Investigating Army Systems and Systems of Systems for Value Robustness

by

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ABSTRACT

This thesis proposes a value robustness approach to architect defense systems and Systems of Systems (SoS). A value robust system or SoS has the ability to provide continued value to stakeholders by performing well to meet the mission intent under a variety of future contexts. The proposed approach encompasses three methods, namely "Needs to Architecture" framework, Multi-Attribute Tradespace Exploration (MATE) and Epoch-Era Analysis. The architecting approach will commence with the "Needs to Architecture" framework. Stakeholders' needs are elicited and design concepts will be formulated. MATE is then used to screen, evaluate and select suitable design concepts. Subsequently, Epoch-Era Analysis is used to guide system architects to anticipate changes across foreseeable epochs, which are time periods of fixed needs and context. The tradespace analysis is repeated across all these epochs. Pareto Trace and Filtered Outdegree metrics will be used to identify passive and active value robust designs. The proposed value robustness approach is demonstrated conceptually using an Intelligence, Surveillance and Reconnaissance (ISR) system and an Army SoS case study.

The proposed value robustness approach offers a potential methodology to design and evaluate complex defense systems such that they continue to be valuable to stakeholders over time. The method is also complementary to existing architecting methods such as modeling and simulation. The end product of applying this approach is a cost efficient defense system, which might be passively or actively value robust. High switching and modification costs might be avoided even if changes to the active value robust defense system are required. Through the use of the Army SoS case study discussion, the author suggests that a value robust defense SoS architecture is one that encompasses the desired ilities of changeability and interoperability.

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Acronyms

AO	Area of Operation
BCT	Brigade Combat Team
C4ISR	Command, Control, Communication, Computer, Intelligence, Surveillance, Reconnaissance
DoD	Department of Defense
FCS	Future Combat System
FRES	Future Rapid Effects System
HQ	Headquarter
ISR	Intelligence, Surveillance, Reconnaissance
MATE	Multi-Attribute Tradespace Exploration
MAUT	Multi-Attribute Utility Theory
SoS	Systems of Systems
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
VTOL	Vertical Take Off and Landing

Chapter 1 Introduction

1.1 Background and Motivation

System architecting in defence is often guided by heuristics as well as the stakeholders and decision makers' experience. Increasingly, complex tools such as Operation Analysis, Modeling and Simulation are used to model the behavior of defense systems and Systems of Systems (SoS) so as to experiment with various architectural concepts to meet end users' mission capability needs, and to aid decision making. However, there is little literature in the system architecting field to suggest that there is a structured approach to consider the system or SoS's value robustness, which is the ability to provide high value to stakeholders through its performance across different use contexts and needs requirements. In fact, validation of the value robustness of the system and SoS only take place when the various constituent components are developed or procured and interact with each other to deliver an emergent SoS effect. By then, substantial funds, resources and development effort have already been committed. If the desired SoS effect is not obtained, the investment in building up the SoS will not be worthwhile and opportunity costs will be incurred, which can be better utilized to explore other promising technologies. Stakeholders' perception of value of the system or SoS will be diminished when the system or SoS cannot fulfill end users' mission needs. The value robustness consideration takes on greater urgency in defense because mission needs, contexts and operational environments are likely to evolve to mitigate the changing threat level posed by potential adversaries over time as well as to increase own defense force's capabilities to enhance the protection of the country and its sovereignty. Thus, there is a need to consider value robustness strategies and implement design features in defense systems and SoS at the front-end design stage so that the selected design concept is able to maintain stakeholders' perceived value and its cost effectiveness throughout its life cycle. As such, this thesis attempts to investigate Army systems and SoS for value robustness in the front end planning stage. A value robust system and SoS is desirable because it allows the Army to undertake a wide variety of operations as well as create options for flexibility in its architecture.

1.2 Research Scope

With the background and motivation in mind, the author aims to propose a structured approach to guide the defense system architects to design value robust systems and SoS. The approach will be applicable in the concept synthesis, screening and selection phase. The methods of the approach will be introduced in this thesis and applied to a defense system. The discussion will be expanded to the SoS using a baseline Army SoS as a generic case example. Lastly, the thesis will discuss the benefits and limitations of the approach, and propose recommendations for future research work.

1.3 Research Objectives

The intent of the research is to investigate value robustness in defense systems and SoS. The primary objective is to develop a structured architecting approach that system architects can use to conceptualize, design, identify and select value robust defense system and SoS architectural design options. The second objective is to apply Epoch-based thinking to evaluate a baseline, network centric, Army SoS at a conceptual level and use the analysis to propose measures to enhance the Army SoS's value-robustness. The third objective is to propose recommendations of future work to improve the methods of the approach to sharpen its impact on system architecting of defense system and SoS.

1.4 Organization of Thesis

Chapter 2 presents background information on the SoS. The literature review covers the definition and types of SoS as well as related architecting heuristics. Two case examples of a defense SoS, namely US Army's Future Combat Systems (FCS) program (renamed as Brigade Combat Team (BCT) program) and UK's Future Rapid Effects Systems (FRES) program, will be used for the discussion. These case studies will also highlight success or failure lessons, which affect the value robustness of the programs. The author will also explain the meaning of "value robustness" and how this impacts the SoS design and architecture.

Chapter 3 will introduce the reader to current architecting methods to develop a value robust SoS. Semi-structured interviews with existing system architects from the defence industry will also served as vital information to elicit current practices.

Chapter 4 will highlight the author's proposed approach to investigate the system or SoS's value robustness. A literature review of the methods of the proposed approach, that is, the "Needs to Architecture" framework, Multi Attribute Tradespace Exploration (MATE) and Epoch-Era Analysis, will be presented. The "Needs to Architecture" framework will facilitate the system architect in identifying stakeholders, soliciting needs, setting goals, brainstorming for concepts and high level architecture.

MATE will serve as a concept screening tool to select design concepts for their value robustness. Lastly, Epoch-Era Analysis is similar to scenario planning and aids the architect to infer possible changes in needs and contexts. The insights gleaned from Epoch-Era Analysis will help to the architect select concepts that will provide high value to stakeholders in the future throughout the timescale considered.

Chapter 5 will demonstrate the application of the author's proposed approach and methods using a case study. Intelligence, Surveillance and Reconnaissance (ISR) Systems are highly valued defense systems in today's context as they enable defense forces to acquire enhanced situation awareness in the battlefield. The design and selection of an appropriate ISR concept is critical and the author deems it valuable to use it as a demonstration case study. The case study will also provide a basis for further discussions on the application of the methods to complex SoS in Chapter 6.

Chapter 6 will describe a baseline Army SoS consisting of existing and legacy systems. The author will attempt to enhance the value robustness of the Army SoS by applying Epoch-based thinking to postulate future, possible changes to the SoS and in doing so, identify opportunities to improve its capabilities at the conceptual level. The objective is to demonstrate the usefulness of Epoch-Era Analysis in shaping the design of the SoS to ensure that it remains value robust in future. The author will also attempt to highlight emerging principles to aid architects to design a value robust SoS.

Chapter 7 will summarize the contributions of this thesis. The benefits and limitations of the methods will be discussed. The author will attempt to suggest possible improvements to the methods to make the proposed approach comprehensive for further research and validation.

Chapter 8 will summarize the proposed approach and provide final thoughts to conclude the thesis.

1.5 Data of the thesis

The data for the thesis case studies in Chapters 5 and 6 is obtained from public literatures, product brochures, market research reports and surveys. Detailed technical capabilities and cost information of defense systems are often proprietary and difficult to obtain. As the data used in this thesis is from the public domain, the information may not be comprehensive and may change with time, due to competitive, differentiated pricing strategies adopted by the defense companies, or new upgrades to the systems' capabilities from time to time. Some of the data are also inferred (e.g. unit price of a defense system is elicited from a known, contract price to a customer, divided by the number of acquired systems) so that the author can obtain an assessment to be used in this thesis to demonstrate the proposed approach. Therefore, the author will like to highlight that the assessment is purely based on the opinions of the author and is in no way representative of the defense companies mentioned in the thesis and the author's sponsored company's position. Detailed technical and cost information about the defense systems mentioned in this thesis should be obtained directly from the companies which develop those systems.

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Chapter 2 Literature Review of System-of-Systems (SoS) and Value Robustness

2.1 Introduction

Today, complex systems or products are being developed in many commercial and government industries, especially in the defense sector. Increasingly, many of these systems are integrated together, interlinked or made interoperable with each other. They provide value to the stakeholders as a standalone, independent unit while also operating in tandem with other systems as part of an overall larger system to fulfill global-level goals. As the individual systems interact with one another, emergent functions occur. These emergent functions may be planned or unplanned. The increased interactions and interfaces between the individual systems further enhance the design complexity of the overarching larger system to deliver the emergent effect that each individual system cannot provide on its own. As such, system architecting and engineering tools must be adopted to manage the evolution of complexity in large scale, interconnected systems, termed as "System-of-Systems" or SoS.

2.2 What is a System-of-Systems (SoS)?

According to International Council on Systems Engineering (INCOSE)'s Systems Engineering Handbook (2007), a system is defined as "a combination of interacting elements organized to achieve one or more stated purposes" while a System-of-Systems (SoS) is defined as "an interoperating collection of component systems that produce results unachievable by individual systems alone." Another definition of SoS, which is extracted from United States (US) Department of Defense (DoD)'s System Engineering Guide for Systems of Systems (2008 Version 1.0), states that "an SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities. Both individual systems and SoS conform to the accepted definition of a system in that each consists of parts, relationships and a whole that is greater than the sum of the parts; however, although an SoS is a system, not all systems are SoS."

2.3 Definitions

Prior to further discussion on SoS, it is useful to review the definitions of the other terms that will be used frequently in this thesis. This helps to provide clarity to the reader and shows the intent of the author when these terms are expressed in the following chapters. They are as follows:

a. Value Robustness. Ross and Rhodes (2008) define "a value robust system as one which is perceived to be successful by stakeholders who continue to receive value from the system over time and across changing contexts and needs".

b. Value. Ross and Hastings (2005) define value as "a metric that captures the goodness of something to a stakeholder". On the other hand, Crawley (2009a) defines value as "benefit at cost".

c. Attribute. Ross and Hastings (2005) define an attribute as "a decision maker perceived metric that reflects how well a decision maker's objective is met."

d. Design variable and vector. Ross and Hastings (2005) defined a design variable as “a designer controlled quantitative parameter that reflects an aspect of a concept. Similarly, a design vector will constitute a set of design variables that completely describes the concept and allows the designer to perform trade-offs among the decision variables.”

e. Tradespace. Ross and Hastings (2005) state that “a tradespace is a set of possible design options.” The options are depicted by a combination of all feasible sets of design variables.

f. System. Crawley (2009a) defines a system as “a set of interrelated elements which perform a function, whose functionality is greater than the sum of parts.”

g. Systems Engineering. INCOSE (2007) defines systems engineering as “an interdisciplinary approach and means to enable the realization of successful systems”.

2.4 Background information on SoS

2.4.1 Characteristics of SoS

Shah et.al (2007) highlighted that SoS have three characteristics as follows:

a. “SoS are systems.”

b. “SoS are composed of other systems that are value producing in their own right.”

c. “SoS constituents have some sense of independence after being assembled in their own right.”

It must be highlighted that SoS are not just a collection of systems, as this is not consistent with the definition. With reference to Shah et al. (2007)'s assertion that "SoS constituents have some sense of independence after being assembled in their own right", Maier (1998) also argued that a SoS must have operational and managerial independence of the systems' components. Operational independence means that the individual component systems are able to contribute to the overall global system outcome and emergent effect of the SoS while also being capable of operating separately and fulfilling its own local users' requirements to perform a task. Managerial independence means that the individual components can be acquired and managed separately. These components can operate as an individual system, or integrated together with other systems to form a SoS. However, the local stakeholders or "managers" of the individual systems may have varying degrees of choice whether to allow the system to operate as part of the SoS to fulfill global requirements of the SoS. The following examples are used to further elaborate on what constitutes a system or a SoS. Take, for example, a centrifugal pump in Figure 2-1.

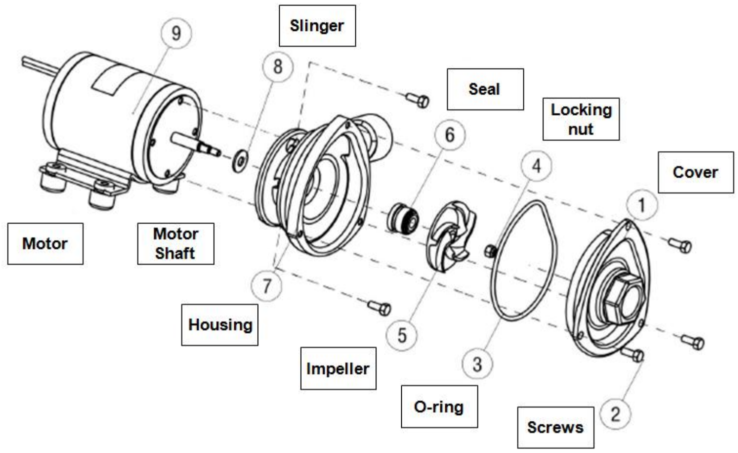

Figure 2-1: Centrifugal Pump (Jabsco, 2009)[1]

The centrifugal pump utilizes the rotation energy of the motor shaft and impeller to increase the pressure and flow rate of the fluid flowing from the inlet to the outlet of the pump. It is commonly used to move fluids along a fluid pipeline. The centrifugal pump is an example of a system but it is not a SoS because it does not satisfy the operational and managerial independence. This is because its components such as the impeller and the seal cannot operate separately on its own. On the other hand, a public land transportation system is a SoS because the bus and train services can be coordinated to allow a passenger to move from one place to another place seamlessly and conveniently. The different transport systems are connected via their communication networks and coordinated to arrive at designated locations and times to reduce passengers' waiting times. On the other hand, the bus and train services are separate systems which can operate on their own and are managed by different

[1] *50830 Series Low Pressure Centrifugal Pump*. *Jabsco Web Page*. Retrieved December 9, 2009 from http://www.depcopump.com/datasheets/jabsco/50830-Series.pdf

companies. Figure 2-2 and 2-3 show an example that Singapore's integrated bus and train services are managed by two separate companies.

Figure 2-2: Singapore's Mass Rapid Transit[2] network map. The red and green lines are managed by SMRT (SMRT, 2010)[3] while the purple line is run by SBS Transit (SBS Transit, 2010)[4].

Figure 2-3: SMRT (SMRT, 2010)[3] and SBS Transit (SBS Transit, 2010)[4] 'buses respectively.

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[2] Mass Rapid Transit system is similar to a subway system.

[3] SMRT. Retrieved January 6, 2010 from http://www.smrt.com.sg/trains/safety_security.asp

[4] SBS Transit. Retrieved January 6, 2010 from http://www.sbstransit.com.sg/nel/systemmap.asp

The operations of a System of Systems are dependent on the “glue” that connects all the systems together to deliver a capability. The “glue” refers to the communication protocols and standards that govern the SoS design. They are critical in ensuring interoperability, linkage and control among the systems. Using the integrated air defense system as an example, information will be collated from the sensors such as radars in the air defense network and they will be fused together at the command center to form a comprehensive battlefield picture for situation awareness. Control information will then be sent to the shooters such as fighter jets and missiles systems to intercept a hostile enemy plane. A common communication protocol will ensure that the required information will be exchanged among the integrated air defense SoS’s constituent systems seamlessly. The SoS’s constituent systems are able to work together to enhance the capability as a collective whole as compared to the individual self and this gives the overall system an emergent capability that is very much desired.

2.4.2 SoS Architecture Heuristics

According to Maier (1998), there are four key architecture heuristics for SoS and these are explained as follows:

a. Stable Intermediate Forms

Maier (1998) mentions that “complex systems will develop and evolve within the overall architecture much more rapidly if there are stable intermediate forms than if there are not”. This heuristic articulates the importance of having stable, non-changing systems within the SoS that continue to execute their functions regardless of the development of the SoS.

These stable systems can be robust and insensitive to external changes. This is beneficial because the SoS can evolve through the addition of new capabilities while its stable, robust component systems maintain continued SoS's value to the stakeholders during the transition period. The heuristic can also be interpreted that there must be back up systems that will meet the mission needs of the SoS if the SoS fail to perform.

b. Policy Triage

Maier (1998) states that triage means: "Let the dying die. Ignore those who will recover on their own. And treat only those who would die without help." This heuristic emphasizes the need to prioritize and divert scarce resources to develop the aspects of the SoS that a SoS management team can influence and control. An appropriate level of control and influence must be exerted based on the type of SoS. One such example is the Integrated Air Defence SoS which relies on linked radars, fighter jets, surface to air precision weapons and command centers to detect, intercept and destroy enemy's aircraft. Since these component systems of the SoS are independently managed and controlled by separate organizations, it is impossible for a SoS design team to influence the development of each of these systems. This is especially true in a collaborative SoS setting, where participation in the SoS is not mandatory in the absence of a central control. As such, it will be beneficial for the SoS design team to focus its resources to dictate and influence the ability of the systems to be interoperable with one another to forge an effective defensive shield against incoming threats.

c. Leverage at the Interfaces

Maier (1998) also states the heuristic “the greatest leverage in system architecting is at the interface. The greatest dangers are also at the interfaces.” Using the example of an Air Defence SoS, the SoS design team will have the greatest leverage to dictate the communication protocols and ensure that all systems can communicate with one another. As explained in the heuristic “Policy Triage”, the SoS design team often does not have the ability to affect component systems’ designs. Therefore, the SoS design team should dictate the interface standard of the component systems to ensure interoperability and allow the technical designs of the component systems to be developed separately and optimally.

d. Ensuring Cooperation

Maier (1998) also states that “if a system requires voluntary collaboration, the mechanism and incentives for that collaboration must be designed in.” If the participation in the SoS is voluntary or collaborative, it is critical that the SoS design team is able to incorporate features in the SoS such that the benefits outweigh the costs of participation. If participation in a SoS will bring about significant disadvantages to the stakeholders of the individual systems that constitute the SoS, it is likely that the local stakeholders will choose not to participate in the SOS and this creates a disadvantageous situation for all parties involved. Without the constituent systems participating in the SoS, the SoS global capability will be degraded or even prevented.

2.4.3 Types of SoS

Maier (1998) asserts that there are three different classes of SoS, namely, Directed, Collaborative and Virtual SoS. Dahmann and Baldwin (2008) assert that a fourth class of SoS, namely Acknowledged SoS, exists.

a. Directed SoS. This type of SoS is built under a central control agency, which is able to influence how the SoS is built and how the SoS can be set up and when it is required. The systems in the SoS are centrally operated and managed by a control agency, which has full authority over its development and deployment. Operationally, the individual systems are able to operate independently by their local stakeholders or custodians. However, the individual systems will be available for integration and function as a SoS whenever the central control agency deems fit. One such example is the defence SoS where the Commander-in-Chief has the power to dictate that the defense assets be made available in times of war and crisis.

b. Collaborative SoS. The distinctive difference between a collaborative SoS and a directed SoS is the degree of control and power over the individual systems in the SoS. In a collaborative SoS, the central control agency does not have the control, authority and power to dictate that the individual systems participate in the SoS. However, the individual systems' stakeholders know the purpose and goal of the SoS and they are willing to collaborate with each other based on their free will. However, they will not be able to commit to the central control agency that the individual systems will always be available for collective function as a SoS when the central control agency wants. The key point is for the central control agency to convince the individual systems' stakeholders that it is beneficial and win-win for all parties to collaborate and work together as a SoS. For example, the mobile-entertainment system is a collaborative SoS. As the Apple iPhone becomes increasingly popular among consumers, other companies will also like to collaborate with Apple by interfacing their products with iPhone to form a mobile phone with computing and entertainment function. Online music stores and games will collaborate with the iPhone to provide customers with songs and games. The iPhone also has standard interfaces for memory cards and is able to be connected to other mobile phone devices and computers through the blue tooth and data network.

c. <u>Virtual SoS</u>. This type of SoS has no central control agency and the individual systems have no common goal or mission to work together as a SoS. As such, in order for the systems to work together as a SoS, they must rely on mutual benefits to bring all the individual systems to work together as a SoS. One example is the World Wide Web which does not have a central governing body that dictates its evolution. Maier (1998) explains that "standards for resource naming, navigation and document structure "were available but website developers were not obliged to follow the standards for their design. In this case, Maier (1998) further highlights that certain standards were followed merely because of the "market success of their innovators", which cause other web sites to follow and use the perceived successful standards in order to emulate their success. As such, the evolution of the standards, websites and World Wide Web is not structured and coordinated in a planned manner in this type of virtual SoS.

d. Acknowledged SoS. Dahmann and Baldwin (2008) suggest that this type of SoS has a central control agency like the one in a Directed SoS. However, unlike the Directed SoS, the constituent systems of an Acknowledged SoS are managed independently by the organizations which fund their development and have their own systems' development roadmaps. Dahmann and Baldwin (2008) explain that the SoS's objectives and development roadmap will be dictated by the central control agency and this agency will have its own funding with regards to developing SoS capabilities. On the other hand, the central agency will allow the individual constituents systems' development plan to be managed by their owners. Dahmann and Baldwin (2008) assert that this type of SoS is found in defense context and have the following characteristics:

i. The composition of the SoS will comprise existing and new constituent systems. The new systems will serve to increase the capability gaps of the existing systems, which will form the baseline SoS architecture.

ii. The SoS central control agency has limited influence over the existing systems and new constituent systems. The challenge is to assess the performance of the SoS as a whole and identify capability gaps and opportunities even though the individual systems are evolving in their own right.

iii. The existing systems will form the baseline SoS architecture. The base architecture will be improved to meet the capability needs of the stakeholders from time to time. In view of the evolutionary nature of the SoS, the SoS should be changeable to meet new needs in future

iv. The SoS capabilities will be improved gradually using a staged deployment methodology. The augmented SoS performance will be reassessed to determine areas of further enhancements.

v. The constituent systems' development plans will be planned and discussed in conjunction with the SoS's development roadmap.

The above discussion reveals the degree of control that the SoS design team has in each type of SoS. Chattopadhyay (2009) coined the concept "Effective Managerial Authority (EMA)" to reflect the degree of control of the SoS design team. She argues that "Effective Managerial Authority" is dependent on "Managerial Control (MC)" and "Influence (IN)". A simple graphical representation of EMA is shown in Figure 2-4.

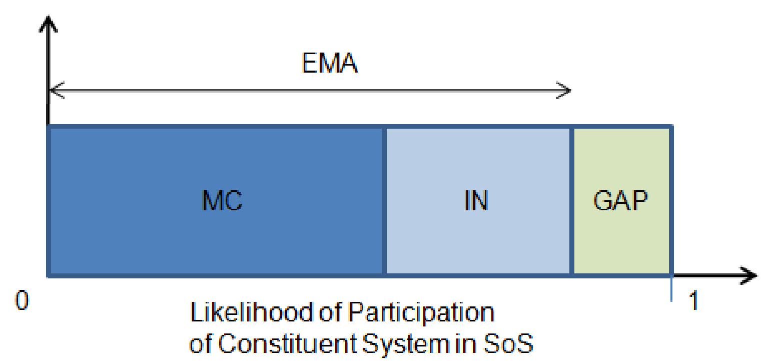

Figure 2-4: Chattopadhyay (2009)'s EMA Model

Chattopadhyay (2009) suggests that a Directed SoS has a central control agency that has complete power over the participation of constituent systems. Therefore, MC = 1, IN = GAP = 0 in a Directed SoS. A Virtual SoS has no governing agency. Hence its

MC = 0. Its constituent systems must be influenced to participate in a SoS. This is possible when the management team of the constituent systems perceive benefits in joining the SoS as compared to operating individually. High perceived benefits will translate to high degree of influence and participation likelihood of the constituent systems. Hence a virtual SoS's IN is between 0 and 1. The “gap” represents the risk of non-participation by the constituent systems while the sum of MC and IN represents the EMA. In a virtual SoS, the IN and GAP will add up to 1. A Collaborative SoS will have all the 3 components having the value of between 0 and 1. The summation of all 3 components will add up to 1. Lastly, the Acknowledged SoS can be viewed as similar to the Directed SoS in terms of the degree of control that the SoS team has over the participation of the constituent systems. The metrics of MC, IN and GAP are discussed in Chattopadhyay's work and will not be discussed in this thesis.

Each of these different classes of SoS may involve large number of stakeholders over the life-cycle of the SoS. Stakeholders' needs will change with time. With substantial cost and effort being expended on the design and realization of SoS, it is important that the SoS is able to provide value to its global and local stakeholders, even in times of changing context and stakeholders' preference so that large switching or modification costs will not be incurred unnecessarily. In view of this, one possible way to ensure that the SoS are able to deliver sustained high value to the stakeholders is to consider possible scenarios of changing contexts or stakeholders' preference and incorporate as many design features upfront in the concept phase to address these changing requirements. This is especially critical in defense SoS. Two case examples of a defense SoS - US Future Combat Systems (FCS) and UK's Future Rapid Effects

Systems (FRES) - will be discussed to illustrate the importance of the concept of value robustness of SoS to provide sustained value over time. The meaning of “value robustness” and how this impacts the SoS design and architecture plan will be discussed in the subsequent section.

2.5 Case Examples & Value Robustness

2.5.1 Future Combat System (FCS) / Brigade Combat Team (BCT) Modernization

The US Army’s FCS program (renamed BCT modernization program) is the modernization program for the US Army to undertake a wide spectrum of missions (US Army, 2009a). US Army (2007) has stated that “the FCS program initially consisted of eighteen systems, which are broadly categorized as Manned Ground Vehicles, Unmanned Ground Vehicles, Unmanned Aerial Vehicles and Unattended Ground Sensors, connected by the communication network to the soldiers.” The goal of this networked SoS is to enhance the solders comprehensive situation awareness and to allow them to have greater access to the networked precision fire capabilities to augment their ground combat capabilities so as to perform decisively across a full spectrum of missions. Figure 2-5 shows the initial composition of the FCS force.

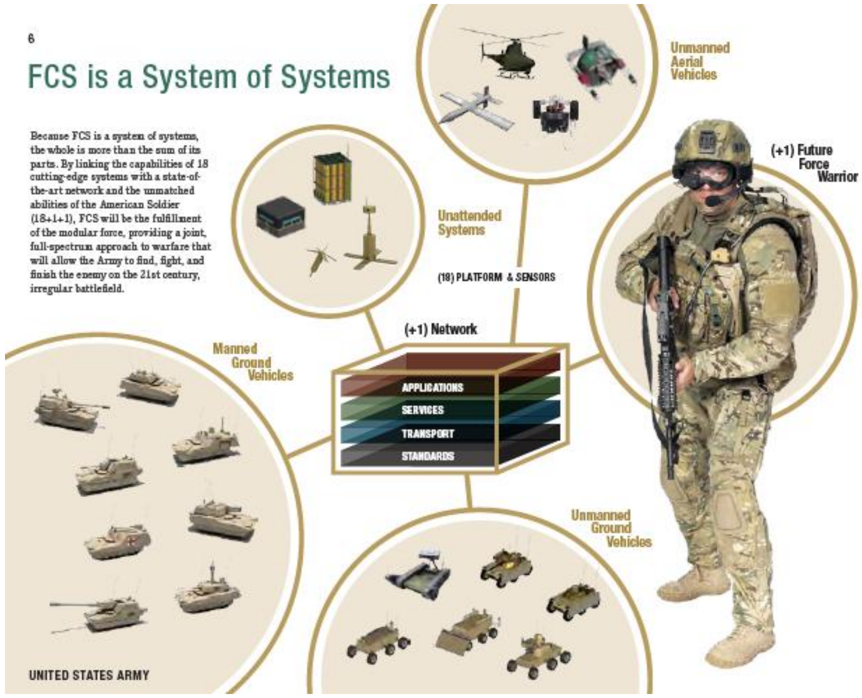

Figure 2-5: FCS Structure (US Army, 2007)

The FCS program was slated for system development and demonstration from 2003 onwards. However, a series of refined changing needs from the US Army resulted in increases in program scope and changes to development strategy. In addition, budget constraints in Year 2007 have also forced the program to reduce its scope from 18 to 14 systems (GlobalSecurity.org, 2009). On 23 Jun 2009, an acquisition decision memorandum from US Department of Defense (DoD) declared that the “new manned combat vehicles in the FCS did not adequately reflect the lessons of counterinsurgency and close quarters combat in Iraq and Afghanistan” (US DoD, 2009). This led to the cancellation of the Manned Ground Vehicle portion of the program as well as reorganized the FCS program under the umbrella of the Brigade Combat Team (BCT) Modernization. The BCT program’s key deliverables is to quickly develop, test and deliver several technologies that are deemed critical to support the US forces currently fighting insurgents in Afghanistan.

