Assessing the Value of a C4ISREW System-of-Systems Capability

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Abstract

This paper highlights the implicit reliance of various concepts, motivated by the emerging Revolution in Military Affairs (RMA), on the development of a Joint C4ISREW System. It also proposes a framework, which can be used to assist the Australian Defence Organisation in meeting its joint C4ISREW capability requirements, by way of an overall architectural schema. This framework extends the concept of a system-of-systems to include a hierarchy of C4ISREW systems-of-systems with different requirements associated with each level. The hierarchy is then used to develop two architectural views to govern the activity of developing Australia's C4ISREW capability. The first is the Joint Force Migration view, which provides the structure, inter-relationships and principles and guidelines governing the evolution of the ADF's C4ISREW resource base. The second is the Joint Systems Synthesis view, which provides the structure, inter-relationships and principles and guidelines governing the rapid assembly of specific C4ISREW systems-of-systems designed to meet the operational requirements of a particular contingency. These two architectural views are then used as a basis for developing assessment concepts and methodologies specifically targeting questions associated with the evaluation of C4ISREW systems-of-systems at each level. Both the architectural framework and assessment concepts outlined in this paper have significant implications for the application of current practices as they highlight both the narrow scope of current architecture thinking and the deficiencies associated with traditional assessment techniques.

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1. Introduction

The so-called Revolution in Military Affairs (RMA) or the information revolution, much of which is being driven by commercial developments in the civil sector, is changing the nature of warfare all over the world.

Australia's Strategic Policy, 1997. (p. 55)

Revolutions occur whenever a new idea or paradigm fundamentally alters the existing cultural status quo[1]. We are presently experiencing the beginnings of a revolution in military affairs (RMA) as the application of a range of new technologies and paradigms radically changes the nature of warfare. Vickers defines an RMA as a major discontinuity in military affairs brought about by changes in military-relevant technologies, concepts of organisation, or resources, which abruptly transforms the conduct of war and make possible order-of-magnitude gains in military effectiveness [Vickers, 1997]. This change, as experienced in society at large, has also been described as the information era, the third wave of human civilisation, following the agrarian and industrial eras [Toffler and Toffler, 1980] or, as experienced in the commercial world, the revolution in business affairs [Department of Defence, 1999].

Information Technology, as the centre-piece of the modern era is driving much of this change. However it is a mistake to believe that the acquisition of revolutionary technologies in itself constitutes a revolution in military affairs [Dibb, 1997]. What is needed is a paradigm shift within the organisation, which enables the military to leverage from these emerging technologies. The concept of a paradigm shift was first introduced by the philosopher and science historian Thomas Kuhn [Kuhn, 1962] to describe scientific revolutions. We are currently experiencing a paradigm shift in the commercial sector as Information Technology moves from platform-centric to network-centric computing. This shift is perhaps best described by Sun Corporations' slogan, "The network is the computer", and most obvious in the explosive use of the Internet and Intranets in day to day business [Cortese, 1996]. In the commercial sector, dominant businesses such as Wal-Mart and Deutsche Morgan Grenfell have gained significant competitive advantage by making the shift to network-centric operations [Cebrowski and Garstka, 1998]. Networking is enabling the creation of new types of information-based relationships with and among organisations, information is being passed quickly and efficiently and the tempo of operations increased. The cumulative impact of better information distribution and new organisational behaviour evolving from the emerging new paradigm in the commercial world is providing companies with the potential to dominate their competitive space [Alberts et al., 1999].

The paradigm shift from platform-centric computing to network-centric computing has profound implications on the way warfare is conducted. The themes emerging in the commercial sector, if applied wisely, will transform the military organisation into an information-age organisation that will have the potential for significant advantages within its competitive domain. The US have integrated this paradigm shift into their concepts for future joint operations, Joint Vision 2010

[1] The term "paradigm" has been used to describe several distinct concepts. Its original meaning is the set of all forms containing a particular element (for example: boy, boys, boy's and boys' constitutes the paradigm of the noun boy). It has also been used as a synonym for pattern and example. However the term "paradigm" is widely used today to describe a broad model or way of thinking.

and Joint Vision 2020. These policy documents assert that the primary mechanism for generating increased combat power in the period to 2020 will be networks of sensors, command and control, and shooters [Joint Chiefs of Staff, 1997], thus the emerging operational concepts can be characterised as network-enabled. A central theme of the US Joint Vision 2010 is the attainment of full spectrum dominance. This will be enabled through information superiority: the ability to collect, process and disseminate an uninterrupted flow of information while exploiting or denying an adversary's ability to do the same [Joint Chiefs of Staff, 1997].

Network-Centric Warfare (NCW) is the concept developed by the United States to describe the paradigm shift central to the revolution in US military affairs [Alberts et al., 1999]. It is defined as an information superiority-enabled concept of operations that generates increased combat power by networking sensors, decision makers, and shooters to achieve shared awareness, increased speed of command, higher tempo of operations, greater lethality, increased survivability and a degree of self synchronisation [Alberts et al., 1999]. It is important to keep in mind that NCW is only one response to the perceived need for an RMA (that of the United States). Australia will need to determine its own response to the RMA, which incorporates all three services. We propose that the term Network-Enabled Warfare is perhaps a more precise description of the paradigm shift central to the Australian RMA as it highlight the enabling role of the network. It also leaves the claim of centrality to higher-level concepts such as information superiority, knowledge superiority, decision superiority or decisive maneouvre[2]. Furthermore, we propose that the development of a joint C4ISREW information environment is the "entry-fee" to these emerging RMA-motivated concepts of operations for the ADF.

