1.29	59.85
11	1.34	1.23	59.19
12	1.36	1.53	58.8
13	1.31	1.29	58.81
14	1.33	1.33	60
15	1.31	1.23	59.47
16	1.31	1.33	59.88
17	1.27	1.12	59.9
18	1.29	1.07	59.46
19	1.31	1.43	59.68
20	1.3	1.2	59.39

Table D-10 Technology-Training Trade-off Effectiveness Measures

Equipment Costs[...	Blue Ph	Belief & Training
1e+06	0.3	1.50
1.1e+06	0.321	1.45
1.1e+06	0.342	1.39
1.2e+06	0.363	1.34
1.3e+06	0.384	1.29
1.3e+06	0.405	1.24
1.4e+06	0.426	1.18
1.5e+06	0.447	1.13
1.5e+06	0.468	1.08
1.6e+06	0.489	1.03
1.7e+06	0.511	0.974
1.8e+06	0.532	0.921
1.8e+06	0.553	0.868
1.9e+06	0.574	0.816
2e+06	0.595	0.763
2e+06	0.616	0.711
2.1e+06	0.637	0.658
2.2e+06	0.658	0.605
2.2e+06	0.679	0.553
2.3e+06	0.7	0.5

Table D-11 Increasing Missile Performance and Cost While Decreasing Training

Run #	Cost Exchange Ratio	Casualty Exchange Ratio	Blue Cost Effectiveness
1	1.39	1.07	65.42
2	1.37	1.07	64.45
3	1.39	1.07	63.51
4	1.4	1.14	62.88
5	1.38	1.2	62
6	1.37	1.2	61.15
7	1.35	1.2	60.32
8	1.36	1.23	61.3
9	1.34	1.23	60.57
10	1.36	1.29	59.86
11	1.34	1.18	59.51
12	1.35	1.23	61.05
13	1.32	1.11	61.48
14	1.3	1	60.96
15	1.14	0.5	52.56
16	1.16	0.59	55.04
17	1.21	0.5	61.57
18	1.23	0.5	63.35
19	1.24	0.8	64.23
20	1.24	0.31	66.04

Table D-12 Technology-Training Trade-off Effectiveness Measures

D.7 Optimise Individual Performance Experiment

The two tables below (Table D-13 and Table D-14) provide additional details regarding the experiment carried out under section 6.5 of Chapter 6. Table D-13 shows the input variables for Graph 6-7, and Table D-12 represents the output results in numerical forms. They are the numbers scored for three measures of effectiveness (MOEs) shown in Graph 6-7.

	Input Variables
Run #	Blue Tx Power
1	1e+07
2	2e+07
3	3e+07
4	4e+07
5	5e+07
6	6e+07
7	7e+07
8	8e+07
9	9e+07
10	1e+08
11	1.1e+08
12	1.2e+08
13	1.3e+08
14	1.4e+08
15	1.5e+08
16	1.6e+08
17	1.7e+08
18	1.8e+08
19	1.9e+08
20	2e+08

Table D-13 Increasing Blue Tx Power

Run #	Cost Exchange Ratio	Casualty Exchange Ratio	Blue Cost Effectiveness
1	1.12	0.73	63.79
2	1.07	1	55.94
3	1.04	0.92	53.69
4	1.04	0.92	53.69
5	1.04	0.92	53.69
6	1.04	0.92	53.69
7	1.04	0.92	53.69
8	1.1	1.2	51.63
9	1.1	1.2	51.63
10	1	1	49.2
11	1	1	49.2
12	0.98	1.07	46.96
13	0.98	1.07	46.96
14	0.97	0.83	46.96
15	0.97	0.92	45.83
16	0.95	0.83	44.71
17	0.96	0.92	44.71
18	0.96	0.92	44.71
19	0.95	0.73	44.71
20	0.95	0.73	44.71

Table D-14 Radar Transmitter Power Trade-off Effectiveness Measures

Appendix E: Source Material for the Simulation Model

E.1 Introduction

Attached to this appendix is a single CD-ROM, which contains the STELLA™ representation of the COEIA white-box simulation model. The CD also contains a public-domain STELLA™ viewer, which will allow the model to be displayed and executed. Please follow these steps to explore this STELLA™ model on the CD:

1) Install the STELLA™ viewer by double clicking on st51_32 2.exe.
2) Open the viewer.
3) Close the open window in the viewer.
4) Use the 'File-Open' option to select the model on the CD (Model20.STM).

The STELLA™ simulation model should now be open and ready for experimentation.

E.2 Simulation Development Requirements

The development of the COEIA white-box simulation model, using STELLA™, was performed with the following resources:

a. Hardware: 200 MHz MMX processor PC with 32 MB RAM.
b. Software: Microsoft Windows 95.
c. Tools: STELLA™ Research, version 5.1.1.

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Please attach CD-ROM holder here.