2.5.1.1 Value Robustness

From the above case example, it is apparent that there is a need for system architects to take into account possible, future changes during system architecting. System architects use scenario planning to postulate possible architecture concepts to meet user's needs. However, more effort needs to be put in to ensure that the system meets user's requirement across "multiple time periods and perspectives" (Roberts et al., 2009). In the case of the FCS, the program has to be overhauled to reflect changing needs of the US Army in Afghanistan and budget constraints. Defence Secretary Gates has recommended that the FCS program be amended on the basis of incorporating lessons learnt from the wars into the program (Bennett and Osborn, 2009). Mr. Gates has asserted that the Army has to reflect the change in mission context to fight an irregular warfare against insurgents as compared to fighting enemy soldiers in conventional warfare. This includes the ability of the systems to protect against the roadside bombs or Improvised Explosive Devices. Bennett (2009) reported that Mr. Gates quoted the example the FCS's Manned Ground Vehicles' design being vulnerable to IED attacks and assessed that the vehicles were not useful for the current operating environment of the Army in Afghanistan. Hence, the amended FCS program, that is the BCT program, will have to focus on the immediate needs of the ground commanders while evolving the program to modernize the force incrementally in the future. Based on today's information, Intelligence, Surveillance and Reconnaissance

(ISR) capability is one of the most pressing needs of commanders on the ground fighting the insurgents in Afghanistan (US Army, 2009a). As such, the BCT program is currently expediting the system development and testing of mature technologies spun off from the defunct FCS program and aims to equip current forces with feasible solutions. Some of these include “Class 1 Unmanned Aerial Vehicle (UAV), Unattended Ground Sensors (UGS), and part of the Joint Tactical Radio System to ensure data information from the ISR elements can be transmitted to all the Brigade elements” (US Army, 2009c). This staged deployment process of capabilities to modernize the fighting force will keep the BCT modernization program at an affordable cost while ensuring that the needs of the Army are met at any particular point in time in the future (US Army, 2009a). The goal of modernizing the Army has also certainty shifted from fighting conventional wars to the focus of building a force that has the capabilities to deal with full range of security challenges. All these represent changing context and needs, which affect the value delivery of the FCS program. A value robust FCS architecture would likely be able to handle these types of shifts and continue to deliver value to the US Army.

2.5.2 Future Rapid Effects System (FRES)

As reported by (Dabrowski, 2009), the British Army’s FRES program is envisaged as a next generation family of medium-weight armored fighting vehicles in the 25 – 35 ton class, which utilize a common modular chassis and are networked and rapidly deployable to tackle a wide range of missions. The FRES was initiated in 2003, but since its inception, there have been a series of delays. In 2009, the UK MOD announced that the FRES project will be put on hold. The reasons are primarily attributed to a change in operational requirements and budget constraints (Grouille, 2009). Similarly in the US FCS program, the lessons learned in the two wars have led to a review in operational requirements and context. The need for equipment and systems to tackle asymmetric threats from insurgents has become utmost priority. Dabrowski (2009) reported that this has shifted the focus from “conventional warfare to asymmetric warfare” and as such, represents an opportunity for the restructuring of the FRES program. In addition, acquiring a family of armored fighting vehicles represents a “platform-centric concept of operation” and this does not fulfill UK MOD’s needs of acquiring capabilities that will address a full spectrum of missions (Dabrowski, 2009). As such, UK MOD’s decision to review the lessons learnt from the existing combat missions represents a need to consider rapidly changing operational conditions when considering the system design and architecture of FRES. If the changing operational condition is not considered in the architecture selection, stakeholders’ value in the FRES program might change. A new fighting concept might emerge to deal with the changed mission context. When this scenario occurs, the FRES might not be relevant and adequate to meet the new mission objectives. The FRES will not serve the interests of the troops and taxpayer’s funding will be wasted, which can be better-invested in other emerging technologies that give the British Army a competitive edge over its adversaries.

The short analysis of the two Army systems programs highlights the criticality of ensuring that the front end architecture and conceptual phase is value-robust. Dr. Marvin Sambur once highlighted in a Lean Aerospace Initiative/Air Force System

Engineering Robustness Workshop in 2004 that a “value robust system is a system that is capable of adapting to changes in mission and requirements, expandable/scalable, designed to accommodate growth in capability, able to reliably function given changes in threats and environments, effectively/affordably sustainable over their life cycle and easily modified to leverage new technologies” (Rhodes and Ross, 2007). Subsequently, Rhodes and Ross asserted that a value robust system must take into account possible external influences such as changing customer needs, context and expectation. They further propose two strategies for achieving value robustness: 1) develop a design that does not require any change under different operating scenarios and context, or 2) develop one that can be readily changed to accommodate many different contexts and needs. Some of these different contexts involve changes in regulation, corporate strategy, customer needs, competitive business environments, technology availability and obsolesce. If all of these are not considered upfront, substantial costs and design efforts will be invested and part of them may not be recovered if there are changes in the architecture. As such, developing a value robust system should be a consideration upfront at the architecture stage and an approach to design value robust systems or SoS will be helpful to the system architect.

Chapter 3 Architecting Methods

3.1 Introduction

Dwight D. Eisenhower once said “Plans are nothing; Planning is everything” (Spinler, 2009). It is extremely crucial for development teams to plan how they should go about developing their systems and introducing them to the market. The planning stage, that is, the mapping of the Voice of the Customers to the technical requirements and the system conceptual development stage, is a key stage that determines the ultimate success or failure of a system. It is also a stage where the problem defined in the real world is being “solved” in the conceptual world. Architecting seeks to communicate the needs of the customer to the concept idea of designers. The system’s architectural form and functions will be articulated in the product/system design, which will form the basis for further development. Further funds will be made available to the development team to verify the design through various methods such as rapid prototyping, mock ups, and production units for trials and evaluation. However, by these stages of production, substantial funds will have to be channeled into the development and any corrections to the design will be extremely costly. Refer to Figure 3-1 to obtain the relative cost of correcting an error in various stages of the system design. From Figure 3-1, Hale (2009) highlighted that the cost of correcting an error in the development and testing stage is at least two times more than the design stage, which involves system architecting. If the system is operational in the field already, the cost of correction is at least six times more that the design stage.

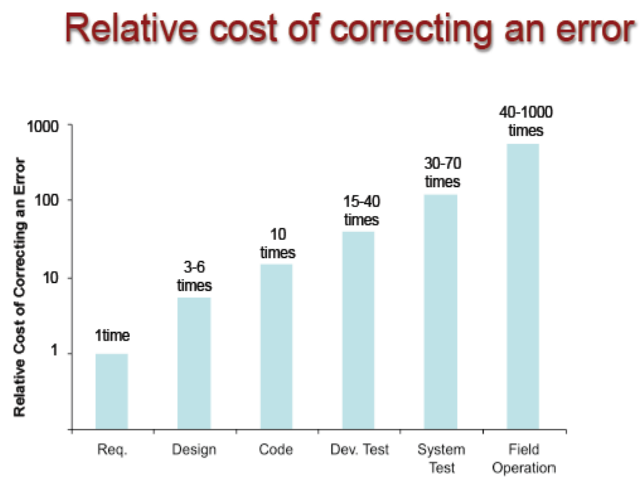

Figure 3-1: Cost of Error Correction (Hale, 2009)

As such, it is extremely important to architect the system so as to build the “right” system. As systems become highly complex and inter-connected, the architecting phase takes on a more critical role to ensure that the overall system functions as intended as compare to the stakeholders’ expectation. SoS architecting plan will also serve as a blueprint to articulate and communicate to various system/product development teams on the over-arching SoS forms and functions. As such, good system architecting will ensure that all possible solutions are devised, analyzed, and considered upfront without bias or sloppiness by the design team intentionally or unintentionally. A set of value robust solutions, generated as a result of good architecting practices, will provide the impetus for further analysis and deliberation by stakeholders. The following sections will discuss current architecting practices. The section will also share some findings on architecting practices within an organization. The findings are derived from semi-structured interviews with system architects, and key stakeholders of an organization tasked to manage complex defence weapon acquisition.

3.2 General Problem Solving Model

Prior to the discussion of architecting methods, it is important to understand the general problem solving model as follows in Figure 3-2:

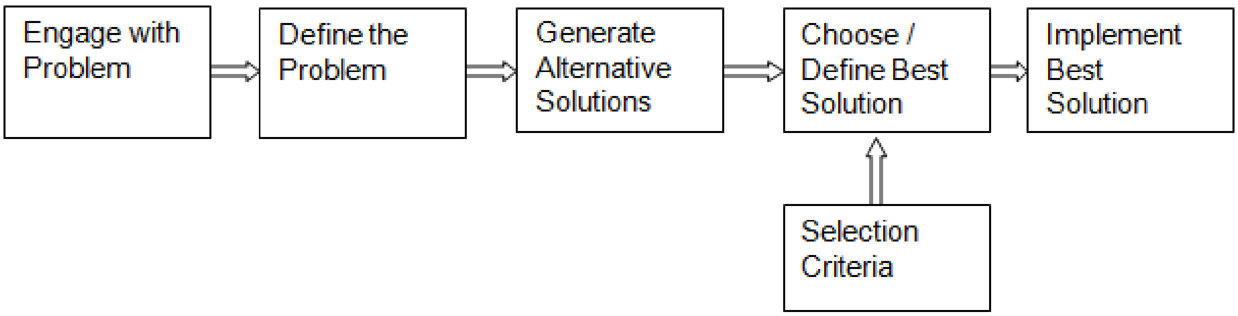

Figure 3-2: General Problem Solving Model (Quayle, 2009)

This methodology refers to the creative method of solving a problem. Design teams intuitively generate as many concepts or solutions as possible using creative techniques such as Brainstorming, Mind Mapping and Six Thinking Hats (Quayle, 2009). This generation of ideas represents a divergent exploration of concepts which will subsequently be followed by a convergence on a best solution based on a set of selection criteria depicted by the design team and the customers. Maier and Rechtin (2009) also defined the “divergence as a creative exploration”. While this represents a creative and intuitive method of mapping solutions to problems, there exists structured, architecting methods in system design.

3.3 System Architecting Methodologies

Maier and Rechtin (2009) discuss 4 classical system architecting methods as discussed:

a. Normative method
b. Rational method
c. Participative method
d. Heuristics method

3.3.1 Normative method

The normative approach is based on established findings and results. Constructing a building or structure in compliance with the building code is an example of using a normative approach. By following the building code, architects and engineers are sure that the building or structure is constructed safely with these established, certified procedures. There is no other way of construction that will guarantee this minimum level of safety to the occupants and the building codes are strictly adhered to. As such, a normative approach will involve using a set of hard, fixed rules to ascertain the successful delivery of the system. On the other hand, a normative approach will not be useful for system design that requires deviation from a set of established rules. The deviations may arise due to customers' specific needs and different use contexts that require amendments to the procedures, which is not possible under a normative approach.

3.3.2 Rational Method

Given the rigidity of the normative approach towards system design, a method based approach - i.e. rational approach - may be used. The rational approach also involves the use of a structured, well established methodology to guide concept generation and decision making in system design. Maier and Rechtin (2009) highlighted that system engineering approaches, engineering handbooks and mathematical formulations are well defined, quantifiable measures that can help a system architect communicate his ideas to stakeholders for concurrence. A structured, engineering framework using models is also often used in a rational approach. As such, it is possible to attain an optimal or “best” solution. However, the rational approach will not be appropriate if there are uncertainties which are assessed qualitatively and not easily measurable for validation. In addition, a rational approach may not incorporate viewpoints from different stakeholders. This is because advocates of the rational approach will use the “optimized” solution as a means to justify that the solution is the best in terms of performance and meeting the project goals.

3.3.3 Participative Method

A participative approach is used for the primary purpose of seeking consensus amongst multiple stakeholders on the architecture design of a system. Discussion and deliberation is critical to solicit agreement. Stakeholders will be able to present their views and influence the decision making process. Drawbacks to this approach include having an unstructured methodology to narrow down to the design solution, dependencies on experiences of stakeholders to make an informed decision, having bias or mental models such as “groupthink”, and the possibility of a strong stakeholder dominating the discussion. There may also be the possibility of a stakeholder having a secondary goal of trying to win an argument, which does not necessarily result in a preferred group decision outcome. There is a high chance that the decision on the architecture system may not be optimal due to the need to accommodate the needs of all stakeholders to gain concurrence on the architecture design. A compromise design may meet the interests of all parties but may not achieve the overall objective well.

3.3.4 Heuristics Method

Maier and Rechtin (2009) state that heuristics are derived from “common sense” and “codified experience”, which are lessons derived from failures or successes from previous projects. They serve as qualitative measures to guide system architects in their work. Three examples are used in Table 3-1 to illustrate the use of heuristics (Maier and Rechtin, 2009).

Table 3-1: Maier and Rechtin (2009)’s Heuristics Examples

Applied Area	**Heuristics**
Prioritization of concepts	“When choices must be made with unavoidable inadequate information, choose the best available and watch to see whether future solutions appear faster than future problems. If so, the choice was at least adequate. If not, go back and choose again.”
Aggregation of subsystems	“Subsystem interfaces should be drawn so that each subsystem can be implemented independently of the specific implementation of the subsystems to which it interfaces.”
System Certification	“Next to interfaces, the greatest leverage in architecting is in aiding the recovery from, or exploitation of, deviations in system performance, cost or schedule.”

Similar to heuristics, axioms and corollaries are also used in system design. An axiom is a proposition which cannot be proven from laws of nature but has been shown to work well (Quayle, 2009). A corollary is something that can be inferred from the axioms. One example of an axiom is Suh's Independence Axiom (Suh, 1998) which states "Maintain independence of the functional requirements."

This axiom highlights Suh's point about uncoupled, decoupled and coupled designs. An uncoupled system design has each of its functional requirements independently fulfilled by one design parameter exactly and each functional requirement is independent of one another. A decoupled system design is such that the functional requirements can only be independent if the design parameters are changed in a proper sequence. A coupled system design has interconnected functional requirements. Suh's independence axiom expresses the importance of having an uncoupled design to ensure good traceability and independence between the design parameter and functional requirement. A coupled design makes error tracing and changes to design parameters difficult because a change in a design parameter may lead to changes in other functional requirements and this makes fault isolation difficult. Similar to heuristics, axioms are equally helpful to system architects to guide them in the thinking and architecting process.

The four mentioned classical architecting methods have their own strengths and weakness. As such, a good system architect should not be fixated in his preference to use one or two types of methods. The system architect should utilize different methods at different stages of the system design. The quantitative (i.e. normative and rational approaches) and the qualitative (i.e. participative and heuristic approaches) can be combined together. For example, at the early stage of architecting, where the system architect is grappling with the ambiguity of identifying stakeholders' needs and upstream influences to architecture, participative and heuristics methods coupled with creativity are helpful to a system architect to overcome complexities through abstraction to understand the problem or needs and propose specific concepts. Once the concepts and interfaces are defined, normative and rational approach can be used to guide the system engineering process.

3.4 Concept Selection

After the concepts have been laid down, the final concept has to be selected for the system design or architecture. There are many ways to come to a solution involving multiple stakeholders. One of the commonly used methods is deliberation, where members of the decision making team discuss the pros and cons of the concept or architecture and come to a unanimous consensus. However, unanimous consensus rarely occurs. Another way may be in the form of majority preferred solution. Others may take the form of a participative discussion whereby the Chairman of the selection committee makes the final decision or the committee concurs with the view of a stakeholder who is able to influence the decision-making through his convincing arguments. While these methods are established norms of coming to a conclusion, the decisions may not reflect the views of all the stakeholders in the decision making process. To enhance the decision making process, the analytic-deliberation process by (Apostolakis, 2009) can be adopted and is shown in Figure 3-3:

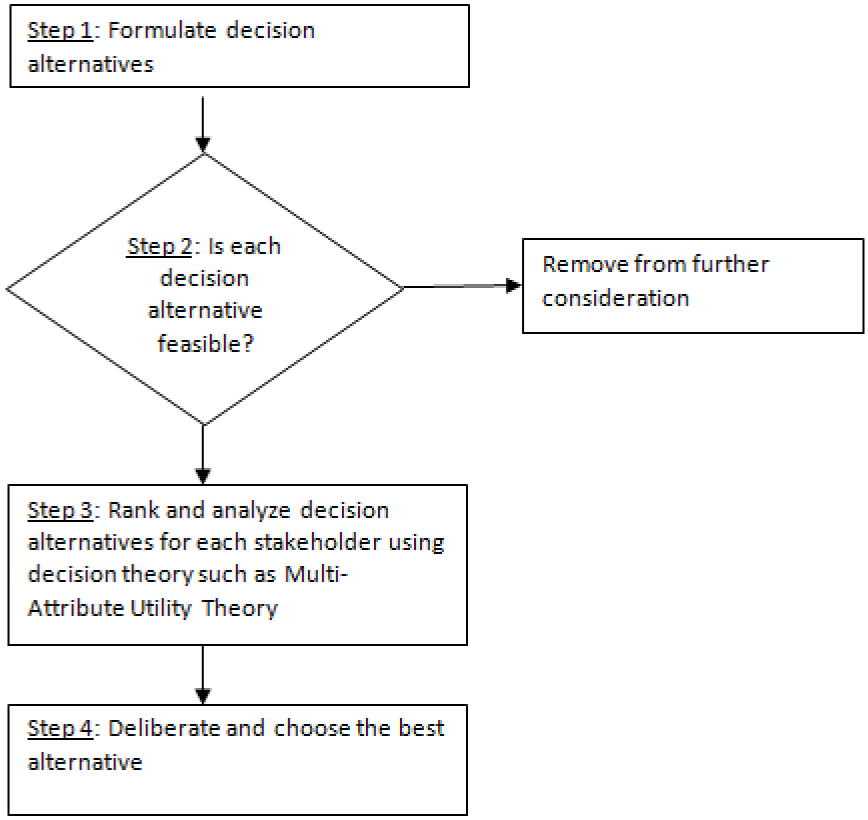

Figure 3-3: Apstolakis (2009)'s Analytic-Deliberation Process

In this analytic-deliberation method, direct beneficiaries, indirect beneficiaries and stakeholders are identified. The various decision alternatives in the form of concepts in architectural designs are identified and presented to all system stakeholders. The decision options are reviewed. Identified infeasible decision options are removed from further consideration. The rest of the alternatives are analyzed and ranked for each stakeholder using decision theory. With the results, the alternatives are deliberated for a final concept. The key advantage of this analytic-deliberation method is that it provides some form of structure or framework to help decision makers make their decisions. It helps to present all concepts to all stakeholders for consideration and their preferences are clearly mapped out. It also helps stakeholders articulate their reasons for choosing a particular choice over another during the deliberations and facilitate deliberations. Deliberations using a structured framework will also help to address some cognitive biases in the choice selection and helps in clarification and negotiation. There are a couple of variants to this method, for example using value tree analysis in the ranking stage. One key variant of the analytic-deliberation process will be discussed in the subsequent chapters.

3.5 Architecting Process

Maier and Rechtin (2009) term the architecting process as an "architecture generation and selection" process. Maier and Rechtin propose an architecting process model in Figure 3-4.

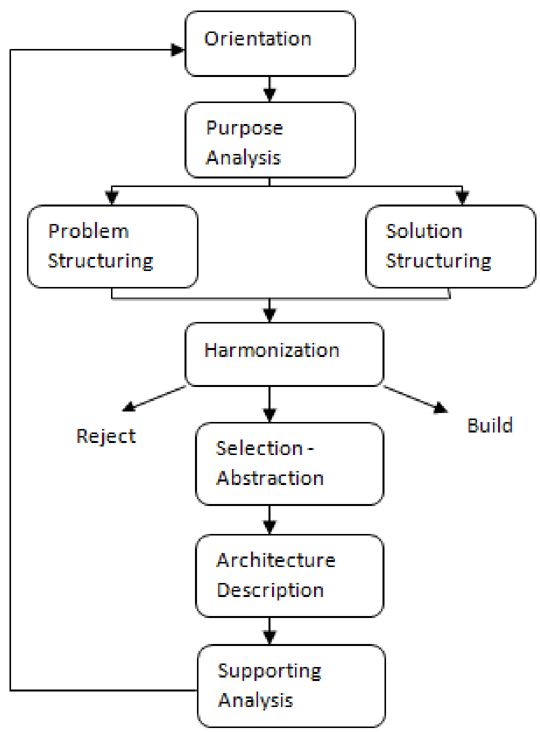

Figure 3-4: Architecting Process Model (Maier and Rechtin, 2009)

Table 3-2: Maier (2009)'s Definition and Output of Architecting Process Model

Major Element	Definition	Outputs
Purpose Analysis	Broadbased study of why system has value	Rich picture of stakeholder stories Essential assumptions and constraints
Problem Structuring	Translation of interwoven elements of rich picture into tractable systems attributes	Use-cases Structured narratives Scenarios of Sys Operation Performance Models Conceptual Models
Solution Structuring	Creation of candidate solutions which must be widely disparate in technology and degree of problem coverage	Models of the solution
Harmonize	Combine problem and solution statements into workable system concepts. Perform consistency and completeness checks	Group of candidate systems
Selection/ Abstraction	Select candidate system and move on to acquisition	Formalized architecture description

Maier and Rechtin (2009)'s architecting process model will commence with the orientation of the project to determine the purpose, problem statement and scope of the project. Heuristics are used to guide the design team to elicit the required goals, objectives, resources and constraints to build the desired product that the customer envisions. This orientation stage will be followed by the core architecture stage whereby the decomposition and aggregation of the system in the problem and solution space are carried out. In the problem structuring process, an example of the heuristic used in decomposition is "Do not slice through regions where high rates of information exchange are required" (Maier, 2009). On the other hand, a heuristic associated with aggregation or synthesis is "Group elements that are strongly related to each other, separate elements that are unrelated" (Maier, 2009). Harmonization is the stage whereby the different solution concepts in the solution space are mapped to the problem and its requirements in the problem space. This involves analysis and deliberation to eliminate those solutions that are infeasible. The remaining feasible solutions will then be put through a selection process using selection criteria. Once this has been completed, the selected architecture concept and models will be described and defined formally. Appropriate architecture frameworks may be used in the description. Concurrently, certain aspects of the architecture concept may require further understanding and information for completeness. As such, supporting analysis may be initiated separately to delve more into the details of the architecture concept. Certain aspects of the architecture may also be subjected to the whole design process again to obtain further clarity on the details.

3.6 Architecting methods and process used by an existing organization

Scenario planning is commonly used by military commanders to assess current and future threats to the nation. The time span for the assessment usually spans five to ten years and can be twenty years ahead of the current time. Based on the perceived threats, the military commanders will take stock of their current capabilities and decide what other capabilities to acquire to counter the threats. Policies and plans will be formulated to meet the needs of the military.

A semi-structured interview was conducted by the author to obtain an understanding of how system architecting of large scale defense SoS was performed. Five interviewees consisting of system architects and program managers in charge of developing the land forces' defense technology capabilities helped provide valuable insights into the general architecting process of defense SoS for the land forces. It was shared that scenario planning was used by the military commanders to determine their needs. Based on these high level needs, the “agents” or officers from the military’s program executive office will work with the system architects in charge of technology acquisition to develop an operational and engineering master plan for the SoS. The combined “ops-tech” input (i.e. the knowledge from the operations and technology) will serve to provide a holistic view of the current operational landscape, the available technology to meet the needs, the estimated cost, and the concept or means to meet the needs. The operational and engineering master plans with combined “ops-tech” input will be forwarded to several channels of committees to solicit stakeholders’ views. These committees will consist of officers and subject matter experts from the various divisions of the army. They may include direct and indirect beneficiaries and other stakeholders of the SoS. Collectively they provide guidance, deliberation, adjustment and endorsement. The amended plans will be forwarded to a decision committee for final deliberation and approval. The approved operational and engineering master plans will provide the direction to realize the concept and global goals of the SoS. The plans will be separated into smaller areas of focus to be managed by different Project Management Teams (PMT). The PMTs will determine the final form of the smaller systems. The system architects and the officers from the program executive office will serve as the “interface” for multiple PMTs to ensure that the systems developed by each team are interoperable with one another and meet the global goals of the SoS. The individual PMTs will be solely responsible for the development of the individual systems to meet local goals.

While the process of front-end planning and deliberation is clear and transparent, the architecting of the SoS and systems may not be well defined and may differ across different system architecting teams within the same organization. While the plans are supported by good data and heuristics, the concept generation and deliberation process can be enhanced by better defined ways of exploration the architecture tradespace comprehensively. The approved architecture may have implicit robustness to meet the military's needs, but could be further fine-tuned to consider value robustness to meet not only the perceived threats, but also opportunities to meet unexpected outcomes, such as the drastic changes in operational context in the case of FCS/BCT program. Explicitly considering value robustness will further ensure that the developed or acquired systems can continue to perform their role in the new context without spending vast amounts of taxpayers' money to acquire new systems for the new needs. In order to do so, the needs for concepts have to be clearly articulated. At the same time, the concepts generated at the global SoS level and at the system level have to consider all possible dynamic changing contexts, as well as be compared on, what is known in system architecting, a same "tradespace". Only then, can decision makers have a clear over-sight of all possibilities and select a concept that best meets their needs over a period of time. With this end state in mind, this is a tremendous motivation to further add value to the current system architecting process with a structured methodology, which will be proposed in the following chapters.

Chapter 4 Proposed Value Robustness Approach

4.1 Introduction

This chapter presents a proposed value robustness approach to architect systems as well as System-of-Systems (SoS). The proposed approach encompasses three methods, which include “Needs to Architecture” framework (Crawley, 2009a), Multi-Attribute Tradespace Exploration (MATE) and Epoch-Era Analysis. Figure 4-1 shows a simple diagram of the proposed approach.

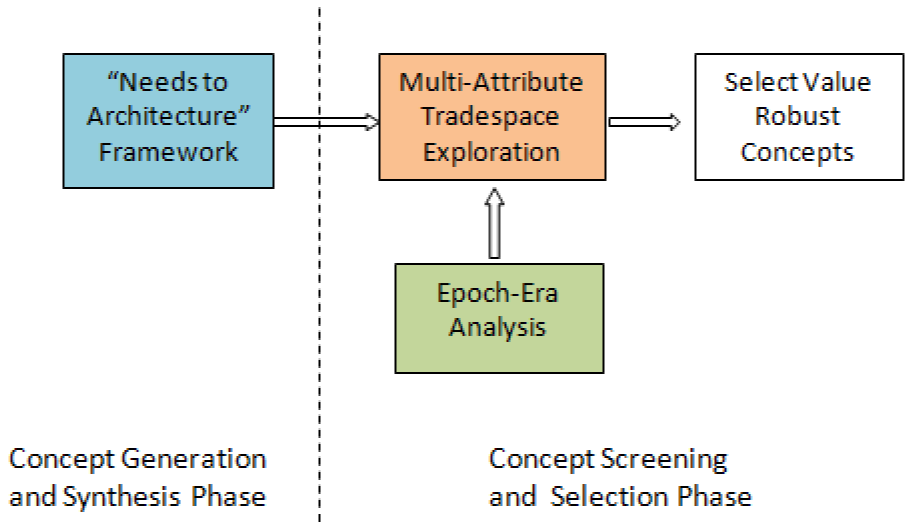

Figure 4-1: Proposed Value Robustness Approach

A “Needs to Architecture” framework (Crawley, 2009a) will be used as a general method to help architects elicit needs, define goals as well as derive concepts and architectures. Specifically, Epoch-Era Analysis will be applied to elicit possible dynamic changes, which can impact the stakeholders’ perceived value of the system concepts and their architecture. This Epoch-Era Analysis will complement the concept screening and selection methodology, known as the Multi-Attribute Tradespace Exploration (MATE). The concepts will be evaluated under the same tradespace across different possible time periods of fixed context known as epochs. A value robust concept will be chosen from among the various concept alternatives.

One of the intended consequences from the architecting process is to ensure that the system or SoS is value robust and able to satisfy stakeholders' needs in a variety of dynamic contexts. As such, the focus of the thesis will be on value-robustness and the associated "ilities" such as scalability and modifiability. Other "ilities" will be briefly described for completeness and awareness. This thesis will also attempt to apply heuristics, methods and principles proposed by author to better design and select a value robust system and SoS architecture.

4.2 Concept of Value Robustness and its relationship with "ilities"

McManus and Hastings (2005) defined robustness of a system as its ability to do its basic job in unexpected adverse environments. In other words, there is no need to change the system even if there is a change such as an unexpected use context. When a system remains insensitive to external "noises" or influences to its design, the system is able to execute its function consistently. This effect might be achieved through high reliability of the system's components and their inter-connections. Another method is to build in redundant systems, which serve as back-up systems if the main system fails (Whitney, 2004).