Admiral W. Owens while serving as VC of the US Joint Chiefs of Staff noted that superior technologies were emerging in three areas; Intelligence, Surveillance and Reconnaissance systems (ISR), Command, Control, Communications and Computing systems (C4) and systems involving Targeting and Weaponry [Owens, 1996, Laird and Mey, 1999, Libicki, 1999]. Coalescing these three systems into a system-of-systems (SOS), which provides a flexible and seamless sensor to shooter capability is central to the achievement of NCW as proposed by the US Navy [Alberts et al., 1999]. In fact, Admiral W. Owens defines the RMA as being essentially a system-of-systems whose main components are ISR technologies, C4 systems, real time systems integration, and doctrine, strategies, tactics and military organisations that can take advantage of the inherent potential in the information revolution [Nye and Owens, 1996].

Whilst no clear definition of the term "system-of-systems" found within the literature has been generally accepted, the phenomena is widespread and generally recognised [Maier, 1997]. Systems-of-systems are considered classes of systems, which have been built from components that are large-scale systems in their own right [Owens, 1995]. Prominent examples include the Internet, intelligent transportation systems and enterprise information networks. Maier provides five principal characteristics useful for distinguishing very large, complex monolithic systems from true systems-of-systems [Maier, 1997], these are:

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[2] Definitions of these concepts can be found in the documents "Network Centric Warfare: Developing and Leveraging Information Superiority" [Alberts, et al., 1999], "Australia's Strategic Policy" [Department of Defence, 1997] and "Decisive Manoeuvre: Australian Warfighting Concepts to Guide Campaign Planning" [Department of Defence, 1998].

1. *Operational Independence of the Elements*: If the SOS is disassembled into its component systems the component systems must be able to usefully operate independently. The SOS is composed of systems, which are independent and useful in their own right.

2. *Managerial Independence of the Elements*: The component systems not only can operate independently, they do operate independently. The component systems are separately acquired and integrated but maintain a continuing operational existence independent of the SOS.

3. *Evolutionary Development*: The SOS does not appear fully formed. Its development and existence is evolutionary with functions and purposes added, removed, and modified with experience.

4. *Emergent Behaviour*: The system performs functions and carries out purposes that do not reside in any component system. These behaviours are emergent properties of the entire SOS and cannot be localised to any component system. The principal purposes of the SOS are fulfilled by these behaviours[3].

5. *Geographic Distribution*: The geographic extent of the component systems is large. Large is a nebulous and relative concept as communication capabilities increase, but at a minimum it means that the components can readily exchange only information and not substantial quantities of mass or energy.

2. The Place of C4ISREW

To make a smaller force more effective, DOD is planning to rely more than ever before on the use of high-technology C4I systems to leverage its military assets[4].

Realizing the Potential of C4I (1999)

We define a Joint C4ISREW System (JCS) as a system-of-systems that provides a military capability synthesised from command & control, surveillance, reconnaissance, intelligence and electronic warfare systems by exploiting technical, doctrinal and cultural synergy, across any or all services, to achieve a total force effect, which surpasses the sum of the individual systems. It provides relevant, timely and assured information to support decision superiority in planning, command, tasking, deployment and sustainment of a wide range of military operations.

According to Maier's criterion a joint system for C4ISREW (JCS) can be viewed as an instance of a system-of-systems [Laird and Mey, 1999]. A JCS, as defined above, would necessarily include the real time integration of ISR systems, C4 systems and EW systems. However it should also comprise the integrated logistics information environment and be intimately intertwined

[3] Arguably, the key issue in the conception of systems (or of system-of-systems) is that of emergence. An Emergent property of a system is a property that is meaningful when attributed to the whole system, not to its components. Emergence occurs when a system, created by integrating components into a complex whole, exhibits properties that are qualitatively different from the properties of its components. Accordingly, an emergent property of a system is defined as a property of a whole system that is qualitatively different from the properties of its components. Dependent on the nature of the components and system involved, emergent properties may or may not be predictable before the system is synthesised [Burke, 2000]

[4] This quote is taken from a US DOD policy document.

with joint force personnel, processes, training and doctrine. All of these factors enable the JCS to deliver the desired effects for any given operational situation. A JCS spans the entire sensor-to-shooter network and provides the military with the potential to achieve decision superiority over a regional adversary. We provide a conceptual template[5] of a JCS below.

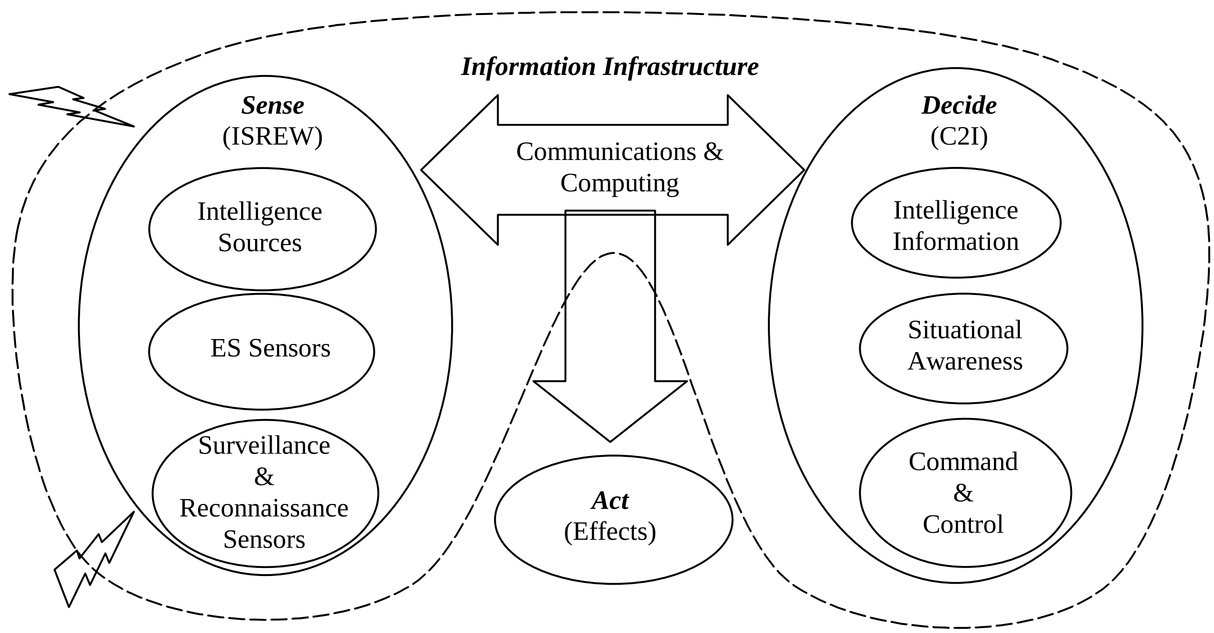

Figure 1: C4ISREW Top Level Conceptual Template.

At the sensor end of the sensor-to-shooter network, is a network of sensors and information sources. This network comprises Intelligence sources, Surveillance assets, Reconnaissance assets and associated control and reporting organisations (collectively known as ISR). Data is the main output of all ISR activity and is usually focused on foreign forces, resources, activities or meteorological, hydrographic or geographic characteristics of a particular area [Department of Defence, 1994b][6]. An essential requirement for network-enabled operations is the ability to collect and transmit data from ISR systems, to systems of decision-makers for processing and analysing in near real time.

Command, Control, Communications, Computing and Intelligence systems (C4I systems) are an integrated system of doctrine, procedures, organisational structure, personnel, equipment, facilities and communications which provides authorities at all levels with timely and adequate information to plan, direct, coordinate and control their activities [Department of Defence, 1994b]. It is usually within the C4I system that data obtained from ISR systems is given a context and processed into information. This provides a basis for situation awareness, knowledge, and ultimately military judgement and command. The command, along with necessary targeting

[5] The Conceptual Template provided is best viewed as a systemic metaphor and has been developed in conjunction with VCORP Consulting for the purpose of defining a boundary around C4ISREW. Further work on refining this template will continue.
[6] Modern ISR systems often contain some level of processing and analysis of data before it is transmitted to decision-makers.

information is provided to systems of weaponry to complete the sensor to shooter information flow.

Electronic Warfare (EW) plays a role at both the sensor and the shooter end of the sensor-to-shooter network. At the sensor end, Electronic Warfare Support (ES) systems, similar to ISR systems provide information for decision-makers. ES systems aim to identify and locate a threat by means of an adversaries emissions or reflections [Department of Defence, 1994a]. ES information can also be used in target acquisition. However once decision makers have chosen a course of action, EW can once again play a role at the shooter end of the sensor-to-shooter network. Upon recognition of a threat a decision-maker will choose to either engage or avoid the threat. If engagement is chosen EW may play a role as part of the weaponry. This form of EW is known as Electronic Attack (EA) and involves actions taken to prevent or reduce the enemy's effective use of EW, or the employment of electromagnetic weapons [Department of Defence, 1994a].

The development of a JCS is described as the entry fee into the emerging new paradigm for warfare [Alberts, et al., 1999]. A JCS is comprised of the information infrastructure (or infostructure) which enables information to flow from systems of sensors (ISR & EW systems) to decision-making systems (Command & Control) and subsequently to systems of targeting and weaponry. Alberts describes the infostructure as an integrated network of communications and computational capabilities [Alberts et al., 1999]. However, it is important to keep in mind that additional to the infostructure, a JCS also comprises the information environment that dictates what information the infostructure will support and how it will be managed, transformed and presented. It is argued that in order to take full, or even partial, advantage of such a system there will have to be substantial changes in such areas as doctrine, organisation and attitude toward innovation [Laird and Mey, 1999, Dibb, 1997].

3. A Framework for C4ISREW Systems Architecture

There is a difference between acquisition and operational capabilities.