On the other hand, value robustness applies the concept of robustness in technical aspects to the domain of stakeholders' perceived value. A value robust system maintains the stakeholders' utility when it is employed under different use contexts. In fact, Ross and Rhodes (2008) argue that value robustness is a strategy that aims to maintain a system's value delivery throughout the system's life cycle. They assert that there are two types of value robustness, namely active and passive value robustness. A passive value robust system requires little changes to its design when it is deployed under differing operating conditions, contexts and needs. The system is insensitive to exogenous changes. Alternatively, a system architect can pursue the notion of an active value robust system which can be altered to meet stakeholders' needs under changing circumstances to retain high utilities for the stakeholders. It embraces changeability, which involves concepts of flexibility, scalability, adaptability and modifiability. The feasibility of making changes to a system will depend on the cost and the amount of time required to make an alteration. For the purpose of completeness, the concepts of changeability will be briefly discussed to understand their relationship with value robustness.

Assume that a system has a set of design variables {a, b} in a general sense. An adaptable design is one whose design variables can be changed internally in response to a change in environment, use context and needs (i.e. endogenous response). An analogy is the thermostat. The thermostat is the user's stipulated temperature, even though its external environment can be changing. On the other hand, if a design change is activated by an external agent, for an intended purpose, it is termed as a flexible design. One such example is the computer whose motherboard may contain additional ports to hold additional Random Access Memory (RAM). The user of the computer (i.e. an external agent) will have to physically add extra RAM chips to the ports to increase its RAM capacity. Similarly, a design whose design variables can be changed by an external agent from {a, b} to {2a, b} is termed as a flexible scalable change. This is illustrated by the RAM example whereby the computer memory can be scaled from 512MB to 1024MB by adding an additional RAM chip into the computer. On the other hand, a design is modifiable if its design parameter set is increased or decreased easily. An example is a smart phone. By adding new applications such as a word processor, GPS and games, into a cell phone, the cell phone becomes a multimedia system, which allows the cell phone to be used as a small computer, a music player and a gaming device. All these changes are performed through hardware and software upgrades.

4.2.1 Heuristics for Value Robustness

In addition to Ross and Rhodes, there are other researchers who have attempted to put forth heuristics to assist system architects to devise passive and active value robustness strategies. Ernst Fricke and Armin P. Schulz are two researchers involved in the above mentioned works. Figure 4-2 shows their framework for describing their interpretation of changeability (Fricke and Schulz, 2005). Figure 4-3 shows the corresponding heuristics associated with different aspects of changeability (Fricke and Schulz, 2005).

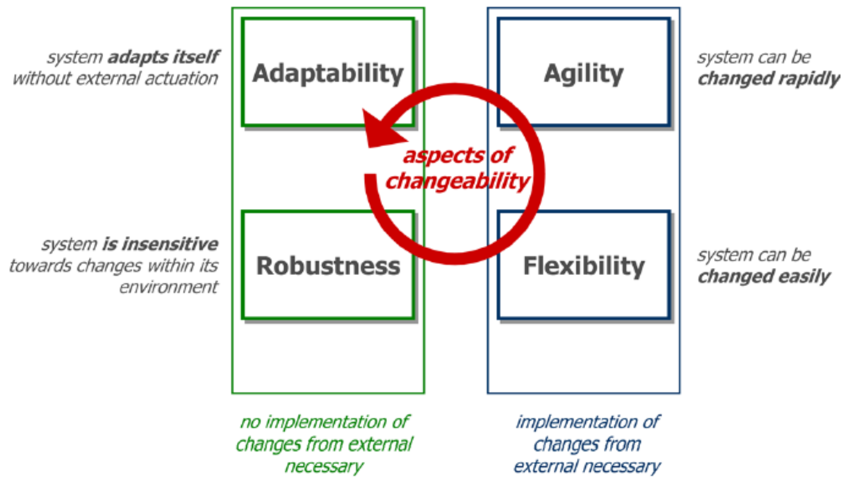

Figure 4-2: Different Aspects of Design for Changeability (Fricke and Schulz, 2005)

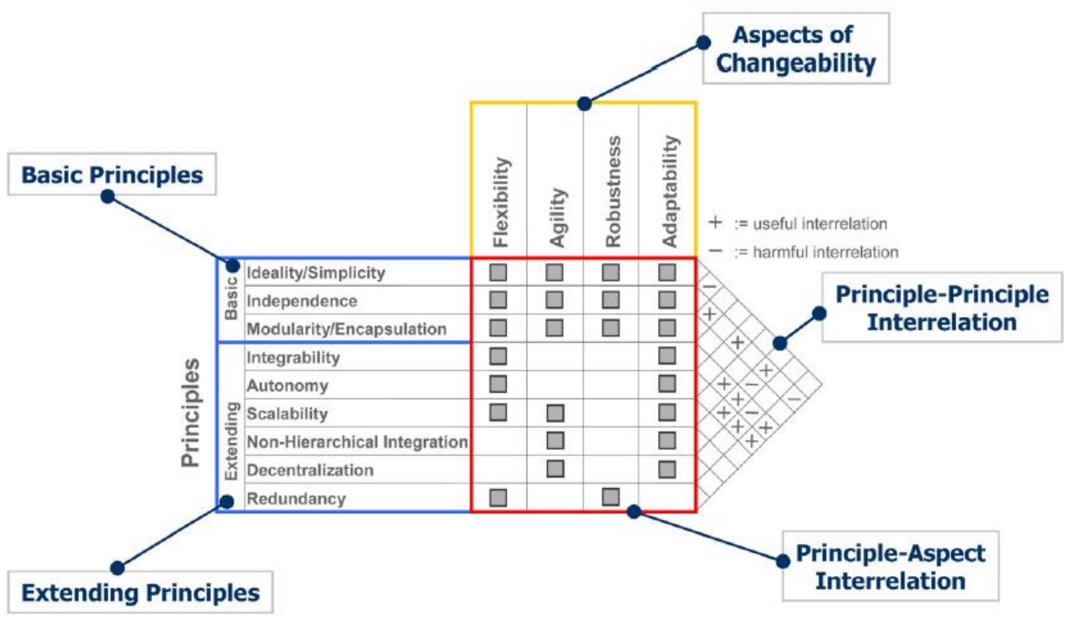

Figure 4-3: Proposed Principles Associated with Changeability in Design (Fricke and Schulz, 2005)

Fricke and Schulz (2005) defined robustness as “the systems’ ability to be insensitive towards changing environment.” Taguchi (1993) and Clausing (1994) also defined robust system as “having the ability to execute the system’s intended functions under different altering conditions, without being changed". This means that the systems' value is preserved because it is able to perform its role under dynamic change in environment.

As indicated in Figure 4.3, the principles of simplicity, independence and modularity can be applied to any systems designed to be robust, flexible, agile or adaptable.

4.2.1.1 Principle of Simplicity, Independence and Modularity.

Reducing complexity and ambiguity is one of the key motivation factors of a system design. A simple system with a minimal number of interfaces and coupling with other functions ensures an architecture which can be decomposed into clear cut functions and forms. While Fricke and Schulz (2005) state that simplicity is one of the basic principles in design, (Tang, 2009) argued that a good architecture design need not be simple. He asserted that the key to developing a valued architecture is a design that has "low complicatedness" to the end user. This design might be of low or high complexity. This relates to (Suh, 1998)'s 2nd axiom of "Minimize the information content of the design" and is very closely linked to the Fricke and Schulz's independence principle. Similarly, the principle of independence is similar to Suh's independence axiom, which advocates the use of uncoupled and decoupled system design over coupled design. Lastly, the principle of modular design affects the maintainability, flexibility and robustness of the system design. Any changes to the system design can be confined to a module and this makes the system easy to change (i.e. flexible to meet changing needs). In addition, system architects are able to add or remove modules in the overall system in order to suit the demands of a new operating environment. This eliminates the high cost of reconfiguration and makes the design desirable to stakeholders for use in multi-spectrum contexts.

4.2.1.2 Principle of Redundancy

The principle of redundancy may be related to a passive value robust design. A system with redundant systems will have additional capacities to deal with contingency situations or operations that are different than originally determined. Take for example, a Mobile Command Post System as seen in Figure 4-4, which serves as an Operations Hub for security forces, requiring power to operate its command and control equipments. Typically, a single generator of suitable power sizing will be required to provide the power. However, if the design can accommodate another generator to provide 100% back up, this additional generator can be used to power additional computer systems, which can otherwise be integrated within the Mobile Command Post in future. This additional generator can also serve as a backup power source if the primary power generator fails. Alternatively, the Mobile Command Post can be equipped with an electrical power inlet which taps power from another nearby generator or building's power supply. This ensures that the Command Post can be equipped with power at all scenarios and maintain stakeholders' value in the system because power is integral in a Mobile Command Post setting.

Figure 4-4: An Example of Mobile Command Post[5]

4.2.2 Value Robustness in a SoS Context

Some of Fricke and Schulz (2005)'s proposed extending principles can be applied in a SoS context. Figure 4-3 shows that the principles of integrability, autonomy and scalability can be applied to flexible designs. Flexibility and adaptability are associated with design changes by an external and internal agent respectively. These changeability effects are commonly found in SoS, which needs to change to allow systems to enter or leave the SoS. SoS evolves with time because there is a constant need to adapt new capabilities to meet the user's changing needs and expectations.

4.3 "Needs to Architecture" Framework

This section discusses a "Needs to Architecture" Framework, which serves as a guide to assist system architects to conceive architecture concepts in a structured manner. Crawley (2009a) has defined that system architects play an important role in

[5] Boey, D. (2007, November 6). Transformer Toy? It's the Army's Command Centre on Wheels. The Straits Times.

identifying needs, defining the boundaries, setting up the goals and creating the concepts for the system for selection. Figure 4-5 shows the pictorial view of the framework for “Needs to Architecture”.

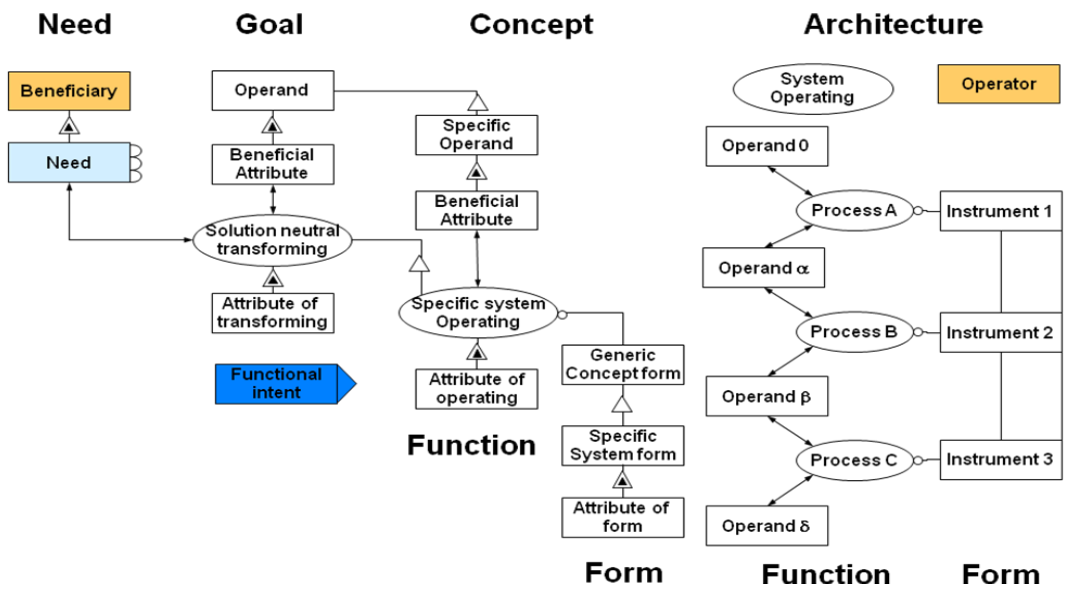

Figure 4-5: Crawley (2009a)’s “Needs to Architecture” Framework

This generic framework maps the needs of the user to the functional intent of the system. Subsequently, the intent is translated to a suitable concept and architecture. The concept will be described based on the purpose (i.e. the functions performed by the system), and the structure (i.e. form of the system). The specific functions and forms will be fully described in the architecture.

The architecting process will commence with the understanding of stakeholders’ needs to reduce upfront ambiguity on the desired system’s behavior and structure. Creativity is applied to generate concepts for the system design. Different permutations of the subsystems can be generated to form the concept. When this happens, the complexity of the interaction between the subsystems has to be managed carefully.

Figure 4-6 shows (Crawley, 2009b)'s detailed steps in identifying the stakeholders, their needs as well as establishing the goals of the system.

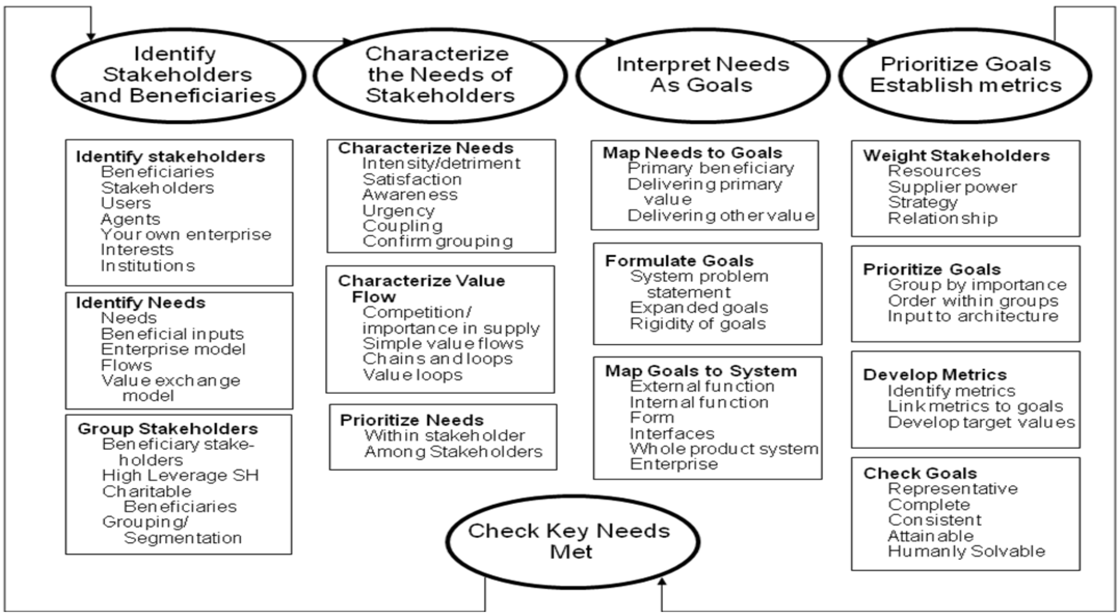

Figure 4-6: Crawley (2009b)'s Steps to Identify Needs and Goals

4.3.1 Needs

During the front end design stage, information is scarce and there is a lot of uncertainty. One of the architects' first initiatives to resolve upfront ambiguity is to identify the needs and the people who have these needs. The people who will be affected by the delivery of the system or SoS can be broadly characterized into beneficiaries and stakeholders. Beneficiaries are people who benefits from the use of the intended system while stakeholders are those who have an interest in the system if it is made available. For example, the direct beneficiary of an acquisition of a Small Unmanned Ground Vehicle (SUGV), as seen in Figure 4-7, in the Brigade Combat Team Program is the ground troops because the unmanned ground vehicle can inspect a suspicious article to determine if it is a bomb, without the need for the ground troops to check it themselves (i.e. the SUGV enhances the troops' safety). On the other hand, the friendly forces in the vicinity of the suspected article are indirect beneficiaries of the UGV because they can be alerted of the possible danger without owning the SUGV themselves. With regards to the stakeholders, one example is the military's safety board. The safety board takes an active interest in the safe design, use and operations of the SUGV. As such, the SUGV's system architect has to understand this important need and conceive a safe product architecture for subsequent implementation.

Figure 4-7: iROBOT (2009)'s SUGV[6]

Once the beneficiaries and the stakeholders are identified, in-depth information about these needs will be solicited. Articulated and latent, unarticulated needs should be surfaced by the system architect. Some of the methods of obtaining the information on articulated needs include interviews with the stakeholders, market research and data from past projects of similar requirements. On the other hand, unarticulated needs can be discovered using the technique of empathic design. Leonard and Rayport (1997) defined the "techniques of empathic design as gathering, analyzing and applying

[6] SUGV 300 Series – Small Unmanned Ground Vehicle. (2009, September 26). *iRobot Corporation Web Page*. Retrieved September 26, 2009 from http://www.sugv300series.com/

information gleaned from observation in the field”. This contrasts with the conventional method of inquiring the stakeholders with regards to their needs and problems faced in using the existing system. Empathic design is employed by observing the stakeholders’ workflow in their operational context. Information of user’s unarticulated needs can be obtained. Empathic design techniques are complementary to the traditional methods of soliciting end user’ input, that is, they should not be viewed as alternatives methods. The traditional methods of surveys and outcome based interviews are useful to provide the first hand information on user’s frustration with existing systems as well as expectations of improved systems. These help to uncover any unsatisfied needs of the customers. These findings should be further complemented through field observations. A combination of these two techniques will help unearth needs comprehensively.

Besides acquiring the stakeholders’ needs, the system architects must also understand what the stakeholders’ values and motivations are. Collectively, this critical information facilitates the definition of goals and the development of different architecture design concepts for the decision makers’ selection. This is known as the Stakeholder Value Approach (Rebentisch et.al. 2005). The motivation behind this approach is to select a concept quantitatively by taking into account the different requirements and views of diverse stakeholders. The way to achieve this goal is to deliver value to the stakeholders through the system, which requires careful considerations for their needs and objectives. Their objectives will determine which system concepts will be selected. There are many tools used to determine how values flow to the stakeholders. One way is to use network diagrams to determine how the value/benefit flows within the network of stakeholders. Figure 4-8 shows two examples of the flow of benefit from one to another beneficiary.

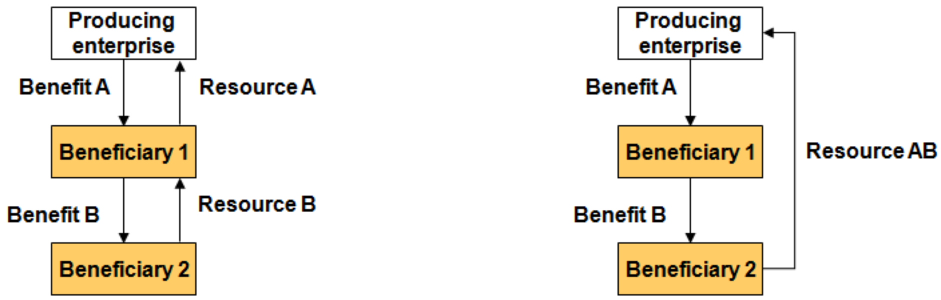

Figure 4-8: Two Examples of Flow of Benefits from (Crawley, 2009b)

In order to illustrate how the needs flow in a network, a value/benefit flow map among the stakeholders has to be performed. The intensity of the benefits can also help to gauge the prioritization of the needs. An example of the value flow map and an assessment of the intensity of benefit will be shown in a case study in Chapter 5, Section 5.2.2 and 5.2.3.

4.3.2 Intent

After the needs of the stakeholders and beneficiaries are identified, the system architect has to interpret and translate them into the goals of developing a system or SoS. Goals are what the architect sets out to achieve and are designed to meet the needs of the beneficiaries. The goals determine the success factors in delivering a right system or SoS to the end users (i.e. the key beneficiaries). As such, it is crucial for the system architects to define representative goals that articulate the intent of the system and the means to achieve them so that end users can obtain value in using the system.

With this background in mind, the key challenge of the system architect is to define the right goals. There are a few guidelines to help the architect. First, Crawley, (2009b) asserts that goals have to be defined such that they are "complete, representative, consistent, attainable and humanly solvable" (Crawley, 2009b). To verify that the goals are complete, they have to be checked against the needs of the end users (i.e. beneficiaries). The goals should be fed back to the stakeholders, subject matter experts and management in the enterprise to ensure that they are complete and representative of all their requirements. The system architect can also make a comparison with the goals of other similar systems to assess whether the goals are comprehensive. Another suggestion is that the system architect can map the goals to all the upstream influences of an architecture such as technology, corporate strategy, marketing and regulatory approvals. To ensure that the goals are consistent, the system architect must ensure that the performance goals do not contradict with one another inadvertently such that an infeasible solution will arise. Benchmarks with past projects can be used as a reference. Simulations may assist an architect to determine if the parametric values make senses when simulations are done at the front end phase. Similarly, to ensure that the goals are attainable and humanly solvable, the system architect can consider factors such as feasibility of technologies used in the system, time required to develop the system and its cost. The system architects can also conduct research on existing proven methodologies and standards, discussed with industry's subject matter experts to get a sensing of whether the goals are achievable, use previous technologies or methods associated with successful projects to ensure that it is humanly solvable. A simple manner of representation can be seen in the Figure 4-9.

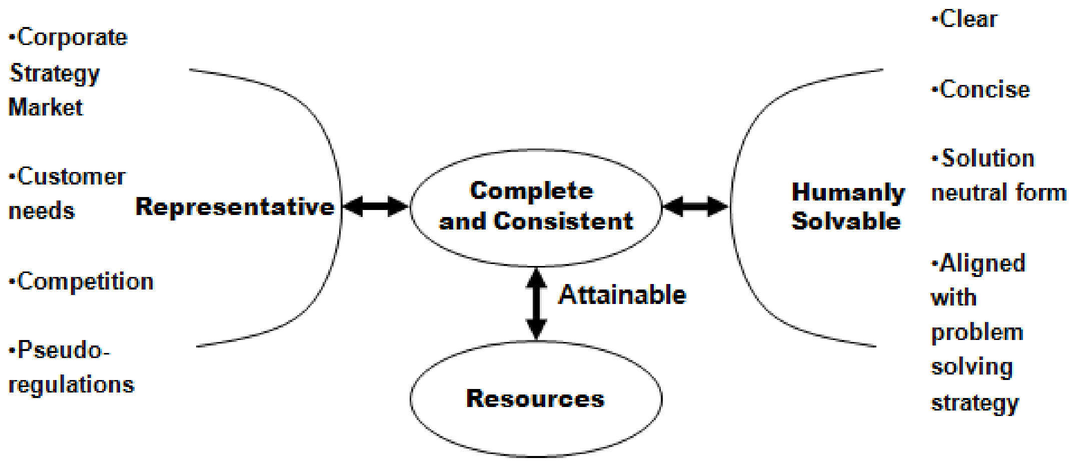

Figure 4-9: Crawley (2009b)'s Checklist on Goals

Secondly, the architect must develop a high level, System Problem Statement (SPS) to articulate the intent of developing the system. The SPS must be clear and concise so that there is no ambiguity about what the architect is trying to achieve. An example of a SPS will be illustrated in the next chapter. The SPS will be the primary goal of the system and provides the primary value to the beneficiaries. Once this is done, the architect can elicit information from the value flow information to determine other descriptive goals. All should be quantifiable with the relevant metrics. The architect must also prioritize the goals into critical, important and desirable goals to determine which goals he should focus on in the front end analysis. These goals should be documented carefully because they highlight the intent of the development of the system or SoS. As an example, Leveson (2000) asserted using an intent specification as an approach to map the goals of the software development project to the software specifications. The intent specification addresses "the system purpose, system principles, black-box behavior, design representation and code" (Leveson, 2000). The intent specification serves as an approach to assist software system architects to design software codes that are effective, consistent and humanly solvable. It also serves to integrate formal and latent requirements of software development. Leveson's concept can be applied to any system to bring clarity to intent of the system development. Figure 4-10 provides a framework to map the needs to the intent of the system.

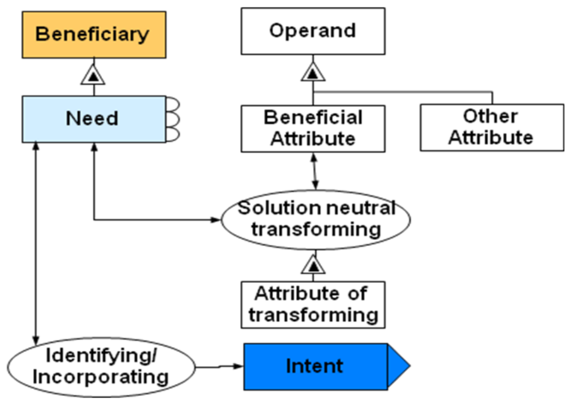

Figure 4-10: Crawley (2009b)'s Needs to Goals Framework

The goals must be solution neutral and independent of bias from the any possible concepts. The system architect must also strive to goals that are measurable with quantifiable metrics. Qualitative descriptive goals can be included to complete the analysis. Chapter 5 will show an in-depth illustration of how the goals are developed and prioritized.

4.3.3 Concept

The next stage of the architecting phase is developing the high level concepts for the system. According to Crawley (2009c), a concept matches the form or structure to the function or behavior of the system. Analogous to Figure 4-5, the basic generic steps adopted from (Crawley, 2009c) to develop concepts are as follows:

a. Use creativity to develop high level concepts to satisfy the intent and the System Problem Statement.

b. Prune and eliminate concepts that do not fulfill the secondary goals and their matrices. Select desired concepts base on context for further analysis

c. Expand and/or decompose concepts to reveal the internal operands, processes and instruments. These sub-processes and instruments are known as concept fragments.

d. Combine concept fragments to obtain new permutation of integrated concepts. Eliminate integrated concepts that are not possible due to different constraints.

4.3.4 Architecture

Concepts provide the high level picture and view of the system. It maps the functions of what it is supposed to achieve to the form and structure. However, Crawley (2009d) asserts that the concept does not provide the details of the internal processes, instruments and operands. It also does not provide an overview of how the internal subsystems are connected and how information flows from one subsystem to another. It also does not provide details of the interface between the internal subsystems and with the external supporting systems. By incorporating all the above, the concept is expanded to form the architecture. A rule of thumb is that the concept has to be decomposed and synthesized to two levels of details to provide clarity about its design. The information will form the basis for the design vector of the concept, which will be used in MATE subsequently. System architects will be able to provide a fairly accurate estimation about its costs. In addition, system architects and stakeholders will also be able to assess the system concept's performance through modeling. The stakeholders' preference will be determined by benchmarking the concept's performance to the desired attributes of the system. This information forms the basis for the tradespace analysis, which will be discussed in the subsequent section.

4.4 Dynamic Tradespace Exploration

The front end planning and architecting phase is an important stage in system design. It is the stage where the system's functions and forms, which constitute the system's concept, are mapped out. Once the architecture design is finalized, the system's specific form will be realized through the system engineering process. As explained in Chapter 3, a good concept selection can mitigate the risk of making changes or rework at a later stage of the system engineering process. However, many project teams may not have a systematic way of generating and pruning the concepts so as to arrive at a good, feasible concept that delivers value to the stakeholders. Project teams might come up with two to three alternative concepts from an unstructured brainstorming session. This may lead to a premature reduction in the pool of feasible solutions for the system. When the concept selection is not robust or comprehensive, the project team will incur the risk of missing out on a design that is superior to the selected concept.

Tradespace exploration is a technique that allows all the design concepts to be evaluated quantitatively and collectively. However, the tradespace exploration has to be augmented with a concept-independent means of evaluating the alternatives, such as utility theory, to facilitate the comparison between the concepts. Collectively, a method that utilizes utility theory for such comparisons is known as Multi Attribute Tradespace Exploration (MATE). Ross (2003)'s MATE method helps to address the concern of premature reduction of solution space. On the other hand, users of a MATE analysis should not expect an optimized solution. This is because the intent of MATE is to allow the system architect and users of MATE to understand the trades between various design concept options at different costs. The end state from MATE is a set of concepts that gives the stakeholders the highest utilities at different costs. When this happens, deliberation between the stakeholders can take place before a final architectural concept is selected. MATE can also be extended to consider dynamic changes over time. By considering different scenarios of what might happen in the system's life cycle, the system architect and users of MATE can observe the changes in utilities and costs of each concept. The detailed discussion on the tradespace exploration will be in the following sections in Chapter 4.

4.4.1 Attributes

In visualizing MATE analysis, it might be helpful to the system architect or MATE practitioner to visualize two realms, that is, the stakeholder's realm and the designer's realm. The first step in implementing a MATE analysis is to identify the stakeholders and their needs, which is conducted using the "Needs to Architecture Framework".