Professor Paul Dibb (1997)

In order for the ADF to develop a JCS capability that meets the needs of an increasingly diverse spectrum of possible future operations we contend that an architectural framework will need to be developed. This paper provides a framework for the various levels of architectural practice and systems analysis needed in the development of the ADF's C4ISREW capability. We have already presented the metaphor of a system-of-systems as a useful tool for understanding C4ISREW. However this metaphor requires some extensions and clarification before it can be successfully applied to the architecture of Australia's C4ISREW systems and associated C4ISREW capability. Maier's distinguishing characteristics of a system-of-systems [Maier, 1997] cannot distinguish between systems-of-systems of different order or between systems-of-systems architected (or evolved) for different purposes[7]. We extend the system-of-systems

[7] Maier's distinguishing characteristics of a system-of-systems are described in Section 1, these are; the operational independence of the component systems, the independence of acquisition of the component systems, the evolutionary nature of the SOS, the

metaphor in order to develop a framework for distinguishing between C4ISREW systems-of-systems of different orders and the set of all possible C4ISREW systems-of-systems that could be developed from the same component elements. This extension allows us to construct two distinct (yet symbiotic) activities associated with the development of Australia's C4ISREW capability.

To extend the concept of a system-of-systems to include a hierarchy we need only to observe the component elements. In this paper we are interested in two orders within the potential hierarchy of systems-of-systems, as described in Table 1 below. It should be observed that when viewing a system-of-systems from a particular level of abstraction, a subsequent change in focus, will also change the perspective of what constitutes a component and what constitutes a system. The examples described in Table 1 thus represent only one level of abstraction.

SOS Order	**Component Elements**	**Example**	**Power Set (Set of all possible sets)**
SOS or SOS_I	System of: • Components • Systems	A component of a larger C4ISREW capability. (eg. An AEW&C).	All possible configurations of existing components and systems. Denoted ***P***(SOS).
SOSOS or SOS_{II}	System of: • Components • Systems • SOS_I	A Joint C4ISREW System assembled for a particular operation (eg East Timor).	All possible configurations of existing components, systems and systems-of-systems. Denoted ***P***(SOSOS).

Table 1: A C4ISREW system-of-systems hierarchy with associated power sets.

3.1 The Portfolio of C4ISREW Assets

The power set of second order SOS's, presented in Table 1, is the entire portfolio of C4ISREW assets that can be used as leverage in order to meet the C4ISREW requirements for a particular contingency or operation. We define this power set as the portfolio of C4ISREW assets (POCA). The development of a POCA is a process that occurs largely in peacetime and operates progressively over a long time-scale. Thus the portfolio is constantly evolving. Principles of portfolio development include the following:

- An assessment of the future security environment and the potential spectrum of capability requirements (Capability Requirements Analysis).
- The minimisation of the risk of being unable to instantiate a C4ISREW system-of-systems to respond to a particular contingency at any time (Risk Minimisation).
- The establishment of guidelines for interoperability, information management and system evolution (Architectural Guidance).
- The optimal use of C4ISREW funding to maintain a balanced portfolio for both current preparedness and strategic capability development (Funds Distribution).

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emergent behaviour of the SOS, and the limited interaction between component systems. The idea of "order" within a SOS hierarchy is presented in Table 1. For a given SOS hierarchy (at a given level of abstraction) a change in order occurs when a SOS contains, as component elements, SOS's of the previous order.

The POCA consist of resources managed by all three services. Whilst components of possible operational SOS's (or SOSOS's) can be integrated, they are not usually integrated with each other in peacetime [Allison and Cook, 1998]. The emergent property of greatest interest is the ability to rapidly assemble a C4ISREW SOS for a particular operation. The effectiveness of a portfolio may thus be measured by its ability to support the rapid assembly of a C4ISREW SOS capable of fulfilling all current and future operational needs.

3.2 The Instantiated Joint C4ISREW System

An example of a second order SOS as described in Table 1 is the instantiated Joint C4ISREW System (JCS) which arises from the portfolio in order to meet a specific operational need. The JCS can be comprised of systems (or systems-of-systems) owned by any of the services. Each component system (or system-of-systems) may perform a particular subset of C4ISREW and should be able to be rapidly integrated to form a system-of-systems tailored to meet the C4ISREW requirements of a specific operation. The assembly of a JCS only occurs in response to an operational requirement. Such operational requirements may occur across a spectrum from planned exercises on one end of the spectrum, to war on the other. The JCS must be able to be rapidly assembled, as many of the operations the ADF could be involved in will have little or no warning time. Unlike the POCA, the JCS exists only temporarily (to support a particular operation), when the requirement no longer exists, the JCS disassociates into its component systems and once more forms part of the peacetime POCA. Principles of JCS assembly include:

- Determining operational requirements (Operational Requirements Analysis).
- Engineering systems solutions (Systems Synthesis)
- Determining system dynamics and behaviour (Systems Analysis & Modelling).
- Determining the convergence of the solutions onto requirements (Systems Assessment).

The JCS must be assembled quickly and optimally with respect to a particular operation and is formed by drawing from the POCA those elements that are best suited for the situation at hand. The formation of a JCS involves meeting a very different set of objectives and time-scales from those pertaining to the formation of a POCA. The emergent property of greatest interest is the systems ability to support "Decisive Manoeuvre"[8] on the battlefield. The effectiveness of the JCS is thus measured by its ability to meet the requirements of a particular operation.