Through the stakeholders' analysis and their cardinal requirements, a set of quantifiable metrics that characterize the concept and reflect how well the stakeholders' requirements are achieved will be formulated. This set of metrics is defined as the attribute set, and each stakeholder will have his or her own set (Ross and Hastings, 2005). In order to be most effective, the attributes should be "solution neutral" and independent of any potential concepts. Keeney and Raiffa (1993) and Ross (2003) suggest that the attribute set should be limited to contain only a maximum of around seven attributes. This suggestion is in view of cognitive limitations that may hinder the ability of the human brain to consider more than 7 items simultaneously. As a rule of thumb, 7± 2 cardinal attributes per stakeholder should be considered for the analysis, though typically in practice a single individual will be unable to consider more than about 5 +/- 2.

After the attributes are elicited from each stakeholder, the system architect will determine each stakeholder's preference with regards to his or her own attributes. Each stakeholder will provide the system architect with the minimum acceptable and maximum desirable levels of the attributes. The minimum and maximum acceptable levels will be mapped to utility level 0 and 1 respectively. Based on utility theory, the stakeholder will be indifferent to any improvements in attribute level if the attribute of a potential system concept exceeds the maximum levels desired by the stakeholder. The system architect will attempt to probe the stakeholders' preference between utility level 0 and 1, which falls between the minimum acceptable level and highest level where the stakeholder is indifferent to further improvements. When this is achieved, the stakeholders' preference curve with regards to a particular level of an attribute can be determined. This process must be repeated for all attributes and all stakeholders.

4.4.2 Utility Function using Multi-Attribute Utility Theory

Subsequently, a utility function for the whole system has to be formulated. Three key pieces of information are required. They are the "weights" of attributes, the utility function for each attribute, as well as how the individual single attribute utilities can be aggregated into a multi-attribute, system level, utility function. The use of a system level, utility function is to assess how desirable a system is as compared to alternative design options. Multi-attribute utility theory can be used to formulate a utility function. The utility function of a system with multiple attributes is in Equation 4.1.

$$U(\underline{X}) = u\,(x_1, x_2, x_3,\ldots,x_N) \qquad (4.1)$$

Where $\underline{X}$ represents the system,

x_i refers to the attribute of $\underline{X}$, for $i = 1, 2\ldots, N$

$U(\underline{X})$ is the multi-attribute utility function of the system.

However, the multi-attribute utility function might be cumbersome if there are many different values within each attribute and the stakeholder has to provide consistent preference values to different combination sets of the attributes. As such, an alternative commonly used method to find the utility function of a multi-attribute system is the additive value model (Parnell and Trainor, 2009). A simple example of an additive utility function is shown in Equation 4.2.

$$U(\underline{X}) = k_1\,u(x_1) + k_2\,u(x_2) + \ldots + k_N\,u(x_N) \quad \text{for N number of attributes} \qquad (4.2)$$

$$U(\underline{X}) = \sum k_i\,u(x_i) \quad \text{for } 1 \leq i \leq N \qquad (4.3)$$

Where $\underline{X}$ represents the system,

x refers to the attribute of $\underline{X}$,

k_1 to k_N are the normalized relative weights of the attributes,

$u(x_1)$ to $u(x_N)$ are the utility functions of the individual attributes

. $0 \leq k_i \leq 1$

$\sum k_i = 1$ where $1 \leq I \leq N$

$0 \leq u(x_i) \leq 1$

In order to use the additive value model, the attributes have to be independent of each other and there should not be any interaction between the attributes (i.e. the increase in utility of one attribute will not lead to a change in all other attributes). This is a strong assumption because the attributes of a real world system may not be perceived independent of each other. Many systems have functional requirements which are decoupled or coupled (i.e. a change in the functional attribute will lead to a change in another attribute). However, the additive value model can still be useful as a first cut approximation to reveal stakeholders' preferences (Apostolakis, 2009).

4.4.2.1 Weights of Utility Function Using Additive Value Model

The weights of the additive value model can be calculated using different techniques. Equation 4.2 and 4.3 assert that the weights of the attributes add up to one and the weights provide a quick assessment of the relative importance of the attributes. The relative weights of the attributes can be obtained through the House of Quality and will be illustrated in Chapter 5.

4.4.2.2 Swing Weights Matrix Theory

A recent alternative method to determine the weights of the attributes is to use the swing weight matrix theory, whereby the weights do not add up to one. The use of swing weights is motivated by the impact of both the importance and variation of the attribute. Instead of focusing on the importance of the attribute as compared to the rest of the attributes, Parnell and Trainor (2009) asserted that an attribute which has significant value ranges, should be weighted more than another attribute that does not vary much among the system concept alternatives. For completeness, the method shall be discussed briefly in the following paragraph. Figure 4-11 shows the elements of the swing weight matrix.

		Importance of the value measure to the decision		
		High	Medium	Low
Range of variation of the value measures	High	A	B2	C3
	Medium	B1	C2	D2
	Low	C1	D1	E

Figure 4-11: Swing Weight Matrix (Parnell and Trainor, 2009)

The swing weight matrix will take into account the importance and variation of attributes to the system. The stakeholders and decision makers have to spread the weights (e.g. 100 or 1000) into the 9 boxes in the matrix. In order to maintain consistency of the weights, the following weighting rules must be observed. They are extracted from (Parnell and Trainor, 2009).

a. Attributes in cell A is weighted greater than attributes in other cells.

b. Attributes in cell B1 is weighted greater than attributes in cell C1, C2, D1, D2 & E.

c. Attributes in cell B2 is weighted greater than attributes in cell C2, C3, D1, D2 & E.

d. Attributes in cell C1 is weighted greater than attributes in cell D1 and E.

e. Attributes in cell C2 is weighted greater than attributes in cell D1, D2 and E.

f. Attributes in cell C3 is weighted greater than attributes in cell D2 and E.

g. Attributes in cell D1 is weighted greater than attribute in cell E.

h. Attributes in cell D2 is weighted greater than attribute in cell E.

The attributes of the desired system are placed in any of the 9 boxes in the swing matrices. The placement is based on the decision makers and stakeholders' evaluation of the attributes. Once all the attributes are placed in the appropriate boxes, the normalized swing weights for each attribute are calculated as in Equation 4.4.

$$w_i = \frac{f_i}{\sum_{i=1}^{n} f_i} \tag{4.4}$$

Where f_i is the matrix swing weight corresponding to attribute i,

i = 1 to n for the number of attributes,

w_i are the normalized swing weights for the attribute i.

Equation 4.4 shows that it is not possible for the weights of all the attributes to be equal to one. This is because it is unlikely that there will be one attribute exactly in each cell. It is highly possible that there is no attribute associated with each cell or there might be more than one attribute in a particular cell.

4.4.2.3 Elicited "weights" accounting for nonlinear preference effects

Keeney and Raiffa (1993) presented a function that derives from Multi-Attribute Utility Theory as shown in Equation 4.5.

$$\mathbf{K}U(\underline{X}) + 1 = \prod_{i=1}^{N} \left(\mathbf{K}k_i U_i(X_i) + 1 \right) \tag{4.5}$$

Where $U_i(X_i)$ is the elicited single attribute utility function for attribute X_i

K is a normalization constant that ensures multi-attribute utility function ranges from 0 to 1

In this method, the k_i values correspond to the essential satisfaction on a 0 to 1 scale of the decision maker when attribute i is at its most desirable level and all other attributes are at their least acceptable level. The k_i values elicited in this way do not have to add up to one. In the special case that the k_i values do add up to one, the multi-attribute utility function becomes the linear weighted sum mentioned above. Otherwise the multi-attribute utility function becomes either a multiplicative or inverse multiplicative function. (Note: as the sum of k_i values approaches N, the attributes essentially become substitutes, as a high score in one will result in a high net utility. As the sum of k_i values approaches zero, a high score in all single attribute utilities becomes necessary in order to have a high net utility score.).

4.4.2.4 Elicitation of Value Functions

The utility function of the attributes can be obtained through a variety of techniques. Some of the techniques include inferring historical data on actual decisions, deriving value function from surveys, direct elicitation, and through a structured interview with the stakeholders. The simplest technique is direct elicitation, though this is subject to biases. Stakeholders will be asked for the values of the attribute where their utility level is 1, 0.75, 0.5, 0.25 and 0. A simple example of a linear utility curve is shown in Figure 4-12.

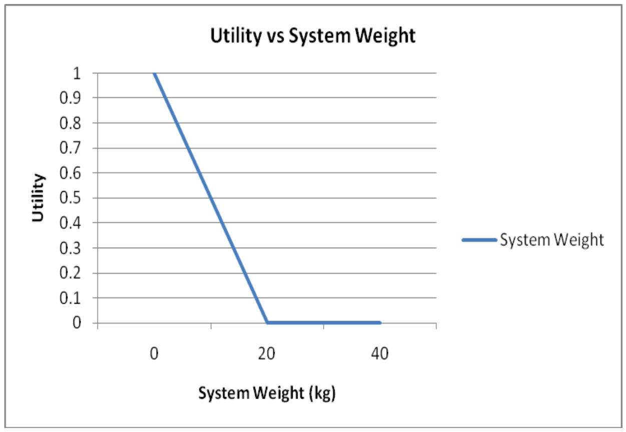

Figure 4-12: Utility Function of System Weight

4.4.3 Design Vector

Next, the system architect has to identify a set of design variables in the design realm. A set of design variables, which are "designer-controlled quantitative parameters, form a design vector that best describes the design concept". An example of a design vector for a mobile shelter is {hard structure container design vs. tent design, integrated with a truck transporter vs. transported with a truck or trailer, onboard power vs. separate power source, power sizing, ventilation system, ventilation sizing, floor space, internal furniture layout, communication infrastructure, communication and control equipment}.

$$Design\ Vector\ of\ Command\ Post = \begin{bmatrix} Shelter\ Design \\ Integration\ of\ Shelter\ to\ Truck \\ Power\ Source \\ Power\ Sizing \\ Ventilation\ System \\ Ventilation\ Sizing \\ Floor\ Space \\ Internal\ Layout \\ Communication\ Infrastructure \\ Command\ and\ Control\ Equipment \\ Number\ of\ Shelters\ in\ a\ Set \end{bmatrix}$$

The elicited attributes will be mapped to the design variables to determine which design variables impact the attributes the most. All the possible values of the chosen design variables will be permutated to form various design concept options.

4.4.4 Tradespace Analysis

A tradespace will describe a system design in terms of a set of design variables. Each of the options will be assessed in their performance based on the attribute set. The utility of each system will be calculated using the multi-attribute utility theory and leveraging on the additive independence rule. Through the design vectors of the various concepts, the system life costs are calculated. The utility and cost of each concept is plotted on a utility-cost graph to form a tradespace. Hence, each point on the tradespace analysis represents a design choice represented by values for the design variables, attribute values, attribute utilities, aggregated multi-attribute utility and lifecycle cost. Choosing a concept that maximizes utility and minimizes costs is the typical goal of the system architect. In view of this, the tradespace will provide a powerful visualization tool to allow system architects to determine the trades between the concept options. The decision makers and stakeholders will understand their personal values among all the concept options and are able to have an informed deliberation on the best option to undertake for the development. It also serves as a traceability tool to allow stakeholders and decision makers to reflect on past decisions made on designs and contemplate how to proceed with reconfigurations, should there be a need to modify the system to meet new needs. A graphical representation of the inputs and outputs of the tradespace analysis is shown in Figure 4-13.

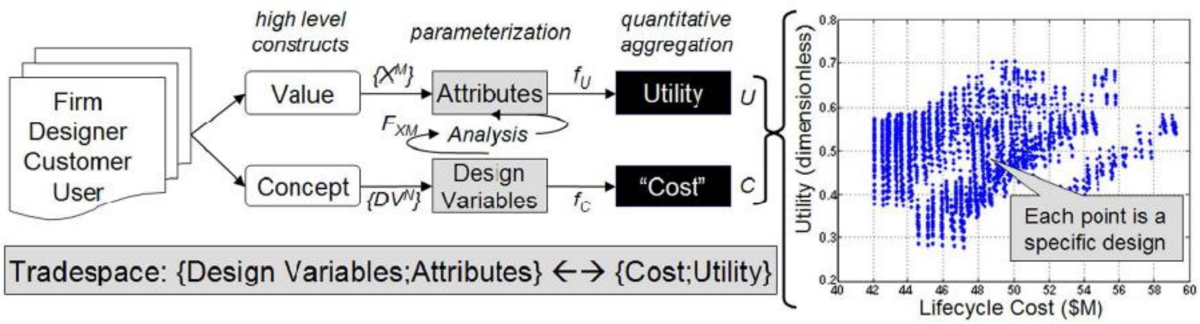

Figure 4-13: Tradespace Methodology (Ross, Rhodes and Hastings, 2008)

One may ask what useful information may be elicited from the tradespace analysis. The first useful information is the identification of designs at the Pareto Front. The Pareto Front is a set of design options that provides the highest utilities to the stakeholders at any given cost, with all else remaining constant. It represents the trade-off between the different design options as the budget to acquire or develop the system increases. The second useful information is the identification of outlier solutions. An outlier solution is one which lies outside of the Pareto Front and is identified as having anomalous utility or cost. If a concept is identified as an outlier, it is because its utility-cost information does not "fit" the coherent data set and is excluded from the calculation to determine the Pareto Set (i.e. concepts that are on the Pareto Front). Otherwise, the "outlier" would be in the Pareto Set. The third useful information could be in the form of comparing to existing Commercial-Off-The-Shelf (COTS) solutions. Some of the solutions may appear to perform better than commercial-off-the shelf systems and a useful question to ask is whether the solutions are infeasible or there are potential opportunities to develop a better, optimized system. The fourth useful piece of information is to determine the natural frontier where there is a limitation in the existing technologies or physics that may not meet customers' requirements. Lastly, the Pareto Trace metric can be used in conjunction with Epoch-Era Analysis to determine systems with high passive value robustness. This will be analyzed after the introduction of Epoch-Era Analysis.

The tradespace represents a static snapshot or "freeze" in time, that is, requirements, needs and context remained unchanged. However, changes will occur throughout a system's long life cycle. In order to sustain value delivery, system architects have to build strategies to deal with changes. The next section will elaborate on how changes can be accommodated and how strategies might be implemented.

4.5 Epoch-Era Analysis

4.5.1 Motivation of Epoch-Era Analysis

Changes are inevitable through a system's lifecycle. Changes are more pronounced for SoS because there is a strong requirement to perform experimentation to evolve to the next level of capabilities. In view of this, it is important to characterize the changes. Ross and Rhodes (2008a) present three types of changes: changes in needs, context and expectations of the stakeholders. The ability to identify and manage these changes represents the first step towards formulating a value robustness strategy for a system or SoS. If the system architect is able to anticipate and accommodate these changes in the system or SoS design in the upfront concept planning stage, the system or SoS stands a higher chance of having a performance able to meet the expectations of the stakeholders. Value will be delivered to the beneficiaries and stakeholders through the system or SoS design over time.

Epoch-Era Analysis is a scenario planning methodology that enables a system architect to postulate the different contexts that will affect a system's value to stakeholders. This method builds on the Multi-Attribute Tradespace Exploration method. While the MATE allows all the possible design concepts to be evaluated and compared on a single tradespace, it represents a static view of the systems based on a given stakeholder's perception of the existing operating concept, environment, context and needs at that point in time. As exogenous changes will happen over time, it is critical to devise an approach that helps system architects anticipate possible dynamic changes for evaluation of these technical systems or SoS for value robustness. By attempting to look at a long term view of the system, the architect is best able to adopt a design strategy upfront in the architecture stage to meet the demands of changes. This will help to eliminate the possibility of incurring switching or high modification cost to meet these needs. Consequently, the method assists planners to allocate a realistic budget to maintain the lifecycle costs of a system or SoS. Although designing the system for value robustness may incur a higher cost at the upfront development stage because it takes into account change situations which may or may not happen in the future, nevertheless, it still presents good information of the overall system costs for the decision makers to make a decision. If the change situation materializes, substantial switching cost or modification costs will be saved.

4.5.2 Definition of Epoch-Era Analysis

In view of this requirement, Ross (2006) introduced Epoch-Era Analysis, a time based analysis method, where the context itself defines the timescale. Ross and Rhodes (2008b) defined an epoch as “a period of time where the system or SoS has a fixed context or fixed value expectation”. On the other hand, an era is a series of epochs connected together to represent a system’s lifecycle with changing contexts and expectations. As such, an era offers a long term view of the system.

Each epoch is a “state scenario” where by all the system concept designs are evaluated based on the context and value proposition of the stakeholders at that period of time. An epoch vector, which is represented by parameters affecting the system in a certain context, will be used as an evaluation criterion for all the system concepts within the epoch time frame. The performance of the system concept will be assessed by individual stakeholders whose utility preferences are elicited. Using the estimated system cost at each epoch, the utility-cost tradespace will be constructed for comparison. This assessment will be performed for all epochs, which form the era. An era is an ordered set of epochs that occur across the entire lifecycle and they are enumerated to provide the evolution of state scenarios from current to future states (Ross and Rhodes, 2008b). During an epoch change, the system or SoS concept will need to operate in a different setting. The system or SoS’s performance in a different setting may change the stakeholders’ perceived value of the concept. To prevent a possible reduction in perceived values, the system architect can adopt a passive or active value robust strategy. The case study in Chapter 5 will illustrate the use of the strategies in greater detail.

4.5.3 Epoch Categories

In order to provide the system architect with a thinking platform to expand the possible epoch parameters, Roberts et al. (2009) suggest the following consideration of the following exogenous categories, which may impact a system or SoS architecture:

a. Strategy / Policy

- The strategy pertains to the mission, vision and direction of the enterprise associated with the system or SoS.
- Rhodes, Ross and Nightingale (2009) highlight that the policy refers to the "external regulatory, political and societal environments in which the enterprise operates".

b. Resources

- The resources represent the budget available to acquire, maintain and upgrade the system or SoS.

c. Capital

- The capital represents the technology, infrastructure and other supporting system in the whole product system that will impact the value delivery of the system or SoS to the stakeholders.

d. Product

- The product may refer to the evolution of the subsystem or end use of the system or SoS.

Figure 4-14 shows a pictorial view of the exogenous epoch categories influencing the system or SoS throughout its life cycle.

Figure 4-14: Exogenous Epoch Categories Influencing the System or SoS

These epoch categories can be elicited from a value-based Enterprise Model. Rhodes, Ross and Nightingale (2009) discussed an eight views framework for enterprise architecting. They define enterprise architecting as ‘applying holistic thinking to conceptually design, evaluate and select a preferred structure for future state enterprise to realize its value proposition and desired behavior”. The objective of enterprise architecting is to understand the relationship between the elements of an enterprise. With this understanding, system architects will be able to relate how these elements influence the technical design of the system or SOS. The eight views include strategy, policy / external factors, organization, process, knowledge, information, product and services. The application of Epoch-Era Analysis is extended from a technical system to the enterprise level. Any changes in any of the eight views of the system can be represented by a new epoch. System architects can analyze the paths between across all epochs and eras and determine a strategy that provides continued high value delivery to all the stakeholders. The application of Epoch-Era Analysis to enterprise architecting complements the study of SoS and is currently an area of intense research. The eight views of enterprise architecting will not be illustrated in this thesis.

4.5.4 Other Exogenous Epoch Categories

Besides Rhodes and Ross, other authors have also provided their own framework of exogenous categories to aid system architects to mull over the influences on the system or SoS design. For example, Crawley (2009a) has proposed system architects to consider the following influences:

a. Corporate strategy
b. Regulatory influences such as regulations and standards
c. Marketing strategy, competitor landscape and business eco-system
d. Downstream competencies such as supply chain, platform alignment, legacy system, enterprise competencies, manufacturing system and suppliers
e. Technology strategy and trends

4.6 Analysis for Passive Value Robustness

A system that is passive value-robust is able to perform consistently at a level that meets stakeholders' expectation across changing contexts without any change in the system. Ross, Rhodes and Hastings (2009) suggest that this type of value robustness can be achieved by “clever” systems designs, which involved risk mitigation strategies such as excess built-in capability, or “latent value” which can be activated as and when required. These “clever” designs are able to consistently provide high utilities to stakeholders across multiple epochs in an era. As such, in order to identify passive value robust systems, the Pareto Sets of multiple epochs have to be analyzed and the concept of a Pareto Trace number is used as the measure of passive robustness. Recall that it is not possible for solutions on the Pareto Front to be improved upon in a certain attribute without causing another attribute to be worse off. To calculate the Pareto Trace metric, the system architect has to first note all the design concepts which appear on the Pareto Front in all epochs. The frequency of the concepts that appear on the Pareto Front in all epochs is tabulated. This frequency of occurrence gives the Pareto Trace. The results are normalized to give the Normalized Pareto Trace Number. Design concepts that have the highest Normalized Pareto Trace Number will be the most passively value robust systems. The calculation of the Normalized Pareto Trace Number will be demonstrated in Chapter 5 through a case study example.

4.7 Analysis for Active Value Robustness

To complete the analysis, active value robustness can be achieved by pursuing a changeability strategy. Mostly, this strategy involves an external change agent to lead the modification of the system so that it can continue to provide satisfactory perceived value to stakeholders in the new context and expectation. For this to take place, the chosen design concept must contain features that allow it to be flexible in design. The concept should have the pre-condition of being able to be modified to meet the new or changed needs. This flexibility feature does not occur by coincidence. It is incorporated in a structured, purposeful manner into the concept design so that it can be exercised at a later stage, if it is ever required. If this pre-condition is satisfied, the next two important questions to ask are “how desirable is the flexibility to the stakeholders?” and “how is flexibility quantified?” Flexibility comes at a cost to stakeholders and there is a limitation on how flexible the design can be. Ross and Rhodes (2008a) proposed the use of a tradespace network to determine the flexibility of a design. The tradespace network is formed from the tradespace analysis whereby each design concept option serves as a node. A design that can be changed into another design is illustrated by drawing an arc that links the two nodes. There is also a cost associated with the modification. However, there is an acceptability threshold for the modification cost, as well as the number of outgoing arcs from a given design. The count of acceptable outgoing arcs from a given design is known as the Filtered Outdegree (FoD). It represents the number of paths that can be followed from a design to alternative designs, with a change cost below the acceptability threshold for modification. To improve the changeability of a system, the number of outgoing arcs must be increased and/or the cost of the outgoing arcs must be decreased. The acceptable arcs can be identified through an “accessibility tensor”. This tensor represents the cost of transition from design i to j through a transition rule k, and it can be searched using an algorithm. Several different types of transition matrices can be applied to multiple epochs to gain an understanding about systems operating in a dynamic context. The end state is to determine the design with the most number of outgoing arcs. A high FoD indicates a potentially active value robust design. This method is currently an active area of research.

Another way to represent flexibility is to introduce the concept of real options. Using real options is a method to design a flexible system under uncertainty. Real options thinking and valuation can be used to estimate how flexible a system is in quantifiable monetary value. In defence acquisition, a flexible design can be quantifiable in terms of cost avoidance without the need to procure a new system or to pay high switching cost or high modification costs. As such, it is important that the system architects think ahead of possible changes in expectations and needs that might impact the system design and factor this into the upfront design. Epoch-Era Analysis is thus a useful tool to help system architects plan ahead. On the other hand, system architects can also adopt modularity as a design strategy. Modules create options which allow the system architect to add or change design features to the system when the need arises. It is most useful in areas where the likelihood of change in the future is high. While modularity reduces switching or modification costs, system architects must also be aware of possible additional upfront architecture costs, such as extra interfaces and redundant support systems, associated with the modularity design strategy. All the benefits and costs will be accounted for using real option valuation techniques to determine if the modularity strategy provides net benefit to the stakeholders.

4.8 System of Systems (SoS) Architecting for Value Robustness

SoS Architecting takes on a similar approach to system architecting. The first step of SoS architecting is to identify the stakeholders in the SoS and the SoS needs, which are commonly expressed in terms of capabilities required to meet an objective. The capabilities will emerge when constituents systems function in an integrated manner to deliver an effect, which cannot be obtained by the working of individual systems. In order to build up the capabilities, the SoS architect will need to understand the context which the SoS is required to perform a role, the relationships between constituent systems of the SoS, their interdependencies and how the functionality of constituent systems contribute to the fulfillment of the SoS objectives. The capabilities needs and inputs by stakeholders will form the basis of the goals of the SoS design. Metrics should be formulated to measure the performance of the SoS in order to gauge whether the capability needs are fulfilled. Once this is achieved, the SoS concept and architecture will be mapped out. Base on the System Engineering Guide for Systems of Systems, Version 1.0 (2008), the "architecture must address the concept of operations and encompasses the functions, relationships, and dependencies of constituent systems, both internal and external. This includes end to end functionality and data flow as well as communications". Lastly, MATE and Epoch-Era Analysis are possible methods that the SoS architects can use to select an SoS architecture based on value robustness considerations. A detailed discussion about value robustness of SoS will be presented via a case study in Chapter 6.

4.9 Summary

An approach to architect a value robust system or SoS has been proposed in Chapter 4. A typical architecting process begins with concept generation and synthesis, followed by concept screening and selection. The proposed method used for concept generation and synthesis is the "Needs to Architecture" framework, while the methods proposed for concept screening and selection is MATE. Epoch-Era Analysis is used to anticipate changes that impact the system or SoS in future. The analysis will complement MATE to select a value robust system or SoS. The proposed value robustness approach to system architecting will be demonstrated in Chapter 5. Subsequently, the Epoch-Era Analysis will be applied to an Acknowledged Army SoS to facilitate the value robustness discussion of the SoS in Chapter 6.

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Chapter 5 Case Study: Value Robustness of ISR System

5.1 Introduction

“Know the enemy and know yourself; in a hundred battles you will never be in peril.”

- Art of War, Sun Tzu.

Information confers a strategic advantage to armed forces. The ability to spot the adversary’s movement in the battlefield is critical and is an important capability in all war-fighting operations. This capability allows the field commanders to have the time and space to orient their forces to the adversary’s location, decide the next course of action to counter the adversary’s intent and possibly engage the adversary faster than what they can do with their own forces. It also implies that the safety of own forces is enhanced because they will not be surprised by the enemy’s initiatives and will be better prepared for the impending battle. Today, the ability to obtain intelligence information is even more valuable and is seen as a key enabler to defeat an adversary in an increasingly, networked defense operational context. In addition, it can be used to expand the territorial reach of the forces. With the intelligence information about an unoccupied area, an armed force can use its weapon systems (e.g. precision strike weapons) to secure and guard the place, without having to deploy any soldiers to that monitored location. As such, there is tremendous value in acquiring and developing Intelligence, Surveillance and Reconnaissance (ISR) systems to fulfill the need for information. The attractiveness of this key advantage has led many armed forces in the world in recent years to focus their resources on the acquisition and development of technologies, which help them to acquire this capability. Many armed forces have acquired ISR systems to be used at the strategic level of operation. However, there is also an increasing demand pull from the ground troops of smaller sized infantry force, for example a battalion, operating in a tactical level mission. For example, it has been identified that one of the key needs of the US's Infantry Brigade Combat Team is field capabilities that can enhance their "lower level unit ISR" (U.S. Army, 2009c). In view of this interest, the author finds it beneficial to use the selection of an ISR system for ground troops in the battalion-level size infantry force, as a case study to be discussed in this chapter.

The objective of the case study is to demonstrate the usefulness of the proposed approach described in Chapter 4 to select a value robust ISR system for the stakeholders in a defense context. As it is not the author's goal to optimize the system but rather to showcase the general value robustness approach, a low fidelity model is used.

5.2 Application of Needs to Architecture Framework

5.2.1 Identification of Needs and Stakeholders

The first step towards architecting a value robust system is to identify the overall need for the system and the stakeholders associated with the need. In this case study, there is a need to provide an ISR system to ground troops of a battalion-sized force. The author will serve as a system architect in this demonstration case study. First, the system architect has to perform a first pass analysis of the stakeholders' landscape and needs. Table 5-1 shows an example of the value related questions that the architect can ask and the response as shown.

Table 5-1: Value Related Questions of ISR system

Value-Related Questions	Response
Who is the direct beneficiary[7]?	Ground troops of battalion-sized infantry force
What is the need?	Intelligence information
What is the value related operand[8]?	Information of intended target
What is the value related attribute or the operand?	Real time, accurate, on-demand
What is the solution neutral process?	Obtaining information of intended target

Once the first pass analysis is mapped out, the architect can dwell further into the detailed needs of the end users or direct beneficiaries of an ISR system through interviews, focus groups and observing the end users in operation (Ulrich and Eppinger, 2008). Other sources of information through which the architect can identify and elicit needs include end user's strategic plans and market surveys. Empathic discovery through observing end users at work can help to uncover latent needs.

In the case of the ISR system for ground troops, the primary benefit to the beneficiaries is to have enhanced situation awareness of what is beyond the obstacle or terrain in front of own troops, or to check for suspicious items (e.g. roadside bombs). Other secondary benefits include (1) enhanced safety of the troops, whereby the troops

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[7] It refers to a specific type of stakeholder who receives benefit through the use of the system.

[8] Crawley (2009a) defined an operand as "an object which is acted on or transformed".

are able to know whether there are enemy forces hiding beyond the obstacles without sending troops near the danger areas and endangering the soldiers' lives, (2) enhanced planning by headquarter commanders (i.e., the updated enemy picture allows commanders to understand the frontline enemy situation and facilitates better planning to deal and shape the fluid battlefield situation) (3) boosted confidence in own soldiers (i.e., confidence and morale will be high if soldiers know what to expect beyond their position and can strategize how to tackle them and (4) identified enemy targets for fighter jets and attack helicopter pilots (i.e., the intelligence information can be relayed to the pilots to assist them in destroying the targets as well as assessing the effectiveness of the missile strikes).

Figure 5-1 shows a snapshot of the possible stakeholders. This list of stakeholders and needs forms the first pass stakeholder analysis.

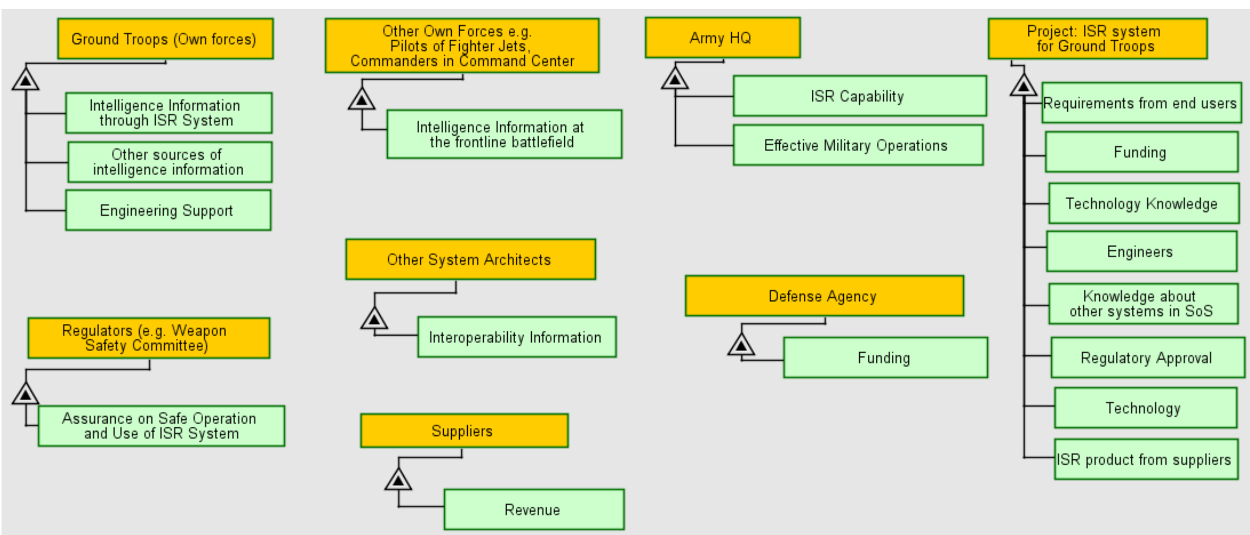

Figure 5-1: ISR Stakeholders and Their High Level Needs

5.2.2 Value Exchange

The next step is to think about how value will be exchanged between the stakeholders involved in the acquisition and development of the ISR system, which is defined as a project in this value map. Figure 5-2 shows a system view of how value will flow among the ISR stakeholders.

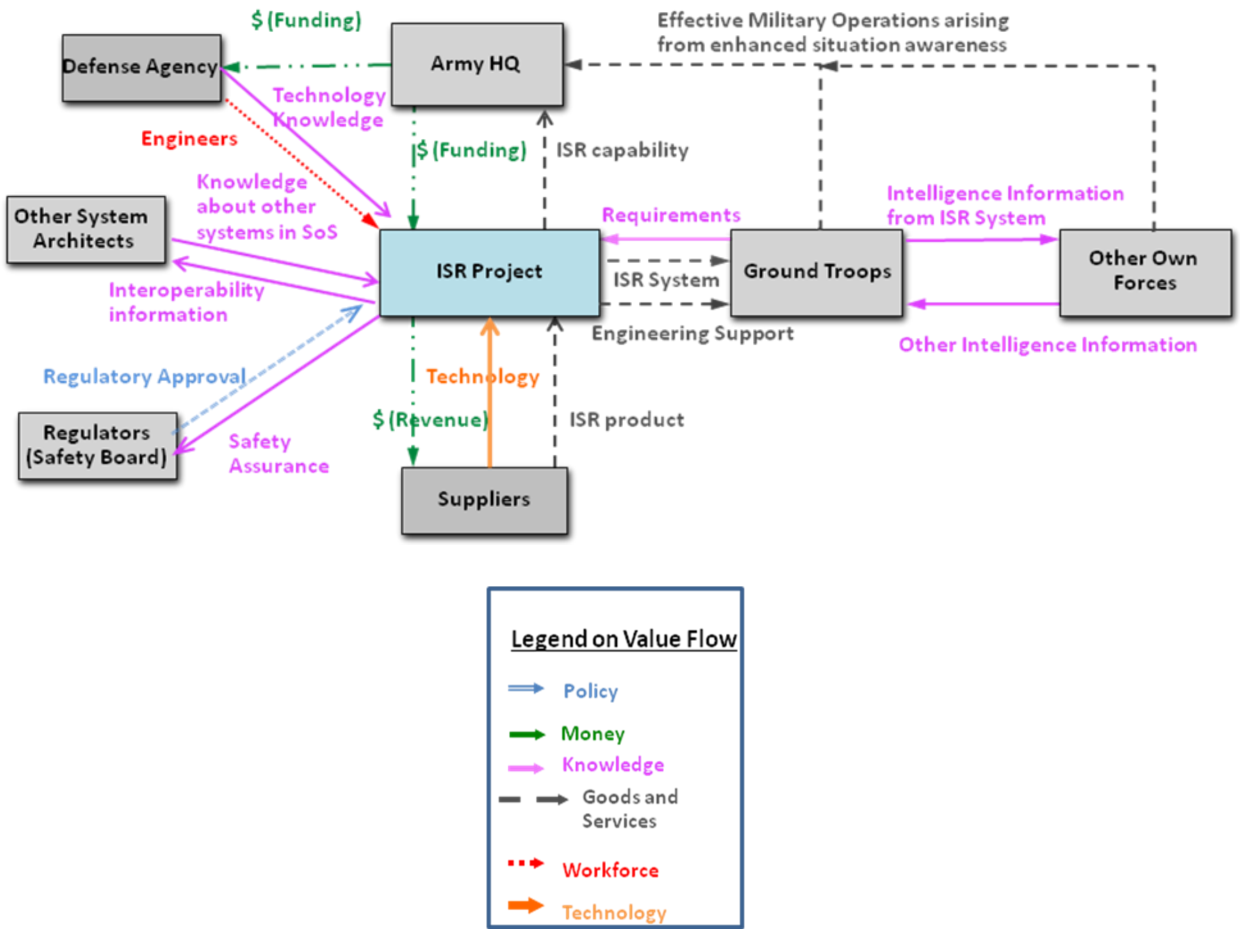

Figure 5-2: A Value Flow Map of the ISR System

A value flow map provides a framework to assess stakeholders' needs and how each stakeholder can benefit from flows in the value chain. Figure 5-2 shows that the acquisition and development of an ISR system for ground troops requires funding from the Army HQ to perform the project. In return, the project will provide a capability and technological edge to the Army HQ, which allows it to develop a variety of war-strategies. Similarly, the ISR project will provide pay its suppliers for their ISR technologies and products. These may include suitable Electro-Optics (EO) and Infra-Red (IR) sensors as well as the ISR platform. The ground troops are the primary beneficiaries of the system and the engineering support that they receive from the project. To allow the system architect to acquire and design a right product for the ground troops, the ground troops have to feedback the requirements based on operational needs. A useful ISR system allows the troops to know where their potential adversaries are, provides good situation awareness, and can be used for force protection. They return value to the Army HQ by executing effective combat operations by using the intelligence information from the ISR system to spot adversaries' intent and act on them. The ground troops can also relay this information to other troops, for example the Brigade/Division Mobile Command Posts. The commanders in the Mobile Command Posts are able to collate all sensors information to form a comprehensive situational picture in the Area of Operation and can make decisions to shape the battle operations. This information will be disseminated to forces that require them for a variety of operations. One example is the relay of targeting information to the "shooters" (e.g. the artillery units and pilots of fighter jets) to bomb specific targets to destroy the adversary. Inevitably, this is tantamount to an effective military operation to carry out the intent of the Army HQ in the event of war.

In addition, engineers and technical knowledge from the Defense Agency are required to develop a good ISR system. The system architect will also need the support from other architects to provide information of other systems working in tandem with the ISR system in a SoS context. The architect has to understand how the intelligence information can be relayed from the ISR system to the Command Posts. Information about interface ports is required by the architect so that the ISR system can be interoperable with the rest of the systems in the Army SoS. Lastly, high leverage stakeholders have the greatest control over the development of an ISR system. For example, regulators, such as the Platform Safety Committee, have tremendous power to determine if the system is safe and can be introduced into field operations. The ISR system must be certified as safe before it can be used by the troops for their operations.

According to Rebentisch et al. (2005), the value delivery system and its mapping are critical in providing an understanding of the relationship between the stakeholders in the enterprise. However, a prioritization of the needs will need to be done because it is often impossible to fulfill all stakeholder needs. As such, Rebentisch et al. (2005) presented a way of prioritization, which involves determining the “Impact” of a need to the objectives and success of the project. To do so, the value flows, or benefits, are categorized into “must have”, “should have” and “might have” to provide an assessment of the impact of a given benefit on the overall project success, which is to develop a right system for the stakeholders. The most important, or cardinal requirements should be the “must have” value streams, followed by “should have” and lastly “might have”. Figure 5-3 shows the intensity of the benefits for the system.

5.2.3 Needs Characterization: Intensity of Benefits

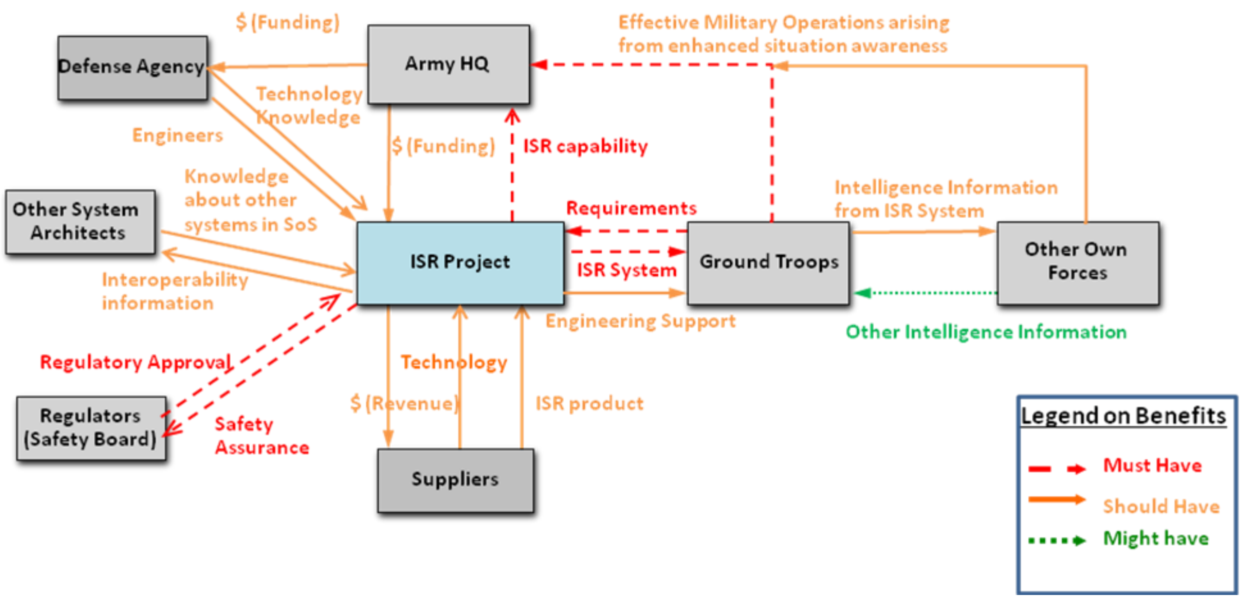

Figure 5-3: Intensity of Benefits

The mapping in Figure 5-3 shows by importance that the ground troops must have an ISR system. The Army HQ will strongly need the capability and the enhanced military operations, while the regulators must require the safety assurance from the ISR project team that the system is safe for use. This mapping helps to identify the values of the stakeholders, (i.e. whether or not the need is a “must have”) and the impact of satisfying a need to the success of the project. In doing so, the needs can be prioritized.

5.2.4 Goals:

Once the needs are identified and prioritized, the next step is to identify the System Problem Statement (SPS) and the goals of the ISR system. The SPS serves to highlight the intent of the ISR system development and is formulated as below:

SPS: To obtain reliably on-demand, real time and accurate intelligence information of the intended target by:

- transporting the sensor payload to the intended location using ISR platforms,
- gathering/surveying clear and seamless videos and photographs of intended target using sensor payload,

  AND

- disseminating the videos and photographs of the intended target to own forces.

Next, the goals of the ISR system are inferred from the SPS and the value flow map in Figure 5-2. Table 5-2 shows the descriptive goals of the ISR system. The goals should be classified as “critical”, “important” and “desirable”. These goals are inferred from the intensity of needs where the needs are classified as “must have”, “should have” and “might have”.

Table 5-2: Descriptive Goals of ISR System

Descriptive Goals • Technical performance of the ISR system for ground troops, for example: - Able to obtain on demand, real time intelligence information - Clear videos and pictures of surveyed object or area - Short time to set up and deploy for operations - Sufficient mission time - Wide coverage • Provide safety to the ground troops • Safe operation of ISR system • High Technology Readiness Level (TRL) • Cost effective system • Engineering support • Capability development • Effective military operations - "See first, Understand more, Decide fast and Act first" • Interoperability with other Army systems • Knowledge sharing

5.2.5 Concept Generation

Table 5-3 and Figure 5-4 shows all the possible high level concepts for the ISR system. This particular case example focuses on the different architecture of the platforms for demonstration purposes. Based on creative brainstorming, the author has generated 5 types of platforms for the ISR system. These types are air platform, land platform, human, naval platform, and space platform.

Table 5-3: Different Platform Concepts

Specific Operand	Solution Neutral Process	Specific Process	Specialized Instruments Objects	Specific Operand	Specific Process	Specific Objects
Sensor Payload	Transporting	Flying	Air Platform (e.g. planes)	Videos, Photos	Surveying	EO/IR Sensors
		Rolling	Land Platform (e.g. wheeled vehicles)			
		Walking	Human (e.g. scouts)			
		Guiding	Naval Platform (e.g. boats)			
		Orbiting	Space Platform (e.g. Reconnaissance satellite)			

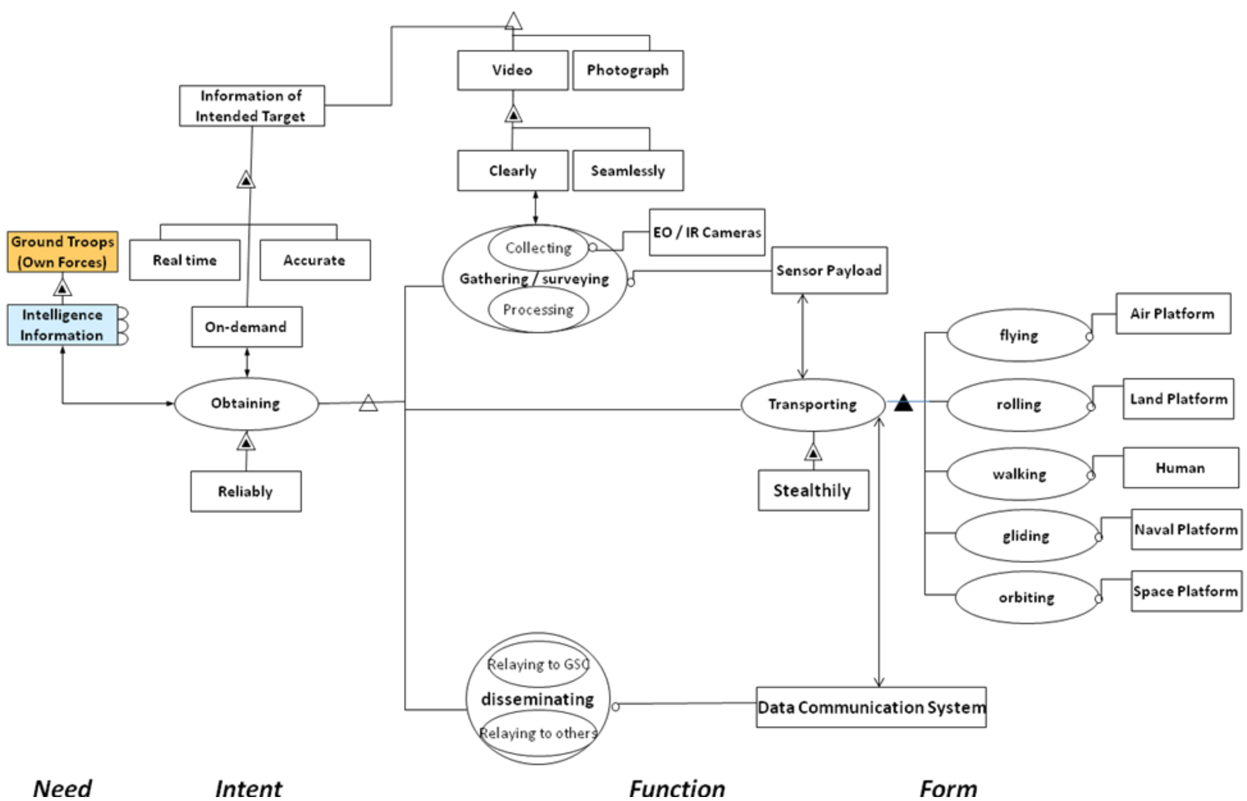

Figure 5-4: High Level Concepts of the ISR system

In order to propose the various concepts, the sources of creativity come from techniques called “evolution”, “reuse” and “pattern matching” (Crawley, 2009c). First, in terms of the platforms, the architect could think about the different types of platforms used to carry the sensor payload to the location of interest. It includes air, land, naval manned and unmanned platforms. There are two types of aircrafts for the unmanned aerial platforms. One is the fixed wing type platform, and the other is the rotary blade, Vertical Take-Off & Landing (VTOL) type. The “evolution” is from traditional manned platforms to unmanned platforms. The VTOL architecture concept also evolves from traditional fixed wing aircraft concept. The evolution can also be envisaged in terms of miniaturizing the platforms (i.e. the size of the platforms can vary from the large, strategic version to the miniaturized, tactical version). Similarly, using the “reuse” creativity technique, the human scouts can also serve as the “eyes” of the infantry ground troop to sense the enemy situation. Lastly, using the “pattern matching” creative technique, the ISR system can be a reconnaissance satellite in the realms of space.

Once the ideas are expanded to incorporate numerous possibilities, they have to be pruned by comparing to the goals. This is done in order to eliminate any infeasible solutions and prevent cluttering the subsequent tradespace analysis with solutions that cannot be implemented. The pruning is as follows:

a. <u>Mission Context</u>. As the goal is to acquire an ISR system for ground troops for ground operations, the sea platforms for carrying the sensor payloads are eliminated. The manned and unmanned, strategic and mini-water based vehicles are not considered in this selection process. While ground troops do at times perform coastal operations and may require ISR capabilities, it is argued that such operations will not be a dominant part of the land campaign and the resources can be shared with the Navy during inter-service joint operations.

b. Safety for Soldiers. One of the motivations for the ISR system stems from the need to enhance safety/reduce risk for the soldiers. As such, using soldiers as scouts to sense possible enemy locations exposes them to the risk of possible surprise ambush. As such, using soldiers, while very cost effective, does not meet the requirement of safety to the soldier.

c. Technology Readiness Level. Space ISR systems are highly classified and the technology is owned by the superpowers of the world. The technology is not available to most armies and it is not used for local operations. It is typically used for strategic-level reconnaissance. As such, for this study, space satellites are eliminated during concept pruning.

After the high level pruning process, two high level concepts remain: flying air platform system and rolling land chassis platform to survey the intended target/location remain. An option tree is created in Figure 5-5 to examine if there are any further infeasible solutions.

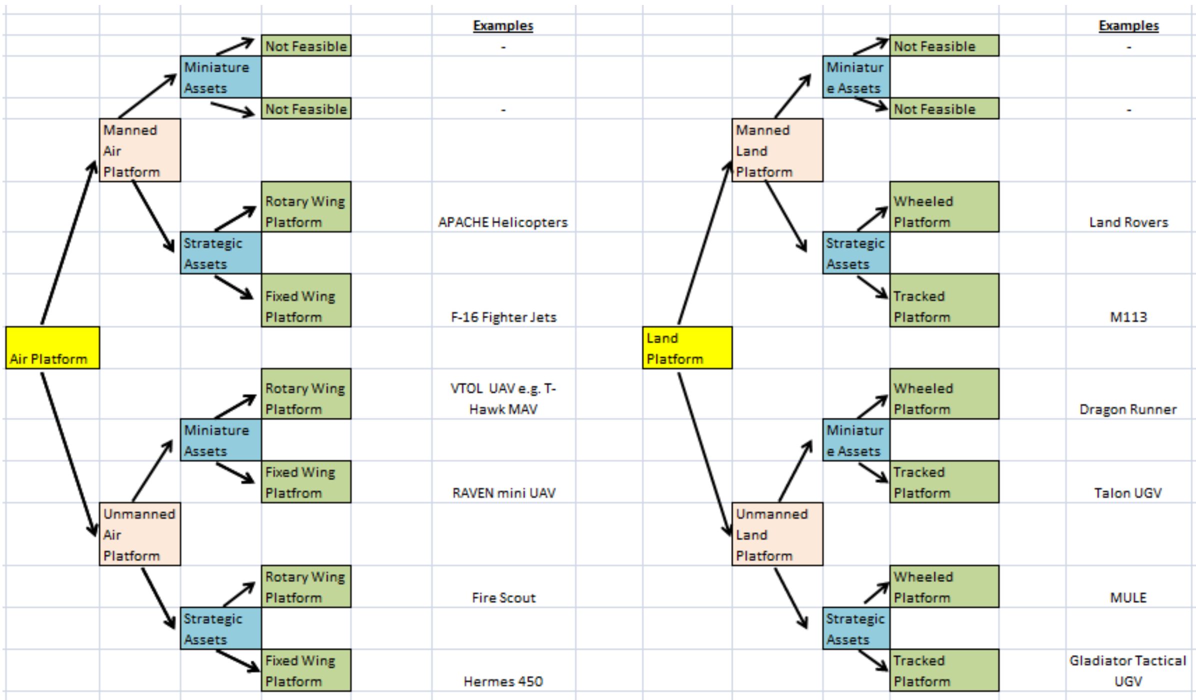

Figure 5-5: Concept Tree of ISR System Concepts

The analysis showed that there are several infeasible solutions. Some of the options in the tree do not make sense. For example, it is not possible to have a manned, miniaturized air platform or land system due to physical constraints in the platform (i.e. the operator cannot be physically within the miniaturized platform). After this, concepts are further pruned by referring to the descriptive goals and System Problem Statement to check for consistency. The checks are as follows:

a. The SPS states that information has to be made available to the ground troops on demand. As such, strategic land platform assets cannot be used. During infantry troop movement, the manned and unmanned, wheeled and tracked platform such as MULE and Gladiator Tactical UGV cannot follow the troops on a foot mission. This is especially made more difficult in tropical terrains where troops have to embark on off-road movement into the jungles. As such, strategic level - land platforms are not feasible for ISR system for battalion force infantry troops.

b. The mini-unmanned, land platform is suitable as an ISR system and is able to stay stationary to survey an object (e.g. survey a junction or move over the hill). Since localized surveillance of a target area does not involve a long distance (usually over the hill or road junction or building), the mini-land platforms have the necessary range to meet the goal of the system. As studies are inconclusive regarding whether the wheeled or tracked platform performs better, plus the fact that their architecture remains the same, these are not differentiated at the concept level and will be grouped together as a concept.

c. Strategic manned air platforms (e.g. APACHE helicopters and F16 fighter jets), allow large sensor payloads to be integrated with the platform but they are usually used for another purpose such as attack missions. As such, they will not be able to be used in localized surveillance missions. Strategic unmanned platforms such as the FIRE Scout and Hermes 450 are meant for surveillance missions but the use of such assets requires prioritization among different competing needs of the Army. As such, localized surveillance may not be of a high enough strategic value to warrant higher HQ to utilize these assets for the ground troop’s situation awareness. In addition, based on the descriptive goals for value for cost, these strategic-level UAVs are too costly and on-demand intelligence information may not be forthcoming to aid the ground troops on demand, which is a critical goal. As such, strategic unmanned and manned air platforms are not considered.

d. One of the critical goals is to be able to zoom in and survey the object or area. Comparing between the fixed wing and rotary wing, unmanned mini-air platforms, the rotary wing, unmanned mini-air platform (e.g. T-Hawk) has the “hover and stare” capability (Honeywell Defense and Space, 2009). This capability is superior to the fixed wing UAV which may not be able to zoom in on an object for continued surveillance. As such, the rotary wing mini-air platform meets the critical goal.

Careful high level concept generation and pruning leads the architect to two concepts highlighted in Figure 5-6.

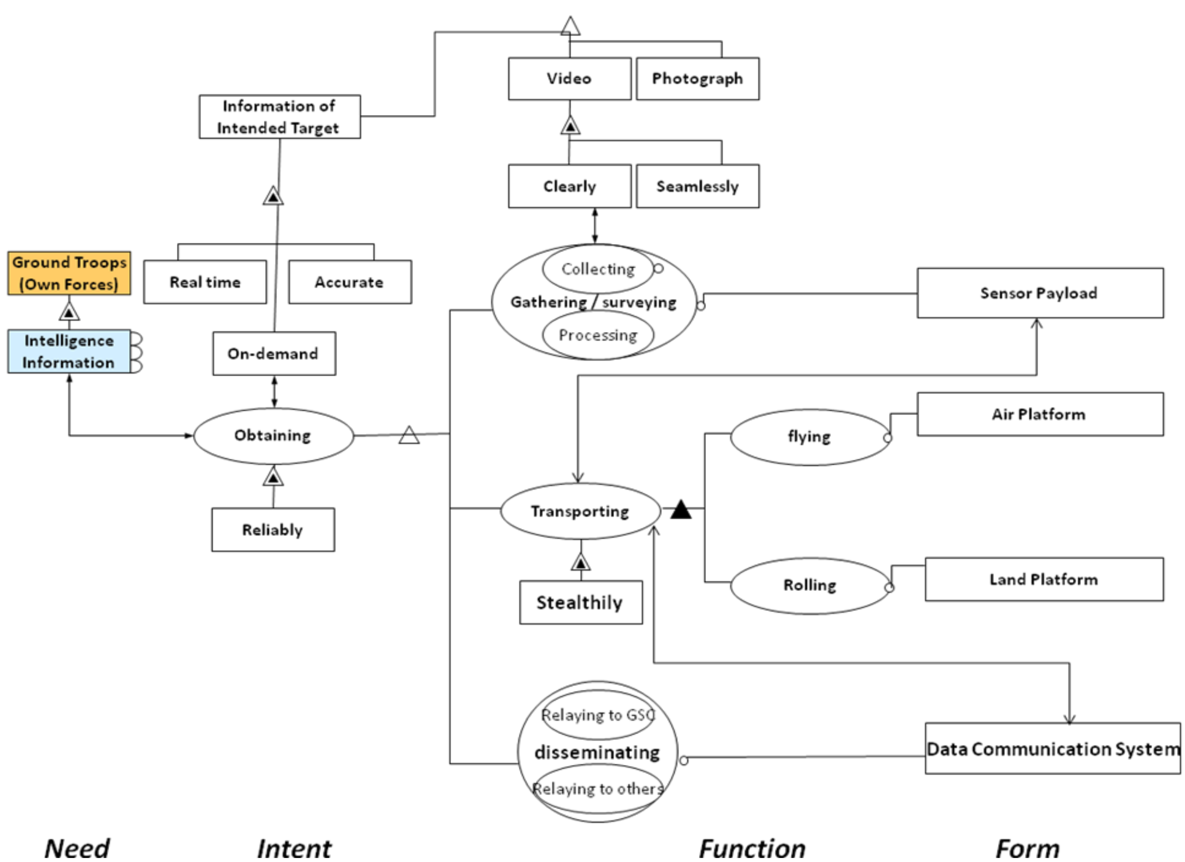

Figure 5-6: Final Two ISR concepts

5.2.6 Architecture Design

Once the concept has been mapped out, the system architect can perform a functional decomposition of the ISR system to map out the primary sub-systems. This allows the system architect to crystallize the design configuration, which can be used to determine the design vector used in the trade-space analysis for concept selection. As an example, Huang (2009) depicted that a fixed wing, micro/mini aerial vehicle may consists of the various subsystem forms as shown in Figure 5-7 (Frank, 2009). Using Huang's Micro Air Vehicle design as a reference, the author performed a general functional decomposition of a possible fixed wing, mini-UAV for illustration purpose.