3.3 Systems-of-Systems, as Components of a C4ISREW Capability

The first order SOS's presented in Table 1, although formally qualifying as a system-of-systems according to Maier's criterion, does not perform the entire function of C4ISREW in its own right. In fact, first order SOS's, at this level of abstraction, are best described as components of a peacetime POCA, or components of a wartime JCS. They usually exist in the form of a single

[8] Decisive Manoeuvre is defined as: The conduct of synchronised operations using assets from and within any or all environments to defeat the adversary by positioning in time and space the most appropriate force to threaten or attack critical vulnerabilities, thereby unhinging the centre of gravity and obtaining maximum leverage [Department of Defence, 1998].

asset that contains several individual C4ISREW sub-systems (for example an AEW&C or RF-111). Unlike a POCA or JCS, which is owned by no particular service, a first order C4ISREW SOS (or C4ISREW component asset, CCA) is usually owned and managed by one particular service and may perform a particular task within the overall JCS.

The development of a CCA occurs as a response to perceived force structure requirements and should be under the guidance of those responsible for C4ISREW portfolio development. The acquisition cycle for a CCA is large and will need to begin several years before the CCA is required to be in service. Principles of CCA design include analysis of CCA affordability, supportability, sustainability, interoperability with other force elements, security, vulnerability, lethality and various other measures of performance for specific sub-systems. The effectiveness of a CCA is measured by its ability to fill the perceived gaps in force structure in a cost-effective manner.

3.4 Inter-relationships in the C4ISREW SOS Hierarchy

The inter-relationship between the three orders in the hierarchy of C4ISREW systems-of-systems is shown below in Table 2.

Name	**SOS Order**	**Objective**	**Assembly Time**	**System to Capability Mapping**
POCA	***P***(SOSOS) or ***P***(SOS_{II})	The ability to support rapid assembly of different JCS's capable of meeting a spectrum of operational needs.	Evolutionary, *never complete*	System ensures the ADF has the C4ISREW capability.
JCS	SOSOS or SOS_{II}	Ability to provide C4ISREW capability for a specific operation.	Rapid, *responds to a crisis*	System provides the C4ISREW capability for a particular operation.
CCA	SOS or SOS_{I}	Ability to fill a perceived gap in POCA force structure in a cost-effective manner.	Slow, *Acquisition cycle*	System is a component of the C4ISREW capability.

Table 2: C4ISREW systems-of-systems and associated characteristics.

The hierarchy described above highlights the need to employ quite different systems architecture strategies, systems analysis techniques and systems assessment techniques at each level. As we have shown, the objective of each class of C4ISREW SOS is distinct, the time-scales in which they operate are distinct and the relationship each has with the development and maintenance of the ADF's C4ISREW capability is distinct. In Section 5 we propose concepts and methodologies for the assessment of C4ISREW systems and highlight the different challenges associated with development and assessment at each level.

3.5 Architectures for Defence C4ISREW

The SOS hierarchy necessitates the development of an overall architectural approach to the enterprise of developing C4ISREW systems-of-systems capable of meeting Australia's warfighting needs. We propose an approach based upon an understanding of the hierarchy and the associated differences in objective, time-scale, and relationship with capability development at each level. The approach is cognisant of the fundamental differences inherent between the activities of:

(1) developing the portfolio of C4ISREW assets (POCA) and,
(2) synthesising a joint C4ISREW system (JCS) to respond to an operational need.

The architectural approach recommended in this paper, is to develop two symbiotic architectural views for the two activities presented above.

The first architectural view is the Joint Force Migration View, which defines the structure, inter-relationships and principles and guidelines for the development and evolution of the POCA. This architectural view must be cognisant of the spectrum of possible future operational requirements and those elements in the POCA that can be assembled to meet these requirements. Similarly it must view capability development from a holistic perspective and include such elements of capability development as doctrine, training and organisational interactions. The Joint Force Migration View seeks to develop a C4ISREW capability to cover a wide range of possible future operations. Strategic guidance can provide weights to options based on the perceived likelihood of a particular contingency arising.

The second architectural view is the Joint Systems Synthesis View, which defines the structure, inter-relationships and principles and guidelines for the rapid assembly of a system-of-systems designed to meet the specific operational requirement of a particular contingency. This architectural view must provide information, principles and guidelines about the specific operation, the functional systems requirements and the technical guidelines for assembly of a C4ISREW systems solution. In this manner, the Joint Systems Synthesis View is similar in scope to the triune US C4ISR Operational, Systems and Technical architectural views [C4ISR Architecture Working Group, 1996]. It seeks to synthesise and deploy a C4ISREW capability that is tailored to the needs of a specific operation.

These two meta-architectural views would support the development of lower-level architectures (such as the US C4ISR Operational, Systems and Technical architectures that could conceivably make up the Joint Systems Synthesis Architecture). The value of this framework is that all architectural practice, systems analysis and systems assessment can be conducted at the appropriate level with a clear understanding of the scope and needs pertaining to the particular level of interest. A joint body, such as the DIEAO, could be responsible for the management of C4ISREW studies which meet specific low level needs, yet also frame these studies within the broader enterprise-wide needs of Defence. Figure 2 is a schematic diagram of the two architectural views and the associated C4ISREW SOS hierarchy.

Much work is still to be done in defining these architectural views in a rigorous manner and developing a suite of architectural techniques, systems analysis techniques and assessment concepts and methodologies associated with each level. The rest of this paper concentrates on assessment concepts and methodologies appropriate for each level in the above C4ISREW SOS hierarchy.