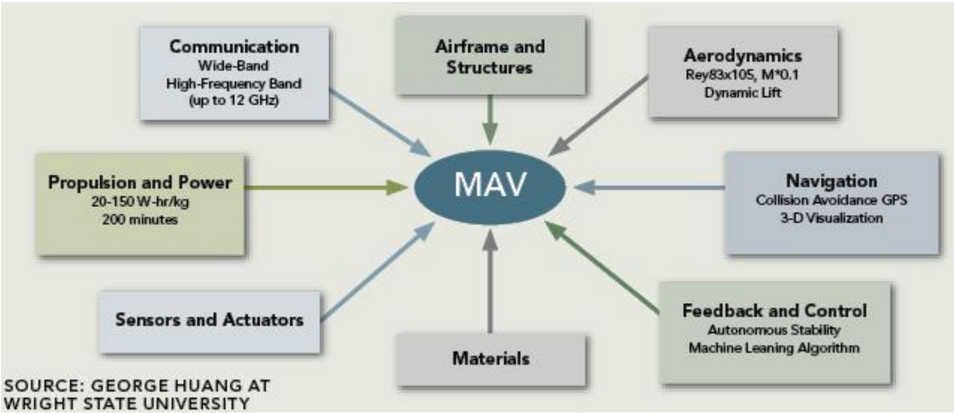

Figure 5-7: Huang (2009)'s Micro Aerial Vehicle (MAV) design[9]

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[9] Huang, G. MAV. Retrieved 26 October, 2009 from http://www.designnews.com/photo/125/125560-Several_interdisciplinary_areas_contribute_to_the_overall_success_of_a_Micro_Air_Vehicle_Specific_details_of_Wright_State.jpg

a. Propulsion System

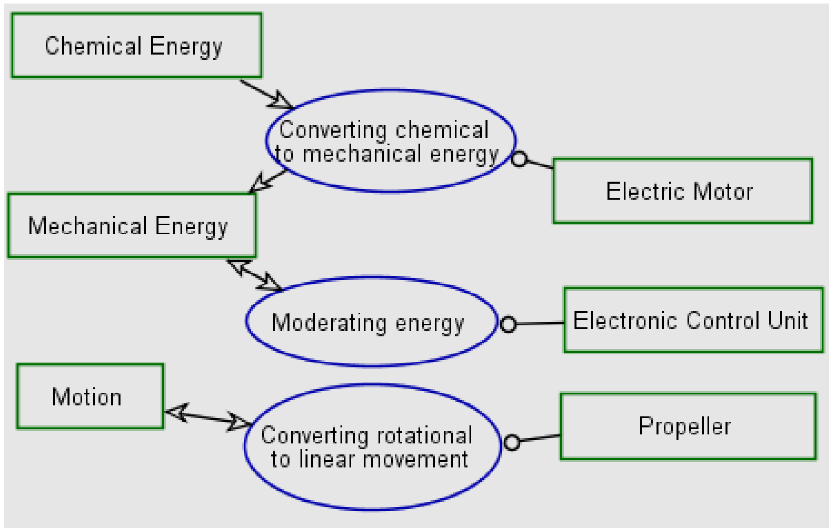


Figure 5-8: Propulsion System of a Fixed Wing Mini-UAV

b. Airframe & Support Structure for Payload

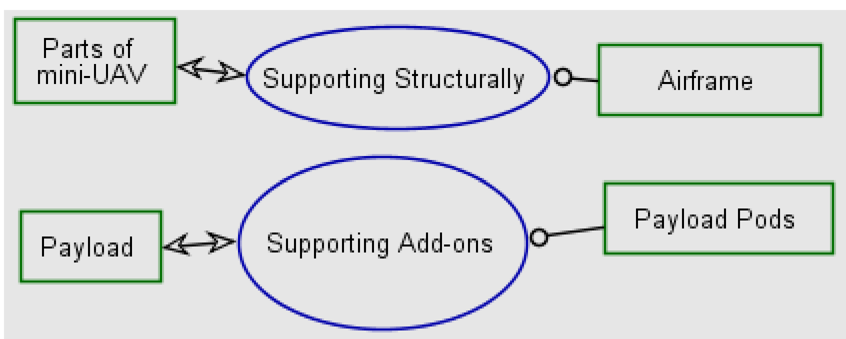


Figure 5-9: Airframe and Support Structure

c. Autopilot System

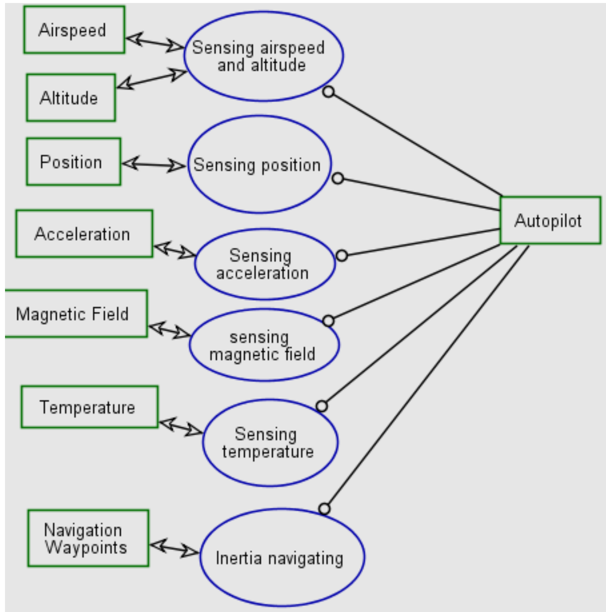


Figure 5-10: Autopilot System (Inferred from Procerous Technologies, 2009)

d. Data-link System

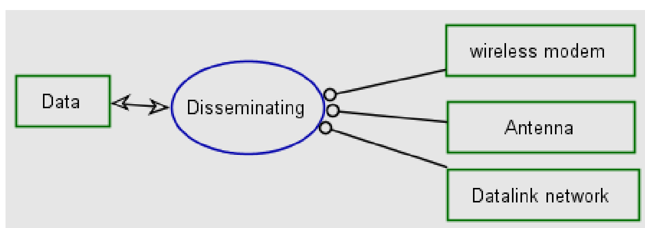


Figure 5-11: Data-link System

e. Payload / Sensor System

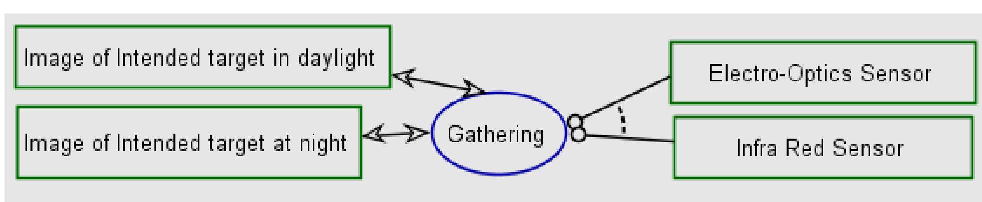


Figure 5-12: Payload / Sensor System

5.3 Concept Screening: Multi Attribute Tradespace Exploration (MATE)

With the establishment of the high level concepts for the ISR system, the system architect can proceed to compare the concepts using the MATE method. Figure 5-13 shows the quick pictorial overview of how the tradespace is constructed. The details are discussed in the following sections.

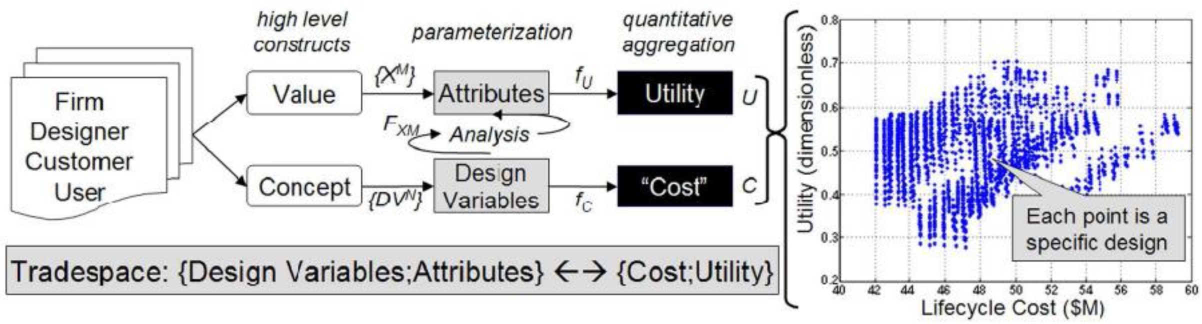


Figure 5-13: MATE Representation (Ross et.al, 2008)

5.3.1 Mission Concept

One of the first tasks of setting up a concept design selection analysis is to define the mission concept. The two important aspects of the mission concept pertain to the mission objective and the Area of Operation. The mission objective will describe the intent and what the stakeholders wish to achieve, while the area of operation describes the use environment of the system. With reference to the author's case study, a generic, global mission statement and the specific mission statement of the ISR system for ground troops are shown in Table 5-4.

Table 5-4: Mission Objectives

Mission	Mission Objectives
Global Mission	To capture Area of Operation within **X** hours with Force Level **Y** with Readiness Condition Level[10] Status **Z**
Local Mission (Specific to ISR System)	To collect reliably on-demand, real time and accurate intelligence information of the intended target by: • transporting the sensor payload to the intended location using miniature unmanned aerial or ground vehicle, • gathering/surveying clear and seamless videos and photographs of intended target using sensor payload, • disseminating the videos and photographs of the intended target to own forces using data transmission system.

Similarly, a broadly defined area of operation will be described for this case study example. The author assessed that the ISR system will be used in a variety of different settings, where a typical Area of Operation includes urban and tropical forest environments. It is envisaged that the infantry ground troops may possibly encounter these terrains within a single mission. The mission needs may require the ISR system to be able to survey over a broad area, for example, over a knoll in a tropical forest area or over a building in a town or city. At the same time, there may be a need to survey suspicious objects which may be within a short range (e.g. one kilometer from the

[10] It provides an indication of the status and level of preparation of a combat unit to be ready for combat missions to realize the intent of the higher command.

operating troops). Figure 5-14 provides an illustration of the type of environments which the ISR system is expected to operate in.

Figure 5-14: Different AOs (Hermans and Decuypere, 2005)

5.3.2 Attributes

The next step involves defining the attributes of the ISR that characterize the type of ISR system to be developed. Hence, the identified primary stakeholders (i.e. the end users) are required to provide inputs of the requirements that are deemed important to them. Ideally, the inputs of actual stakeholders will be sought. As the intent of this case study is to demonstrate the workings of the proposed value robustness approach and not to obtain a precise modeling of the system concept, the role playing technique is used to obtain the stakeholders' input on the mission and needs. Two military officers, namely Stakeholder #1 and Stakeholder #2, who serve in the armed forces and have general knowledge of the combat missions, were asked to assist in the role playing as infantry battalion officers. Their needs, as characterized, in the "Needs to Architecture" framework would be prioritized based on level of importance and their contribution to the success of the system development. A set of "Voice of Customer" (VOC) is shown in Figure 5-15.

One observation about the VOC is that the requirements may appear inconsistent or demanding at first. For example, the end users require a system that can help them to conduct wide area surveillance and close up, point surveillance. However, it may be possible to use the “Needs to Architecture” framework coupled with the tradespace analysis to encourage teams to evaluate various attributes and combine them to develop a new concept which may meet the customer needs. On the other hand, if the users’ requirements are inconsistent and unachievable, the tradespace study can be used to present the various design options and recommend different trades among the attributes for the decision makers and stakeholders to evaluate.

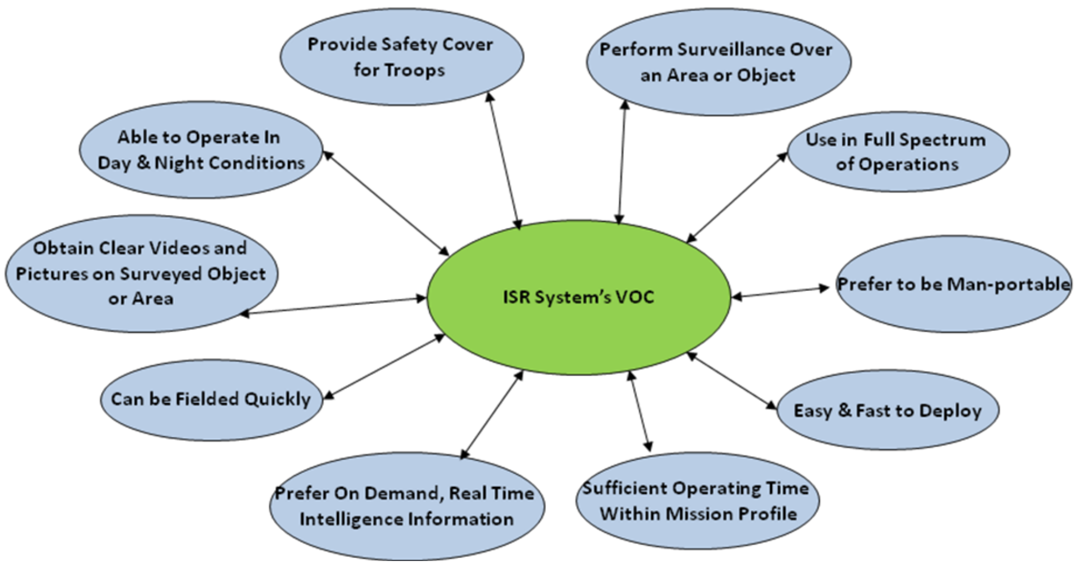


Figure 5-15: VOC pertaining to ISR system

Next, the system’s Engineering Characteristics (EC) or attributes have to be identified. The VOC requirements are described in attributes with quantifiable metrics. These attributes will be divided into two groups of requirements defined by Product Development Systems and Solutions Inc (2009), namely “The New, Unique and Difficult (NUD) attributes” and the “Easy, Common and Ordinary (ECO) attributes”. In the front end concept selection phase, the system architect desires to satisfy the “live or die” and “important” requirements. In order to sharpen the focus of the concept selection process, the “NUD” attributes will be considered by the system architects. The “ECO” attributes are assumed to be easily achievable in all design concepts and will not be factored into the selection process. A 7±2 set of “NUD” attributes may be selected as a guideline. The selected attributes are shown in Figure 5-16.

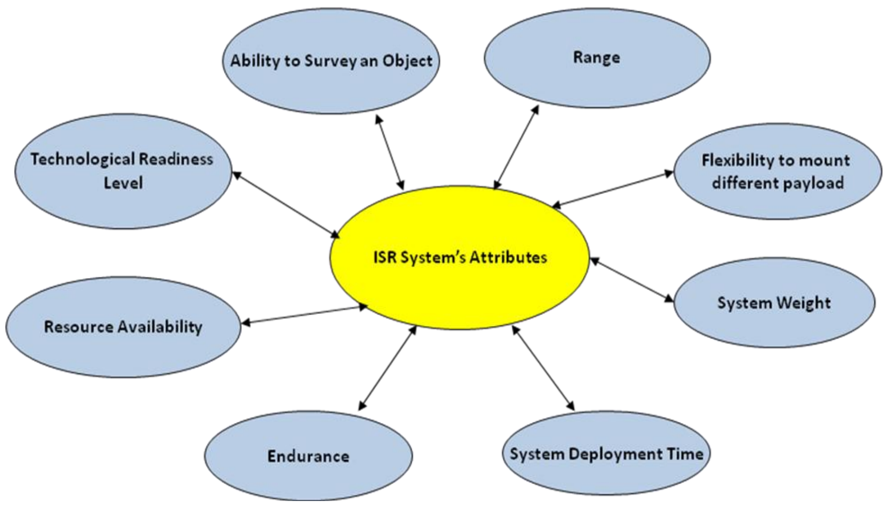


Figure 5-16: Selected Attributes for ISR System

Subsequently, the “House of Quality”, a tool of a management approach (i.e. the Quality Function Deployment) is utilized to map the customers’ needs (i.e. the VOC to the EC or the system’s attributes) of the design concept (Hauser and Clausing, 1988). The purpose of the mapping is to show the strength of the correlation of the EC or attributes to the VOC. In other words, the mapping provides a relative measure of how much the attribute affects the VOC. Once the mapping is done, the House of Quality can be used to provide the relative weights of the EC or attributes (Hauser and Clausing, 1988). Figure 5-17 shows the modified House of Quality that provides the relative normalized weights of each attribute as highlighted in green.

5.3.3 Preference Set of Stakeholders

The value of the system to the stakeholders is measured using utility information. In order to obtain the utility information, the desired attribute range of the stakeholder must be obtained. Figure 5-18 shows the attribute range of one of the two direct beneficiaries with regards to an ISR system used as a surveillance system in war. Figure 5-19 shows the utility curve of Stakeholder #1.

Normalised Weights	Weights by Users	VOC	ECO / NUD	Coverage Range (in km) (+)	Flexibility to mount different cameras payload such as EO or IR cameras (+)	System Weight (-)	Time to deploy (-)	Endurance (minutes) (+)	Resource Availability any time any where (+)	Technology Readiness (+)	Ability to survey an object (+)
				Engineering Characteristics / Attributes							
0.13	5	Able to perform surveillance over an area or object	NUD	9	9	0	0	3	3	9	9
0.10	4	Able to use in full spectrum of operations	NUD	9	3	3	3	3	1	3	9
0.05	2	Prefer to be Manportable	NUD	0	0	9	1	1	9	0	0
0.08	3	Easy to deploy within half an hour	NUD	0	0	3	9	0	3	0	0
0.13	5	Sufficient operating time within a mission profile	NUD	3	0	1	0	9	0	1	0
0.13	5	Prefer On Demand, Real Time Intelligence Information	NUD	0	1	1	3	0	9	3	0
0.08	3	Prefer to be fielded as soon as possible	NUD	0	0	0	0	0	0	9	0
0.13	5	Obtain clear videos and pictures on object of surveillance	ECO	0	9	0	0	0	0	1	3
0.10	4	Able to operate in day and night conditions	ECO	0	9	0	0	0	0	9	3
0.08	3	Provide Safety Cover for soldiers in operation	ECO	3	0	0	0	0	0	0	3
		Relative Weights		2.69	3.67	1.26	1.44	1.90	2.33	3.72	3.00
		Normalised Weights		0.13	0.18	0.06	0.07	0.09	0.12	0.19	0.15

The weights are provided by end user.

How much EC affects VOC

9 – Strong correlation

3 – Medium correlation

1 – Weak correlation

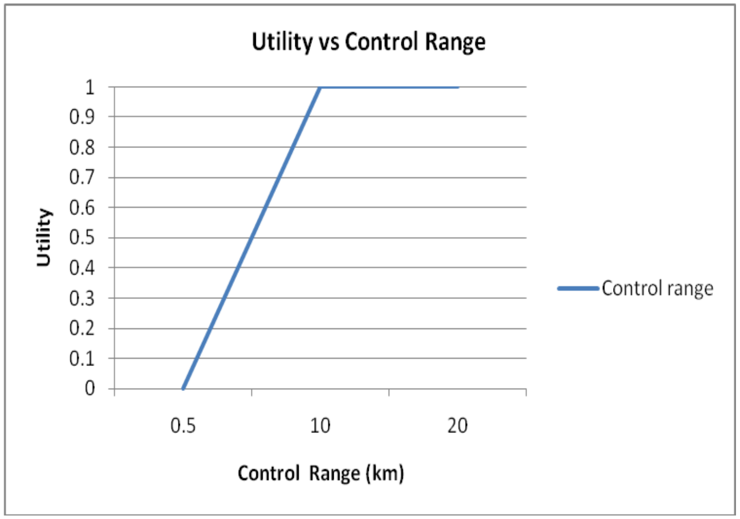
0 – No correlation

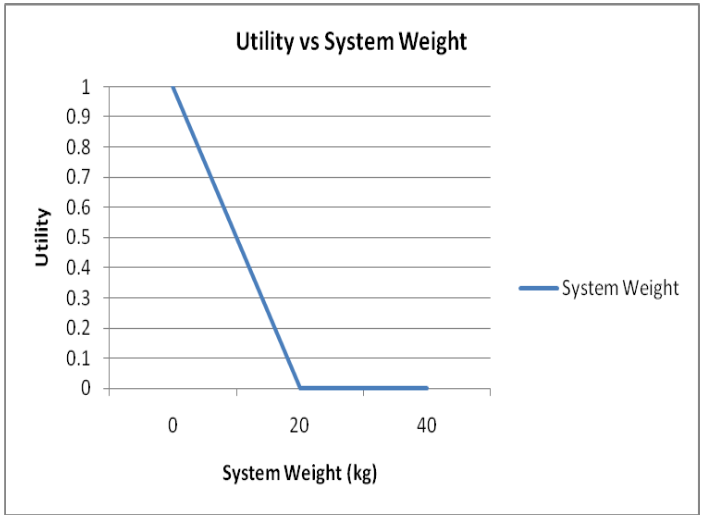
Figure 5-17: Stakeholder #1's House of Quality

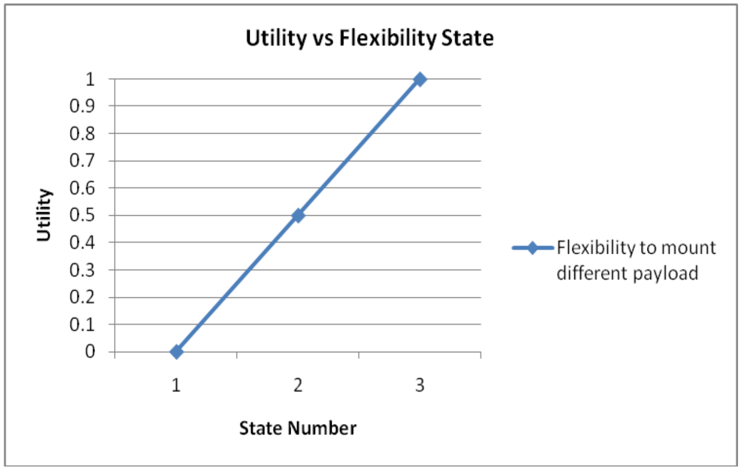
		Stakeholder #1 : Ground Infantry Troop Battalion Commander		
Attributes	**Attributes Units**	**Utility = 0 (Worst)**	**Utility = 1 (Best)**	**Additional Notes About Attributes States**
Control range	km	0.5	10	0.5 - 10
Flexibility to mount payload	dimensionless	State #1	State #3	State #1 = Payload are integrated to the platform State #2 = Modular payload design for 1 set of EO & IR Sensors State #3 = Modular payload design and able to mount additional sensors (more than 1 sensor on the platform at any one time)
System weight	kg	20	0	0 - 20
System deployment time	minutes	State #1	State #2	State #1 = More than 30 minutes State #2 = Less than 30 minutes
Endurance	minutes	30	120	30 - 120
Resource availability at any time required by the ground commander	dimensionless	State #1	State #2	State #1 = No State #2 = Yes
Technology Readiness Level	dimensionless	6	9	6, 7 , 8, 9
Ability to survey an object	dimensionless	State #1	State #4	State #1 - Unable to survey object State #2 - Survey an object from a flying platform State #3 - Survey an object from a stationary ground platform State #4 - Survey an object from a hovering platform

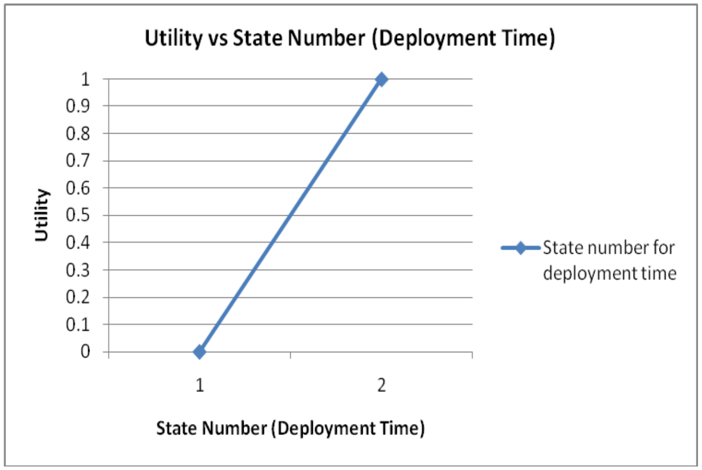
Figure 5-18: Attribute Ranges Preferred by Stakeholder #1

(under mission concept of “surveillance” and operational environment of “war”)


Utility vs Control Range
Utility
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
10
20
Control Range (km)
Control range


Utility vs System Weight
Utility
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
System Weight (kg)
System Weight


Utility vs Flexibility State
Utility
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
State Number
Flexibility to mount different payload


Utility vs State Number (Deployment Time)
Utility
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
State Number (Deployment Time)
State number for deployment time

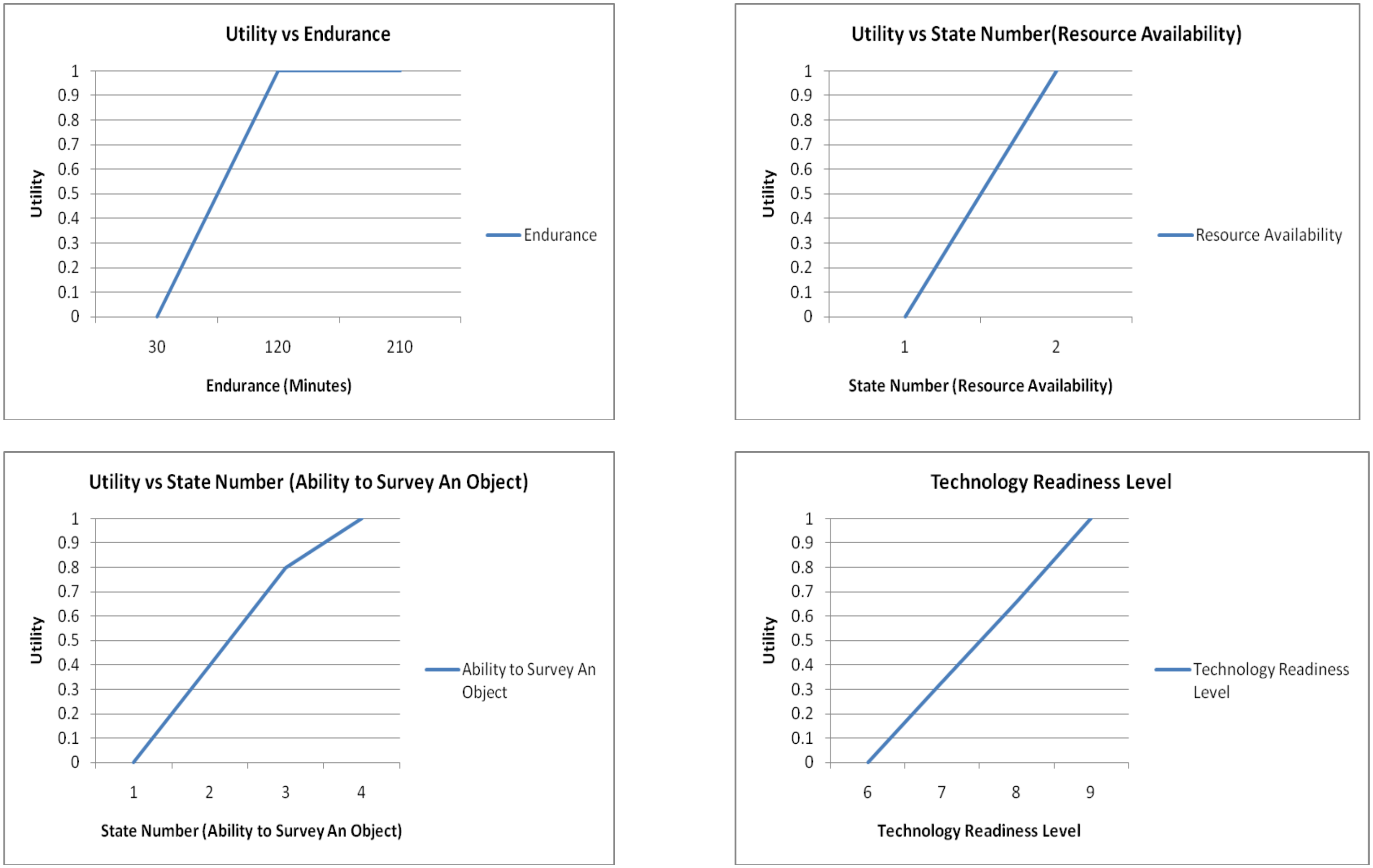


Figure 5-19: Utility Curves of Attributes

The brief descriptions of all the attributes are provided below:

5.3.3.1 Control Range

The control range represents the reach of the ISR system. For example, a mini UAV model, RAVEN, has a control range of ten kilometers. It means that ground troops can deploy RAVEN and use it to survey the area within ten kilometers of the ground control station.