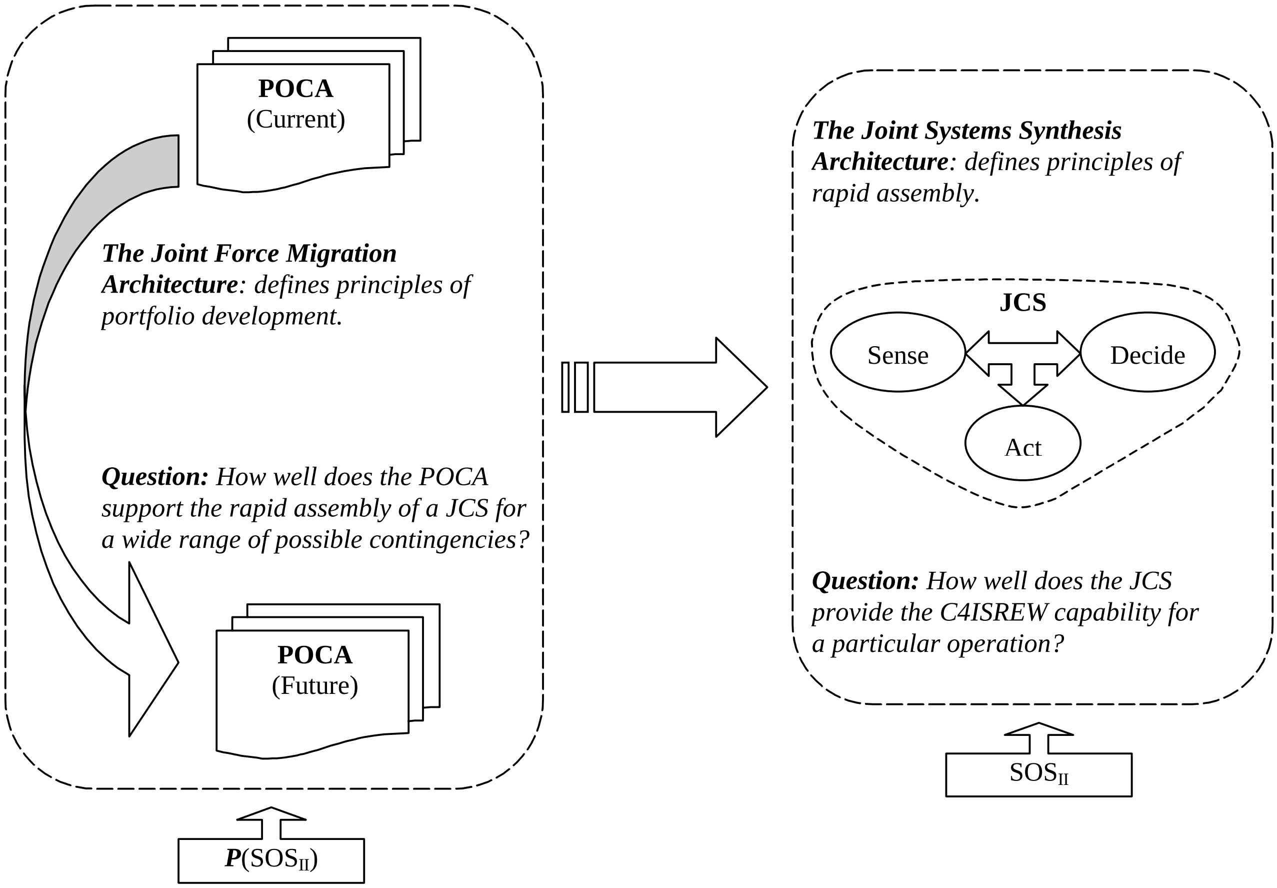

Figure 2: A schematic diagram of the two architectural views governing C4ISREW capability development.

4. Assessment Concepts and Methodologies

Everything in war is simple, but the simplest thing is difficult. The difficulties accumulate and end by producing a kind of friction that is inconceivable unless one has experienced war. … This tremendous friction, which cannot, as in mechanics, be reduced to a few points, brings about effects that cannot be measured, because they are largely due to chance.

Carl von Clausewitz, "On War" (1831)

The Framework for C4ISREW architecture presented above enables the creation of assessment concepts and methodologies that are focused on the specific requirements at each level of the SOS hierarchy. Traditionally, the value of military investments has been assessed in terms of the delivery of military capability to successfully conduct an operation or task. This assessment is usually achieved by conducting scenario-based Operations Analysis on a small number of pre-selected scenarios. However this technique is more suited to the assessment of an instantiated

JCS (although we will argue that it is difficult to justify even in this context) rather than the assessment of C4ISREW investments. The process of assessing the value of C4ISREW investment options is a completely different process than that of assessing the ability of a JCS to meet the needs of a particular contingency. Portfolio development assessments are difficult multi-criterion decision problems and are exacerbated by three environmental considerations:

1. System (and organisational) complexity.
2. Operational requirements uncertainty.
3. Rapid advances in technology.

These three factors combine to create a difficult problem for systems analyses and capability assessments. The difficulty is in developing meaningful assessments of different force development strategies for a complex military system-of-systems which is liable to be called upon to conduct an increasing variety of tasks and also prone to rapid changes as technology advances. Obviously assessments of instantiated JCS's will play an important role in this (although we argue that traditional techniques of assessment are inappropriate). However the assessment of an instantiated JCS is only one part of the assessment of a POCA and its associated Joint Force Migration Architecture.

4.1 Complexity: The Need for Behavioural Analysis of a JCS

It is now understood that the dynamic inter-dependencies inside an organisation such as Defence will produce complex emergent behaviour from both its organisational structure and its systems developed to support war-fighting. Traditional Operations Analysis techniques are unable to effectively model the behaviour that arises as a result of the complexity of both the Defence organisation and the information systems needed to support C4ISREW on the battlefield (ie the instantiated JCS). Thus alternative techniques for conducting behavioural analysis of an instantiated JCS, or modelling capability gain from POCA enhancements will need to be developed.

Obviously the ability to capture the crucial inter-dependencies within the JCS under consideration is key to producing an accurate model of the system. Unfortunately the vast majority of modelling practice occurs in a highly reductionist manner. Reductionist analysis consists of taking large complex problems (or systems) and reducing them to manageable pieces. This form of modelling and analysis works well in environments that are effectively linear. However in systems where the interactions amongst elements are as important as the function of the elements themselves, and in systems where inputs and outputs are not necessarily proportional, the reductionist technique invariably fails. Two such techniques for developing models of the dynamics of systems characterised by high levels of interdependencies and complexity are "System Dynamics" and "Complexity Theory".

System Dynamics was developed by Professor Jay Forrester at MIT in the 1950's and has been increasingly used as a technique for capturing the behaviour of complex systems in management, finance, ecology and engineering since its development. At the heart of System Dynamics is the concept of non-linear feedback, which can produce from the simplest of activities a vast complexity of emergent behaviour. Unlike traditional linear modelling techniques, which focus on prediction (and are notoriously unreliable as predictors when dealing with complexity) System Dynamics shifts the emphasis away from prediction and tries to capture an overall “system picture”. Rather than developing a model to make a forecast about future events or to make quantitative assessment of a system, a System Dynamics modeller will shape the model in order to capture an understanding of the dynamics of the system. The process of model creation and simulation in System Dynamics can produce a greater understanding of the dynamics of a system and its sensitivity to change than that acquired through traditional mathematically rigorous analysis of highly simplified systems. In this way System Dynamics brings to the study of systems a certain amount of quantitative rigour which systems thinking lacks whilst capturing the qualitative complexities that reductionist modelling often overlooks.

The science of Complexity Theory is even younger than that of System Dynamics and only began to emerge in the late 1970’s. Complexity Theory arose as a means for the modelling and analysis of complex adaptive systems. Complex adaptive systems are fundamentally different from most systems that have been successfully studied scientifically [Czerwinski, 1998]. The defining features of linear systems, namely proportionality, additivity, and the demonstrability of causes and effects [Czerwinski, 1998] usually do not apply to the study of highly complex adaptive systems. The axiom that a small variation in inputs leads to a small variation in outputs and vice-versa (proportionality) usually does not hold. In fact small variations in input can produce large directed changes in a complex adaptive system, in the language of the science of Complexity Theory this is known as leverage. Not surprisingly much of Complexity Theory is dedicated to discovering these lever points. Similarly the reductionist principle of additivity, which many traditional modelling techniques for assessing military systems is based upon, fails to capture the crux of emergence and dynamics in systems. Additivity assumes that the whole system is equal to the sum of its parts and that by analysing and assessing constituent parts of a system, a measure of the whole can be gained through the additive assessments of each part. For complex adaptive systems much attention is paid to the interactions between component elements of the system. In fact the emergent properties of greatest value usually arise due to the interactions of component parts and are not to be found in the analysis of any single component element.

The aim of JCS assessment should be the ability to conduct behavioural analysis on the dynamics of an idealised JCS. Due to their ability to capture the crucial interdependencies and interactions that produce the emergent properties of greatest interest, System Dynamics and Complexity Theory offer an opportunity to assess the capacity of an idealised JCS to meet the information requirements associated with a specific mission.

4.2 Uncertainty: The Need to Minimise Risk in POCA Development

The traditional Requirements Engineering technique of designing systems based upon a single task is no longer appropriate for a Military which may be required to participate in a wide variety of potential operations other than war, as well as remain prepared for a general war if one arises. With the increasing uncertainty over what precisely the military force will be required to achieve, performance measures which allow the force greater adaptability (such as interoperability, sustainability and supportability) have gained more attention. Obviously rigid scenario-based models and simulations are no longer appropriate to assess factors such as flexibility and adaptability in systems.

In a future characterised by uncertainty, the key to preparedness for the ADF is to maintain a force structure supported by information systems capable of adapting to any future conflict. It is highly unlikely that a monolithic C4ISREW system developed in peacetime will have the flexibility to adapt to all possible future threats. What is needed is a portfolio of C4ISREW systems and components from which the ADF can draw from to rapidly create a system-of-systems tailored to meet the needs of a particular operation. The development of such a portfolio (POCA) could then be an integral part of any investment plan to transition from the current state of legacy ADF C4ISREW assets to a future envisioned resource base of C4ISREW able to be deployed to meet a wide variety of possible requirements.

This raises a number of questions regarding the structure and composition of such a portfolio of C4ISREW systems. Obviously a key to maintaining the preparedness of the ADF along each stage in a migration plan, is to minimise the risk of the ADF being unable to assemble a suitable C4ISREW system from the portfolio. Risk Assessment models that aim to assess a particular migration plan will need to be informed of Australia's regional strategic outlook and the suite of roles, which the ADF is likely to be required to be prepared for.