5.3.3.2 Flexibility to mount payloads

Three states of flexibility are described in Figure 5-18. State #1 means that the payloads are integrated with the platform. State #2 has a modular payload design. For example, the Electro-Optic (EO) sensor can be detached from the platform and another Infra-Red (IR) sensor can be fixed onto the platform for operations. State #3 means that the platform has additional payload capacity to mount at least two modular sensors concurrently in operation. It can also mean that there is an additional payload slot to mount another type of sensor, other than the camera, to perform other sensing operations.

5.3.3.3 System Weight

The system weight consists of the laden ISR platform and all accessories. For example, the system weight of a mini-UAV system will mainly comprise the aerial platform and the ground control station.

5.3.3.4 Time to Deploy

The time to deploy is the time taken to set up the system for operation in the field.

5.3.3.5 Endurance

Endurance refers to the maximum length of time that the ISR system remains in operation until its power supply is used up. Endurance is limited by the capacities of the onboard batteries or fuel capacity of the platform.

5.3.3.6 Resource Availability

There are two states of resource availability. State #1 refers to a situation where the ground troops do not have the ISR system and its on-demand request for intelligence information may not be fulfilled all the time. State #2 refers to the situation where the ground troops have the ISR system and they can obtain on-demand intelligence information as and when they require it.

5.3.3.7 Technology Readiness Level (TRL)

TRL measures the state of technology readiness of the system. It is adapted from National Aeronautics and Science Administration (NASA) and consists of nine levels. A technology with TRL 9 means that the system is proven to function, has undergone system tests and development successfully, while TRL 1 means that the system is still in basic technology research state. TRL 6 means that the system is in sub-system development or late technology demonstration stage.

5.3.3.8 <u>Ability to survey an object</u>

This refers to the ISR system's ability to survey an object, which relates to the fundamental need of scrutinizing a specific point and study it closely for a period of time. This attribute is useful to help soldiers inspect suspicious objects (e.g. concealed bomb). Stakeholder #1 establishes four states to infer the quality of the surveillance photos and hence his level of satisfaction. State #1 means that the ISR system cannot perform point surveillance. State #2 means that the surveillance is obtained from a flying platform. The object is surveyed by circling past the object in the air from a height. State #3 and #4 means that the surveillance information is obtained from a stationary land platform and hovering platform respectively.

5.3.4 <u>Utility Function</u>

As mentioned in Chapter 4, a utility function is required to aggregate the utility of the attributes. Multi-attribute utility theory can be used to formulate a utility function. However, one simple and quick method to elicit stakeholders' preferences is to utilize the additive independence rule where all the utilities are added up as shown in Equation 5.1.

$$U(\underline{X}) = \sum k_i \, u(x_i) \quad \text{for} \quad 1 \leq i \leq N \qquad (5.1)$$

Where $0 \leq k_i \leq 1$

$\sum k_i = 1$ where $1 \leq i \leq N$

$0 \leq u(x_i) \leq 1$

$\underline{X}$ represents the ISR system and x refers to the attribute of $\underline{X}$. k_i is the normalized relative weight of the attribute i as obtained in the House of Quality[11] in Figure 5.17. $u(x_i)$ are the utility of attribute i while $U(\underline{X})$ is the multi-attribute utility of ISR system.

There should not be any interaction or dependency among the attributes in order to make use of Equation 5.1. However, it can be used as a good, first cut assessment. Clemen (1996) mentioned that "even if used only as an approximation, the additive utility function takes us a long way towards understanding our preferences and resolving a difficult situation." As such, even though some of the attributes may be dependent upon one another, such as system weight, control range and endurance, it is still possible to utilize the additive attribute function to provide a first cut approximation of the utility of the different ISR concepts in the tradespace. Note that the attributes of system weight, control range and endurance are usually cardinal, yet coupled requirements of a system, where changes in one attribute usually affects another attribute.

The additive, independence utility function will be favored by Project Management Teams because it is easy to implement and provides valuable information

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[11] The Multi-Attribute Utility Theory is presented in Chapter 4. The Multi Attribute Utility Theory is a more rigorous approach as compared to the quick method used in Chapter 5 because the Multi-Attribute Utility Function can be multiplicative instead of additive. The swing weights method illustrated in Chapter 4 can also be used to elicit the attributes weights. When the swing weights are used, all the attribute weights do not need to add up to 1.

about the relative preference among the attributes. Decision makers will also be able to understand the method and the thinking behind the concept selection easily.

On the other hand, care must be exercised in using the utility function utilizing the additive independence rule. The author notes that the utility function consists of many single attributes, which may consist of cardinal requirements of the system. By aggregating the utility of the single attribute into a multi-attribute utility function, there may be a possibility that a concept, which does not perform well in a cardinal requirement but perform well in other requirements, will provide stakeholders with a misleading perception that they derive high utility from the use of the concept. As such, the utility value derived from the utility function might draw away focus on the concept's ability to fulfill cardinal requirements deemed critical to the success of meeting stakeholders' need. This limitation is a tradeoff against a quick method to elicit first cut estimation of stakeholders' preferences. This limitation will be mitigated if a more rigorous implementation of MAUT using the Keeney and Raiffa (1993) multi-attribute utility function in Equation 4.5 is used. Future work utilizing the multi-attribute utility function is proposed and will not be discussed in this thesis.

5.3.5 Design Vector

The design vector comprises design variables that completely characterize a concept in the model. In the first pass model, the system architect can utilize information from the concepts developed using the "Needs to Architecture" framework to determine a design vector for the ISR system for ground troops. Realistically, each concept with a different architecture may have different design vectors (i.e. different type and/or number of variables). Some possible design variables of the ISR system include the type of platform, air propulsion system or power pack, control system within platform, autopilot system (if applicable), ground control station, data communication system, payload type, platform launch mechanism and number of assets. The design variables will have a range of possible values. Different permutations of the values of the variables will produce different concepts. Different concepts will have different estimated costs.

While the above method is useful to a system designer, the method can also be adapted for system architects, who serve in an acquisition manager capacity. The architects or managers in this type of organization acquire and customize established systems that are available in the market. They also ensure that the customized systems are interoperable with other weapon systems in a defense SoS context. As such, they require an easy to use concept selection method to assist them to evaluate customized proven weapon systems. Thus the tradespace exploration method is adapted to meet the needs of the acquisition managers and is demonstrated in the following sections.

A single design variable termed "configuration" will serve to describe the architecture concepts. In the case example of the ISR system, there are three principal platform architecture concepts as shown in the "Needs to Architecture" Framework. They are as follows:

i. Miniature Unmanned Aerial Vehicle (fixed wing)
ii. Miniature Unmanned Aerial Vehicle (Vertical Take-Off and Landing) (VTOL)
iii. Miniature Unmanned Ground Vehicles

A total of 6 miniature UAV (fixed wing), 2 miniature UAV (VTOL) and 5 miniature UGV systems were selected for the evaluation. Ideally, the tradespace should involve as many systems as reasonable. However, many defense companies would not typically share their price data as well as strategic, competitive technical information openly in the public domain. In fact, price information on defense products was extremely difficult to obtain. Most of these proprietary cost estimates could only be obtained through formal “Request for Information” contract protocol or in-depth negotiation with the defense companies. Moreover, the price of each system might differ for different customers because there were many other considerations in place, such as configuration differences, pricing strategy in certain markets and offset discount arrangement. For the purpose of the case study demonstration, the system cost information was obtained primarily from purchased defense consultancy reports from TEAL Group Corporation, market survey information, public domain contract information as well as open source information from the World Wide Web.

A second possible design variable is the quantity of the assets required to perform the job. Based on different attributes, certain architectural designs require more assets to perform the same task in a mission. Additional assets will invariably affect the acquisition cost of the system but it may provide more utility to the stakeholder in other aspects of the attributes. However, the number of assets in the design variable will remain as one for each design concept in this ISR case study to simplify the demonstration of the proposed value robustness approach.

In summary, the design vector used in the ISR case study is as follows:

$$Design\ Vector = \begin{bmatrix} Design\ Configuration \\ Quantity\ of\ Assets \end{bmatrix}$$

The design configuration describes a system concept completely. Note that different architecture concepts can have different design configuration because the characterization of each concept will be different. The ISR case study example assumes that the following design configuration completely describes all the concepts in consideration.

$$Design\ Configuration = \begin{bmatrix} Platform\ Type \\ Data\ Link\ System \\ Payload\ Pod\ Design \\ Propulsion\ System \\ Power\ System\ \&\ Capacity \\ Navigation\ System \\ Launch\ and\ Recovery\ Method \\ Payload\ (Sensors) \\ Ground\ Control\ Station \end{bmatrix}$$

Each design vector has an associated system life cycle cost. In the ISR example, the author assumes that the ISR system should fulfill user's mission needs for five years. As such, the system life cycle cost will comprise the system acquisition cost in the first year and maintenance cost for the next four years. Based on historical data from past projects and assessment of the past projects, the annual maintenance cost is estimated at 8% of the system acquisition cost. The Net Present Value method is used to compute the system life cycle costs of each design alternative.

5.3.6 Tradespace Analysis & ISR System Design Choices

Figure 5-20 shows the designs of the ISR system for consideration. The list of systems is not exhaustive. However, due to limitation on the available cost and design data, the research will use thirteen ISR system designs as shown in Figure 5-20 for the tradespace analysis demonstration.

The design vector will determine the technical performances of the ISR systems. As the ISR systems are Commercial-Off-The-Shelf (COTS) systems, the systems' technical performance can be obtained through their product brochures. The performance of the system is mapped to the attributes to elicit the single attribute utilities to the stakeholder. The overall multi-attribute utility of the system can be calculated by substituting the single attribute utilities and attribute weights into Equation 5.1. An example of the calculations is performed using the RAVEN RQ 11-B mini-UAV.

$$\textit{System Performance} \Rightarrow \textit{Utilities of Stakeholder in all attributes}$$

$$\begin{bmatrix} \textit{System Attributes} \\ \textit{Control Range} \\ \textit{Flexibility to Mount Cameras} \\ \textit{System weight} \\ \textit{System Deployment Time} \\ \textit{Endurance} \\ \textit{Resource Availability} \\ \textit{Technology Readiness Level} \\ \textit{Ability to survey an object} \end{bmatrix} = \begin{bmatrix} \textit{Performance of RAVEN} \\ 10km \\ \textit{State \#2} \\ 12\ kg \\ \textit{State \#2} \\ 60\ \textit{minutes} \\ \textit{State \#2} \\ 9 \\ \textit{State \#2} \end{bmatrix} \Rightarrow \begin{bmatrix} \textit{Utility of Attribute} \\ 1 \\ 0.5 \\ 0.4 \\ 1 \\ 0.33 \\ 1 \\ 1 \\ 0.4 \end{bmatrix}$$

Using equation (5.1) and all attribute weights from the House of Quality in Figure 5.17, the utility of RAVEN RQ 11-B mini-UAV for Stakeholder #1 under Epoch #1 (i.e.

Operational Environment => War & Mission Purpose => Surveillance) can be calculated as shown below:

$$Utility\ of\ RAVEN = [0.13 \quad 0.18 \quad 0.06 \quad 0.07 \quad 0.09 \quad 0{,}12 \quad 0{,}19 \quad 0.15]x \begin{bmatrix} 1 \\ 0.5 \\ 0.4 \\ 1 \\ 0.33 \\ 1 \\ 1 \\ 0.4 \end{bmatrix}$$

$$= 0.72$$

Since its acquisition cost is estimated at $100,000 per mini-UAV, the system life cycle cost is calculated at $125,000 using Net Present Calculation over 5 years, a discount rate of 10% and a yearly maintenance cost of 8% of the acquisition cost. As such, RAVEN is now represented as a cost-utility ($125,000, 0.72) point on the tradespace. All the different ISR system designs and architectures will be computed in the same way to develop a tradespace analysis of all the options. The full cost-utility data of all the evaluated systems are in Figure 5-21.

Figure 5-20: ISR Systems

(Note: All pictures are obtained from public literature and the references are cited in the bibliography of ISR systems)

	Stakeholder 1: Ground Infantry Troop Battalion Commander																
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	10	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	[1,2,3]	2	2	2	2	2	2	2	2	3	3	3	3	3
System weight (kg)	20	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	30	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	6	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	4	4	3	3	3	3	3

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	Aladin	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	10	0.13	1.00	1.00	1.00	0.47	1.00	0.79	0.47	0.79	0.05	0.05	0.03	0.05	0.00
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	0.18	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00
System weight (kg)	20	0	0.06	0.40	0.25	0.10	0.45	0.15	0.25	0.15	0.15	0.25	0.00	0.00	0.00	0.00
System deployment time (minutes)	State #1	State #2	0.07	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	30	120	0.09	0.33	0.67	0.67	0.86	0.33	0.33	0.22	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability at any time required by the ground commander	State #1	State #2	0.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	6	9	0.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.15	0.40	0.40	0.40	0.40	0.40	0.40	1.00	1.00	0.80	0.80	0.80	0.80	0.80
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.72	0.74	0.73	0.70	0.70	0.68	0.71	0.73	0.80	0.78	0.78	0.78	0.77
			Estimated Cost (US$)	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Figure 5-21: Analysis of Design Choices for ISR System in Epoch #1 (Operational Environment => War & Mission Purpose => Surveillance)

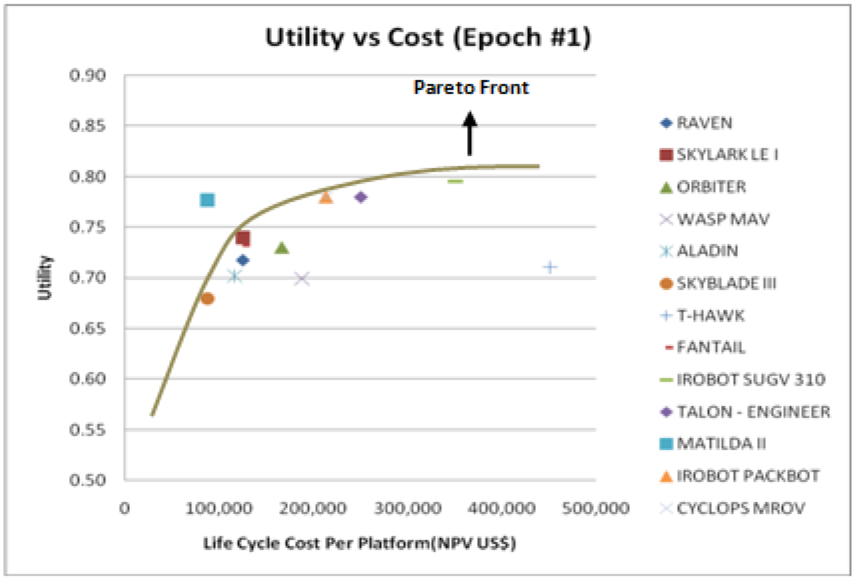


Figure 5-22: Tradespace of ISR system in mission context of war and use context of surveillance

Figure 5-22 shows the tradespace of the ISR system of Stakeholder #1. The detailed calculations and assumptions will be in Appendix A.

Similarly, Stakeholder #2's utility vs. cost tradespace can be analyzed. Figure 5-23 shows his tradespace under Epoch #1, whose mission purpose and operational environment are surveillance and war respectively.

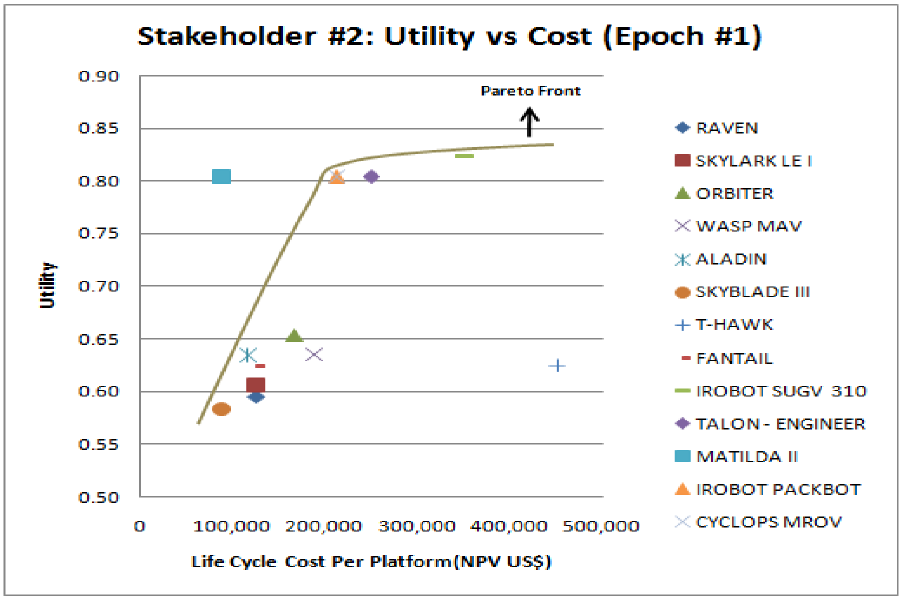


Figure 5-23: Utility vs. Cost Tradespace of Stakeholder #2 in Epoch #1

Another use of the tradespace is to compare the utilities of the two stakeholders. A utility-utility graph can be plotted as shown in Figure 5.24.

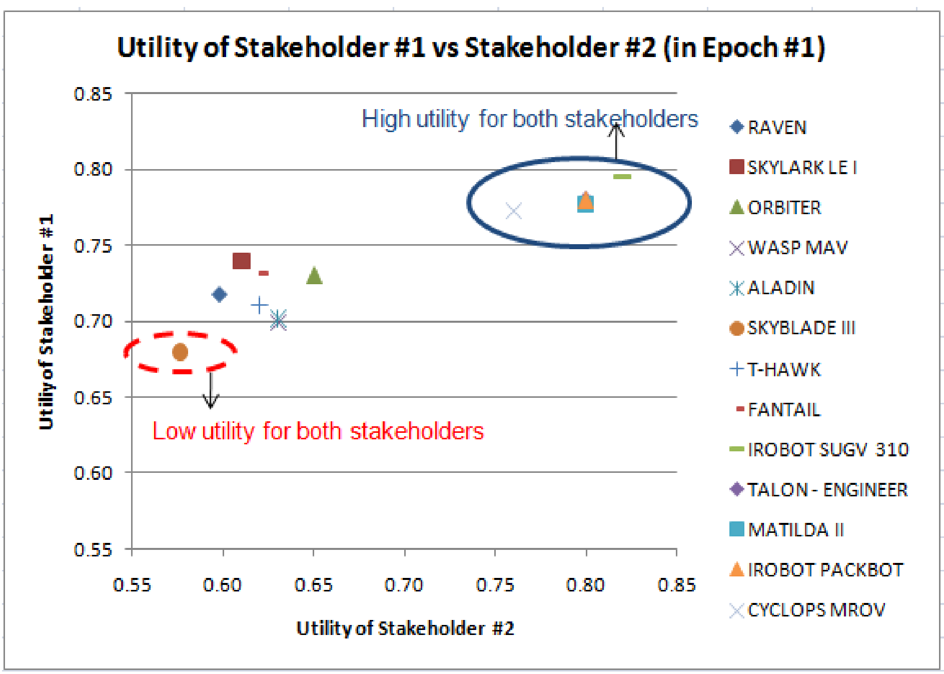


Figure 5-24: Utility vs. Utility Graph

Figure 5-24 shows that both stakeholders regarded the same ISR system highest and lowest as illustrated by the red circles. However, both had different utilities and preference order for the rest of the ISR options. This will serve as a good starting point for stakeholders to discuss their difference and opinions.

5.3.7 Epoch Vector

The tradespace analysis in Section 5.3.6 represents the choices and preferences in any "static" timeframe (i.e. constant user preference in a fixed context). However, stakeholders' preferences will change if the system is deployed in a different operational environment, mission and use context. External conditions such as dynamics of economic cycle, availability of new technology and change in threat level of potential adversaries are possible sources of change that will impact the system's delivery of value to the stakeholders. In order to preserve value to the stakeholders, the system architect must postulate future epochs and select a "value robust" design that is either insensitive to all these changes or one that has the change options incorporated into the design to preserve its value to stakeholders. The Epoch-Era Analysis is the proposed method in the author's value robustness approach to assist the system architect to anticipate changes.

Chapter 4 has provided guidance on possible epoch categories, which include the availability of funding and capital infrastructure, as well as changes in product/system (Chattopadhyay, 2009). The epochs in these categories will lead to possible responses as follows:

a. The shape of the utility curves (utility function) of the attributes of a stakeholder may change with time.

b. The range of the utility curve (utility function) of the attribute may increase or decrease.

c. The relative weights of the attributes may change.

d. The attribute sets themselves may change

In this case example of the ISR system, the author presented that there are two possible epoch variable changes in the strategy category. The specific epoch variables will be mission purpose and operational environment as described in Table 5-5. Eight epochs are postulated. There are other epoch variable changes in the epoch categories of funding, capital and product but they will not be used in the ISR system case study. This is to ensure the benefit of the entire proposed value robustness approach is articulated and demonstrated in a clear manner without complexity. More extensive discussion on Epoch-Era Analysis is found in Chapter 6.

Table 5-5: Epochs of ISR System

Exogenous Variable Category	**Epoch Variables**	**No. of scenarios**	**Enumerated Range**
Strategy	Mission Purpose	2	i. Surveillance function ii. Dual function such as augmenting EOD operation*, HAZMAT detection** or striking the target using munitions.
Strategy	Operational Environment	4	i. War ii. Peacekeeping iii. Counter-Terrorism iv. Humanitarian Assistance & Disaster Recovery

* EOD stands for Explosive Ordnance Disposal

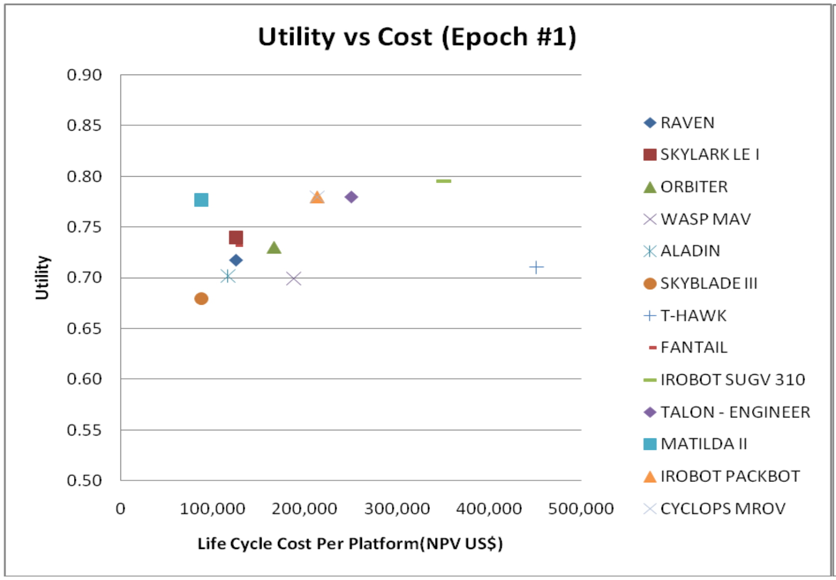
** HAZMAT stands for Hazardous Material

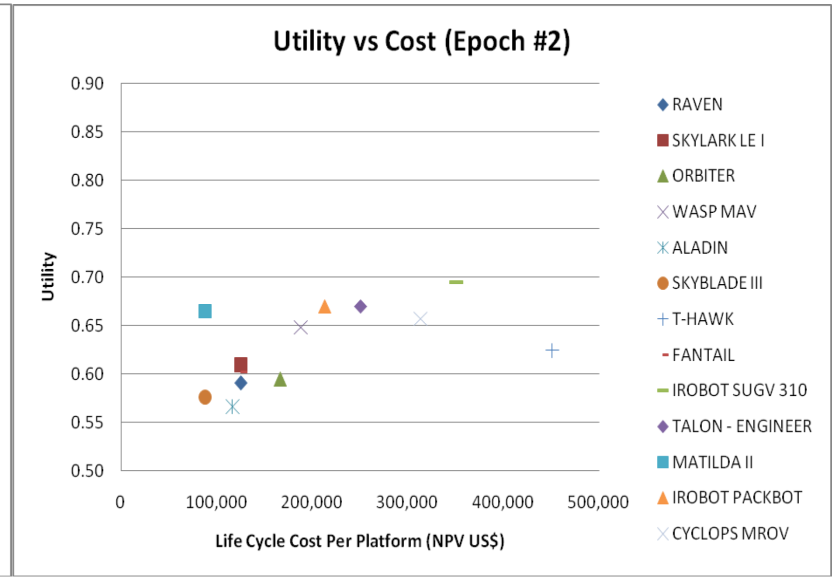
Although the ISR system's primary function is to provide surveillance of intended targets for the ground, the system architect is looking for possible scenarios where the ISR systems can be used to complement other operations besides surveillance. For example, it may be modified to augment EOD operation by helping the EOD team to examine and remove a suspected roadside bomb. Another possible agile change may be to add an additional sensor to detect contaminated chemical or biological environments or hazardous materials. Another flexible change might be to integrate a weapon system, or munitions with destructive power, to the ISR system and this might serve a new strike function. The full description of the possible epochs is in Table 5-6.

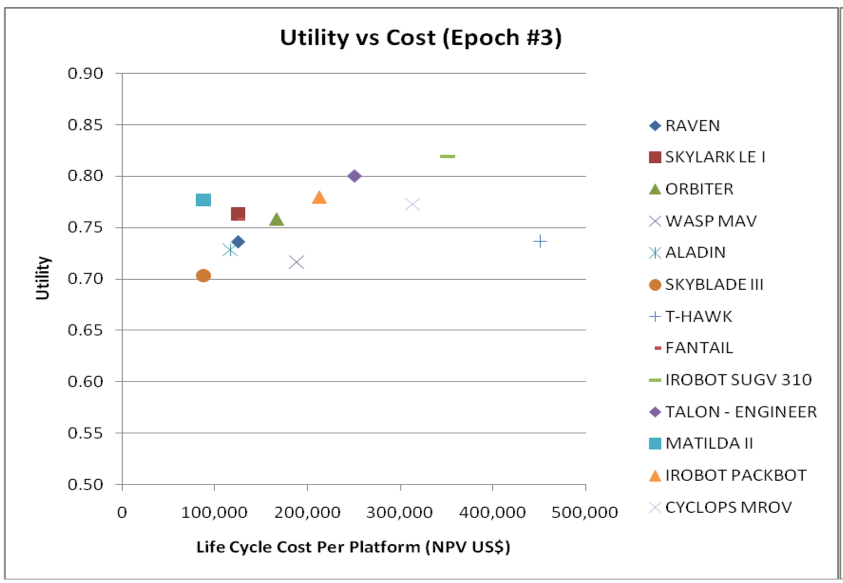
Table 5-6: Full description of Epochs

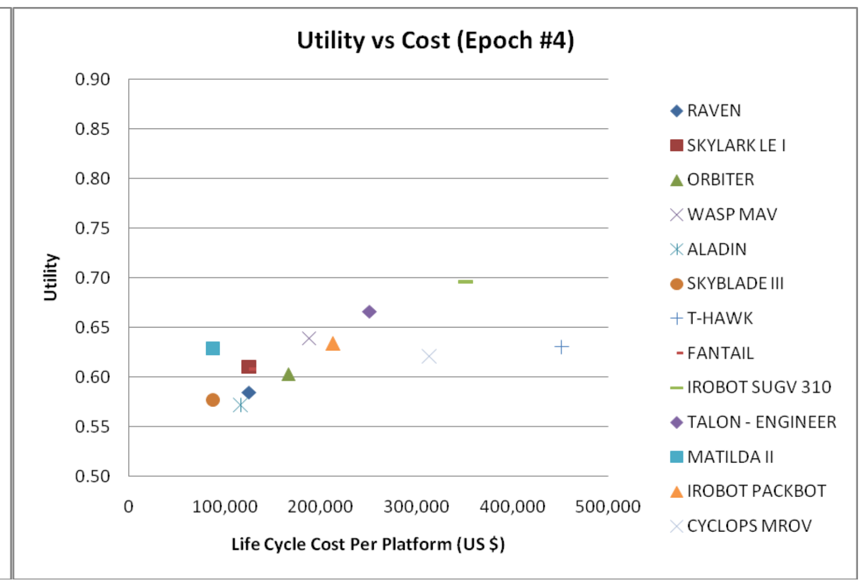
Epoch Number	Description
1	To survey an intended target during war operations using cameras
2	To be modified to perform a new function in war operations such as augmenting explosive ordnance disposal operations, detecting HAZMAT or striking a target using munitions
3	To survey an intended target during peacekeeping operations using cameras
4	To be modified to perform a new function in peacekeeping operations such as augmenting explosive ordnance disposal operations, detecting HAZMAT or striking a target using munitions
5	To survey an intended target during counter-terrorism operations using cameras
6	To be modified to perform a new function in counter-terrorism operations such as augmenting explosive ordnance disposal operations, detecting HAZMAT or striking a target using munitions
7	To survey an intended target during humanitarian assistance and disaster recovery using cameras
8	To be modified to perform a new function in humanitarian assistance and disaster recovery operations such as augmenting explosive ordnance disposal operations or detecting HAZMAT

The tradespace analysis in section 5.3.6 is repeated for all epochs. The detailed utility-cost calculations are in Appendix A. The tradespace plots for Stakeholder #1 is shown in Figure 5-25.