The assessment of a POCA is a fundamentally different activity to that of the assessment of a JCS. The difference is perhaps most obvious when observing the measures of performance/effectiveness that are to be used in the assessment process. Whilst a JCS has a fairly well defined requirements list, a POCA must be flexible enough to produce a JCS to respond to a number of contingencies. Thus the assessment of multiple JCS's synthesised to respond to different scenarios makes up part of the overall POCA evaluation. Additionally, a POCA must meet requirements such as effective use of funds to maintain a balanced portfolio and whole-of-life issues for its component elements. Whereas Systems Theory is the obvious choice of metaphor to understand the complexities inherent in JCS assembly, it can be argued that a Portfolio Theory is needed for understanding the complexities inherent in POCA evolution. Indeed, the whole-of-life, risk minimisation and balanced expenditure issues inherent in POCA assessment are best approached from a theory of overall portfolio development. Future work will be conducted in the application of Portfolio Theory to the development of the ADF's C4ISREW force structure.

4.3 Change: The Need for Architectural Guidance

The rapid change which is occurring within the commercial IT sector has profound implications upon the acquisition strategy for Defence information systems. To begin with the acquisition cycle needs to be sufficiently short to ensure that by the time systems become in-service they are not already obsolete. Thus an architectural approach to acquisition will need to be employed. Similarly, if systems or components are continually being replaced or upgraded then an affordability study will need to be conducted which considers not only the initial outlay, but the costs of maintenance, deployment and replacement over the lifetime of the migration plan. Finally, interoperability (both between services and with regional allies) will remain an essential requirement for all future acquisitions. Traditionally technical interoperability problems have arisen from software-intensive systems being separately specified and acquired, often from overseas [Allison and Cook, 1998]. This has led to the need for architectural guidance when acquiring C4ISREW systems as part of a migration plan for C4ISREW portfolio development.

The approach to managing change in systems is to look for constructs that are invariant over the time horizon of interest. Information architectures are perceived as such an invariant [Levis and Perdu, 1994]. It is through the process of developing architectural principles and guidelines for the design of C4ISREW systems and their evolution over time which will provide the development of a C4ISREW portfolio with the capacity to conform to set standards that ensure interoperability and affordability requirements are met. Architectures, however, are not the end product, they are a framework for designing, assessing, developing and deploying systems that enable ADF forces to carry out their assigned mission.

Modelling architectures for C4ISREW provides a way in which to perform structural and logical analysis of the architecture governing both the migration plan (Joint Force Migration Architecture) and the architecture governing the assembled system (Joint Systems Synthesis Architecture). Architectures can be effectively assessed by the development of an executable model, which captures the information contained in the architecture. This model, along with a formal set of logical, behavioural and performance requirements and a description of the conditions under which the architecture is expected to perform will be sufficient to conduct the necessary analyses and assessments.

The conditions under which the architecture is expected to perform will be different for the two levels of architectural views defined in this paper. The Joint Force Migration Architecture (level III) will use strategic Defence planning as an indicator of the potential environment in which it will be employed. Models of the Joint Force Migration Architecture should seek to answer questions that capability development executives require. The Joint Systems Synthesis Architecture (level II) will use a set of scenarios as the indicators for the potential environments in which it may be employed. Models of the Joint Systems Synthesis Architecture should seek to answer questions that operators require. Architectural Assessments invariably must answer the basic logical question of whether "it" can be done effectively. The scope (or level) of the two architectural views dictate that the "it" will be different in each case, however the purpose for assessing the architecture remains constant.

Petri Nets are often used as the modelling formalism for representing the executable model. The suitability of the Petri Net formalism is largely based upon their ability to support mathematical analysis, simulation and visualisation of information flows, as well as their ability to model concurrency and asynchronous operations. Petri Nets can support logical analysis of architectures developed to govern either joint force migration or joint systems synthesis. The U.S. C4ISR Architectural Framework defines three views, which together attempt to achieve the same kind of objective as the proposed Joint Systems Synthesis Architecture. Much work has been conducted in developing models using the Petri Net formalism for supporting logical, behavioural and performance assessments of this type of architecture, however little of this work has been applied to the ADF. Research into the development of executable models, which attempt to conduct assessments of architectures of the scope of the Joint Force Migration Architecture, is still in its infancy. Future research by the authors will look at expanding this domain.

5. Summary and Conclusion

This paper has highlighted the enabling role of C4ISREW in the emerging concepts of operations motivated by the RMA. We have proposed an over-arching framework for the architecture of Australia's C4ISREW capability and have highlighted two key activities associated with the development of this capability. These activities have been termed joint force migration (governed by the associated Joint Force Migration Architectural View) and joint systems synthesis (governed by the associated Joint Systems Synthesis Architectural View). They sit on different levels in the systems-of-systems hierarchy and operate on different time-scales. The two architectural views are then used as a basis for developing assessment concepts and methodologies associated with the evaluation of C4ISREW systems-of-systems at each level.

In order for the ADF to carefully analyse their C4ISREW capability options for the future an architectural framework and supporting concepts for assessment need to be employed. Both the architectural framework and assessment concepts outlined in this paper have significant implications for the application of current practices as they highlight both the narrow scope of current architectural thinking and the deficiencies associated with traditional assessment techniques. Furthermore it is proposed that the C4ISREW capability development architectural framework described in this paper (and its component architectural views) could be generalised to provide a framework for the development of all future ADF capabilities.

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