Utility vs Cost (Epoch #1)
Utility
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0
100,000
200,000
300,000
400,000
500,000
Life Cycle Cost Per Platform(NPV US$)
RAVEN
SKYLARK LE I
ORBITER
WASP MAV
ALADIN
SKYBLADE III
T-HAWK
FANTAIL
IROBOT SUGV 310
TALON - ENGINEER
MATILDA II
IROBOT PACKBOT
CYCLOPS MROV


Utility vs Cost (Epoch #2)
Utility
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0
100,000
200,000
300,000
400,000
500,000
Life Cycle Cost Per Platform (NPV US$)
RAVEN
SKYLARK LE I
ORBITER
WASP MAV
ALADIN
SKYBLADE III
T-HAWK
FANTAIL
IROBOT SUGV 310
TALON - ENGINEER
MATILDA II
IROBOT PACKBOT
CYCLOPS MROV


Utility vs Cost (Epoch #3)
Utility
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0
100,000
200,000
300,000
400,000
500,000
Life Cycle Cost Per Platform (NPV US$)
RAVEN
SKYLARK LE I
ORBITER
WASP MAV
ALADIN
SKYBLADE III
T-HAWK
FANTAIL
IROBOT SUGV 310
TALON - ENGINEER
MATILDA II
IROBOT PACKBOT
CYCLOPS MROV


Utility vs Cost (Epoch #4)
Utility
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0
100,000
200,000
300,000
400,000
500,000
Life Cycle Cost Per Platform (US $)
RAVEN
SKYLARK LE I
ORBITER
WASP MAV
ALADIN
SKYBLADE III
T-HAWK
FANTAIL
IROBOT SUGV 310
TALON - ENGINEER
MATILDA II
IROBOT PACKBOT
CYCLOPS MROV

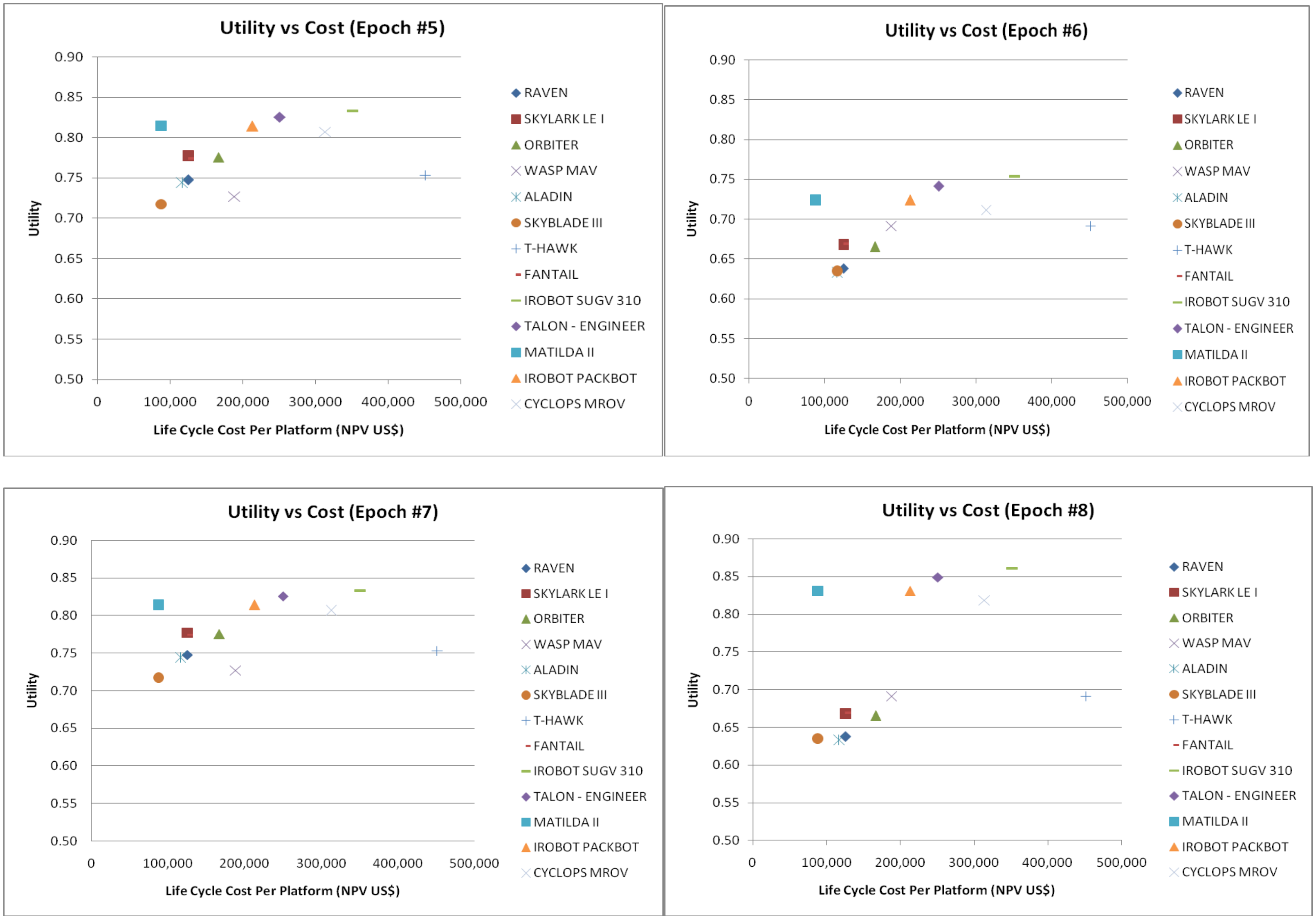


Figure 5-25: Multiple Epoch Tradespaces for Stakeholder #1

5.4 Analysis of Value Robustness

The tradespace exploration is demonstrated in Section 5.3.6. In Section 5.4, value robust ISR system designs are identified.

5.4.1 Statistical Outlier

First, the system architect would need to evaluate the tradespace analysis for any statistical outlier. MATILDA (mini-UGV) appears to be a statistical outlier. Refer to Figure 5-26 of Epoch #1.

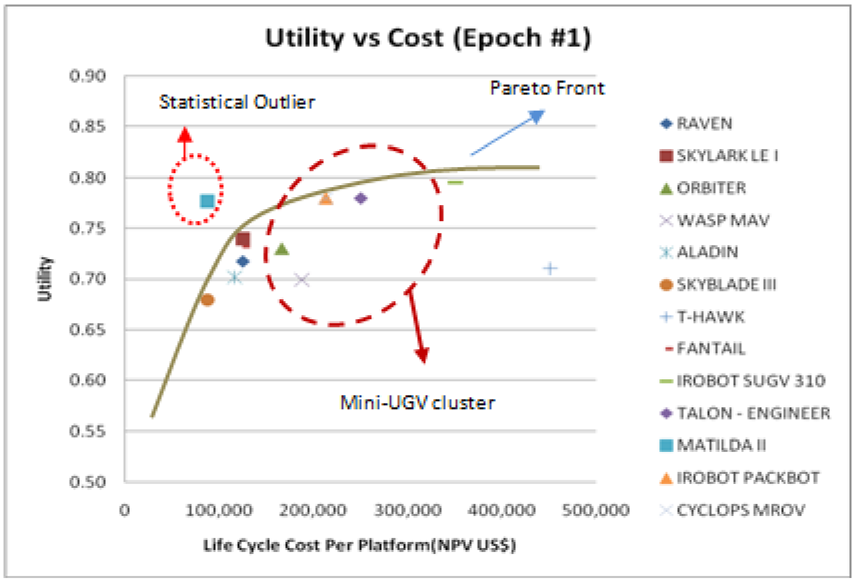


Figure 5-26: Statistical Outlier

Given its cost, it has a utility level that is higher than the Pareto Front. It is noted that the MATILDA’s system lifecycle cost is substantially lower than the rest of the mini-UGVs as shown in Figure 5-26. Therefore, one possible reason might be that the price quoted in the market survey might not be comprehensive and there might be other compulsory add on costs, which might be discovered only through detailed negotiation.

Another possible reason might be that the price might be a market penetration price and the system's price would increase with subsequent purchases. This would inevitably drive up the average system life cycle costs per platform. When this happens, the net benefit per dollar would decrease, which might move the solution off the Pareto Front and into the cluster with other mini-UGVs.

5.4.2 Concept Selection

The main purpose of the ISR system for ground troops is to provide surveillance for the ground troops in operational scenarios. In view of this, Epoch #1 is used to examine the trends of the clusters. Due to the uncertainty in the price of the MATILDA, this outlier solution will be omitted for the time being from further analysis on the tradespace. However, the MATILDA's utility-cost information would still be presented in the tradespace for completeness. If a similar situation occurs in real projects, the system architects would seek further clarification from the system's manufacturers and obtain accurate price information.

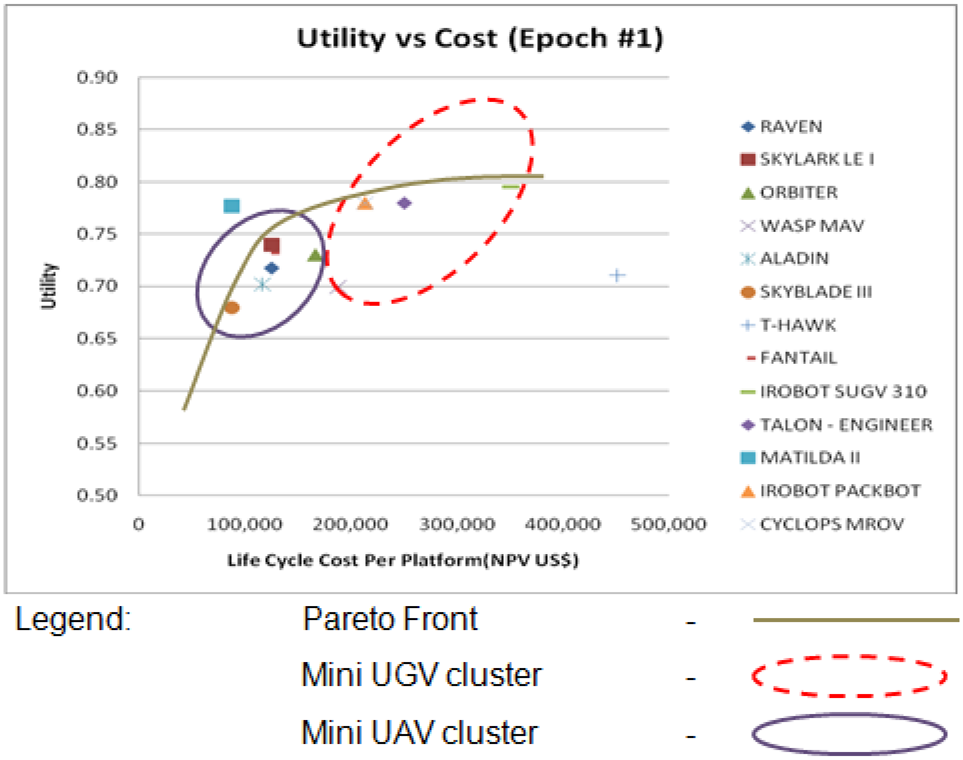


Figure 5-27: Epoch #1's Tradespace

The data in Figure 5-27 shows the Pareto Front of Epoch #1, which shows the maximum utility of the system at any cost. Three mini UAVs, namely the SKYBLADE III, SKYLARK LE I and WASP, and two mini UGVs, the IROBOT PACKBOT and the IROBOT SUGV 310 are on the Pareto Front. The clusters reveal that the mini UAVs are associated with stakeholder's lower utilities and lower costs as compared to the mini-UGVs. The rest of the design options under the Pareto Front are known as dominated solutions. The dominated solutions have higher costs or lower utility than the design solutions on the Pareto Front. The Pareto Front shows the different options available to the decision maker, whose goal is to maximize his utility at a given budget. If there is a budget constraint based on life cycle cost per system, the tradespace analysis will exhibit the design options that a decision maker can consider realistically. For instance, based on a budget constraint of $100,000 per platform, the analysis shows that the design option that provides the highest utilities to the decision maker and still able to fulfill the budget is the SKYBLADE III mini-UAV. The stakeholders and decision makers can also scrutinize the utility calculations to understand why a certain concept is chosen. Hence it provides a means of conveying the preference of the stakeholder as well as provides a basis for further deliberation among stakeholders and decision makers.

5.4.3 Passive and Active Value Robustness

5.4.3.1 Passive Value Robustness of ISR System

In order to consider passive value robustness, the system architect has to consider the possible usage of the system under all possible contexts. The tradespace analysis is repeated for all the eight epochs described in Table 5-6. The number of times a particular system appears on the Pareto Front will be counted. The frequency of occurrence is normalized and the results are shown in Figure 5-28. This is known as the Normalized Pareto Trace.

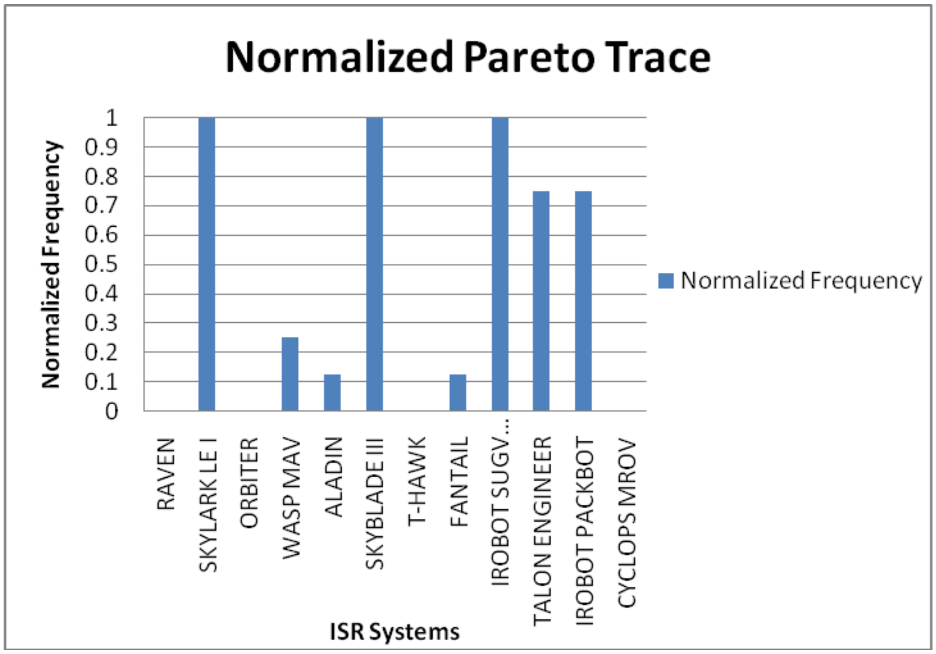


Figure 5-28: Normalized Pareto Trace

The Normalized Pareto Trace shows that the SKYLARK LE I, SKYBLADE III and the IROBOT SUGV 310 are the three most passively value robust systems. The three designs have high Normalized Pareto Trace of 1, which indicates that the designs occur on the Pareto Front in all epochs. Hence, they are the most cost effective designs among the design concept alternatives over the long run across all epochs, as they provide high value to the beneficiary at their respective costs.

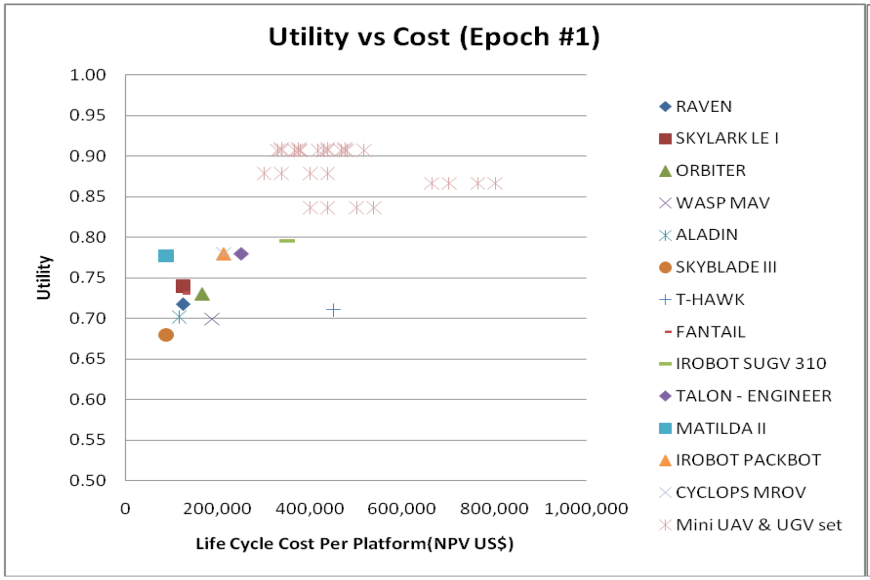
The author notes two observations from the above passive value robustness analysis. The first observation pertains to a hypothetical situation where a passive value robust concept does not occur on the Pareto Front in the epoch which is most important to the beneficiaries, stakeholders and decision makers. In other words, the passive value robust concept is a dominated solution in the stakeholder’s most important epoch. Although the identified concept is passively value robust when all the epochs are considered in totality, the concept does not provide the beneficiary with the highest utility in the epoch that the beneficiary cares most. When this hypothetical situation occurs, decision makers may be concerned that the identified concept does not give provide the beneficiary with the highest net benefit per dollar in the epoch deemed the most important among all. To deal with such a scenario, the author will advocate that the results from Normalized Pareto Trace (i.e. passive value robust designs) must be compared with the most important epoch whose context represents how the end-user or beneficiary would use the ISR system. It is also the most immediate need of the end user, and is the reason for the use of capital investment to acquire or develop the system. However, it is important to explain to decision makers how the other epochs might arise in future and demonstrate to them the value of designing a value robust design upfront as compared to switching cost of acquiring a new system when a different epoch arises. By using the Pareto Trace solely to justify a chosen design might appear misleading to the decision makers because some of the epochs may not materialize. Decision makers may be concerned with choosing a concept, even though it is passively value robust, which may not be the preferred design at that cost based on the intended context for which the system is designed for in the first place. Therefore, an informed presentation must be made to the decision makers to reconcile the benefit of developing the system for today’s context with preparing for future context changes.

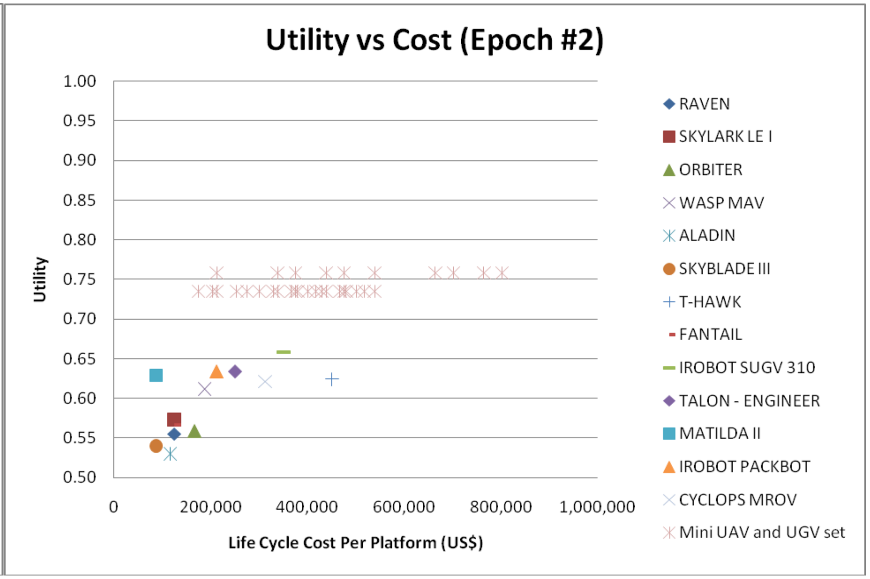
Secondly, it must also be noted that a passive value robust design may not provide high utility to the stakeholder. For example, the SKYBLADE III mini-UAV may be passive value robust, but its utility is not high (i.e. between 0.6 to 0.8) in all epochs. Stakeholders may prefer the utility of an IROBOT SUGV 310 (i.e. between 0.66 to 0.87) in all epochs, but will like to acquire the system at a lower price than that of IROBOT

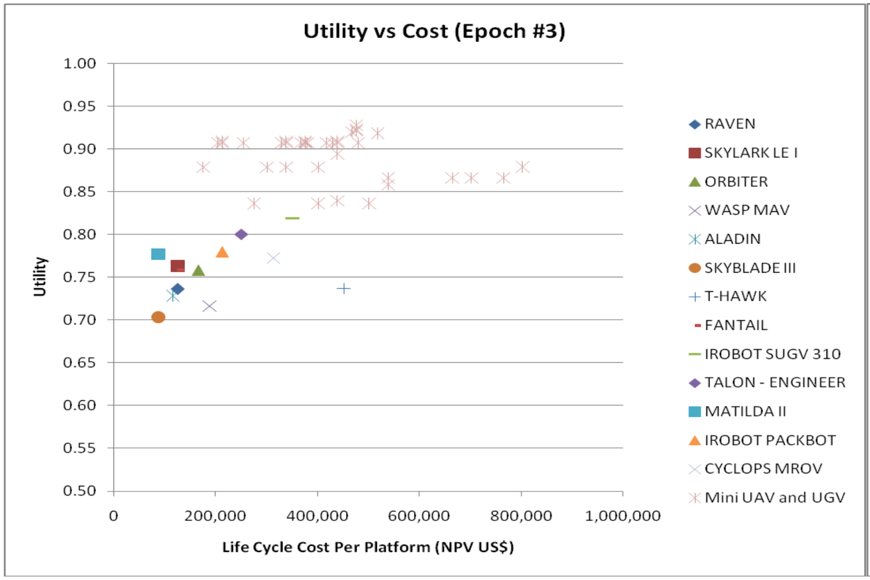
SUGV 310. There are three possible ways to achieve the mentioned stakeholders' intent to increase the utility level of the system. The first scenario might be to brainstorm ideas that will customize the existing system into one with enhanced attributes so that the overall utility can be improved. For instance, if the SKYBLADE III mini-UAV platform can permit more payload to be mounted while miniaturizing its onboard accessories, it will increase the stakeholder's overall utility for using the system. This may in turn shift the Pareto Front higher. The second method will involve the analysis of a combination of systems. Typically, there is a fundamental tradeoff between benefit and cost along the Pareto Front (i.e. the benefit or utility increases when the willingness to pay a higher price increases). In order to obtain a capability that might have a comparable utility and lower price as compared to a design concept with high utility and high price, the system architect can consider a combination of design concepts in the tradespace analysis. Section 5.4.3.2 will discuss this method in detail. The last method is to incorporate changeability into the system so that the value of the ISR system can be adjusted to meet the required utility level in a new epoch. The last method will be discussed in Section 5.4.3.3.

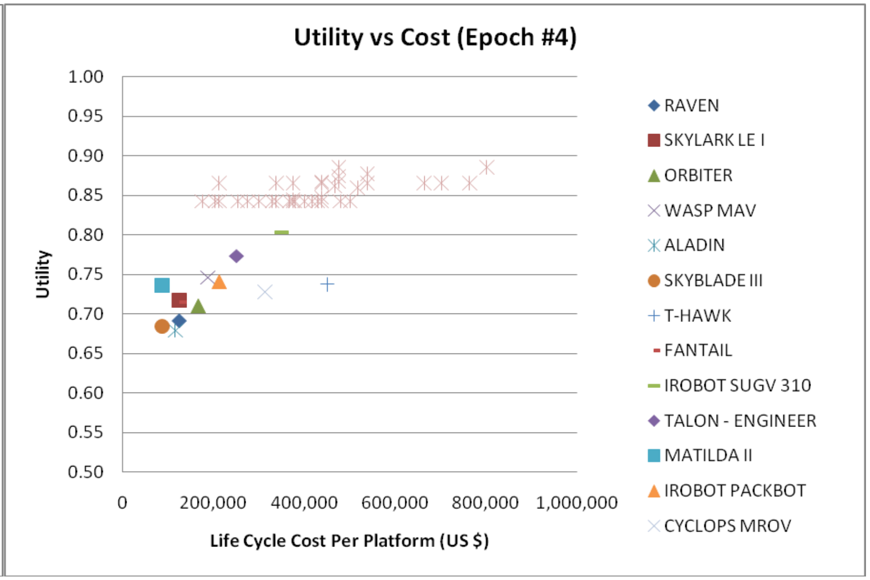
5.4.3.2 Passive Value Robustness of a Combination of Systems

The tradespace also allows discussion between decision makers to explore new possibilities which may improve the Pareto Front. One possible way will be a combination of assets to meet needs. Figure 5-29 shows how the combination of the various assets in the design configurations helps to increase the utility level. While the overall cost of acquiring two systems will increase, there are some interesting insights about the concept selection of combination of systems verses one system. A concept may contain two systems to fulfill stakeholders' needs. In this case study, a mini-UAV and mini-UGV can combine to form an architectural concept. However, two mini-UAVs or two mini-UGVs will not be considered as an architecture concept.


Utility vs Cost (Epoch #1)
Utility
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0
200,000
400,000
600,000
800,000
1,000,000
Life Cycle Cost Per Platform(NPV US$)
RAVEN
SKYLARK LE I
ORBITER
WASP MAV
ALADIN
SKYBLADE III
T-HAWK
FANTAIL
IROBOT SUGV 310
TALON - ENGINEER
MATILDA II
IROBOT PACKBOT
CYCLOPS MROV
Mini UAV & UGV set


Utility vs Cost (Epoch #2)
Utility
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0
200,000
400,000
600,000
800,000
1,000,000
Life Cycle Cost Per Platform (US$)
RAVEN
SKYLARK LE I
ORBITER
WASP MAV
ALADIN
SKYBLADE III
T-HAWK
FANTAIL
IROBOT SUGV 310
TALON - ENGINEER
MATILDA II
IROBOT PACKBOT
CYCLOPS MROV
Mini UAV and UGV set


Utility vs Cost (Epoch #3)
Utility
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0
200,000
400,000
600,000
800,000
1,000,000
Life Cycle Cost Per Platform (NPV US$)
RAVEN
SKYLARK LE I
ORBITER
WASP MAV
ALADIN
SKYBLADE III
T-HAWK
FANTAIL
IROBOT SUGV 310
TALON - ENGINEER
MATILDA II
IROBOT PACKBOT
CYCLOPS MROV
Mini UAV and UGV


Utility vs Cost (Epoch #4)
Utility
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0
200,000
400,000
600,000
800,000
1,000,000
Life Cycle Cost Per Platform (US $)
RAVEN
SKYLARK LE I
ORBITER
WASP MAV
ALADIN
SKYBLADE III
T-HAWK
FANTAIL
IROBOT SUGV 310
TALON - ENGINEER
MATILDA II
IROBOT PACKBOT
CYCLOPS MROV

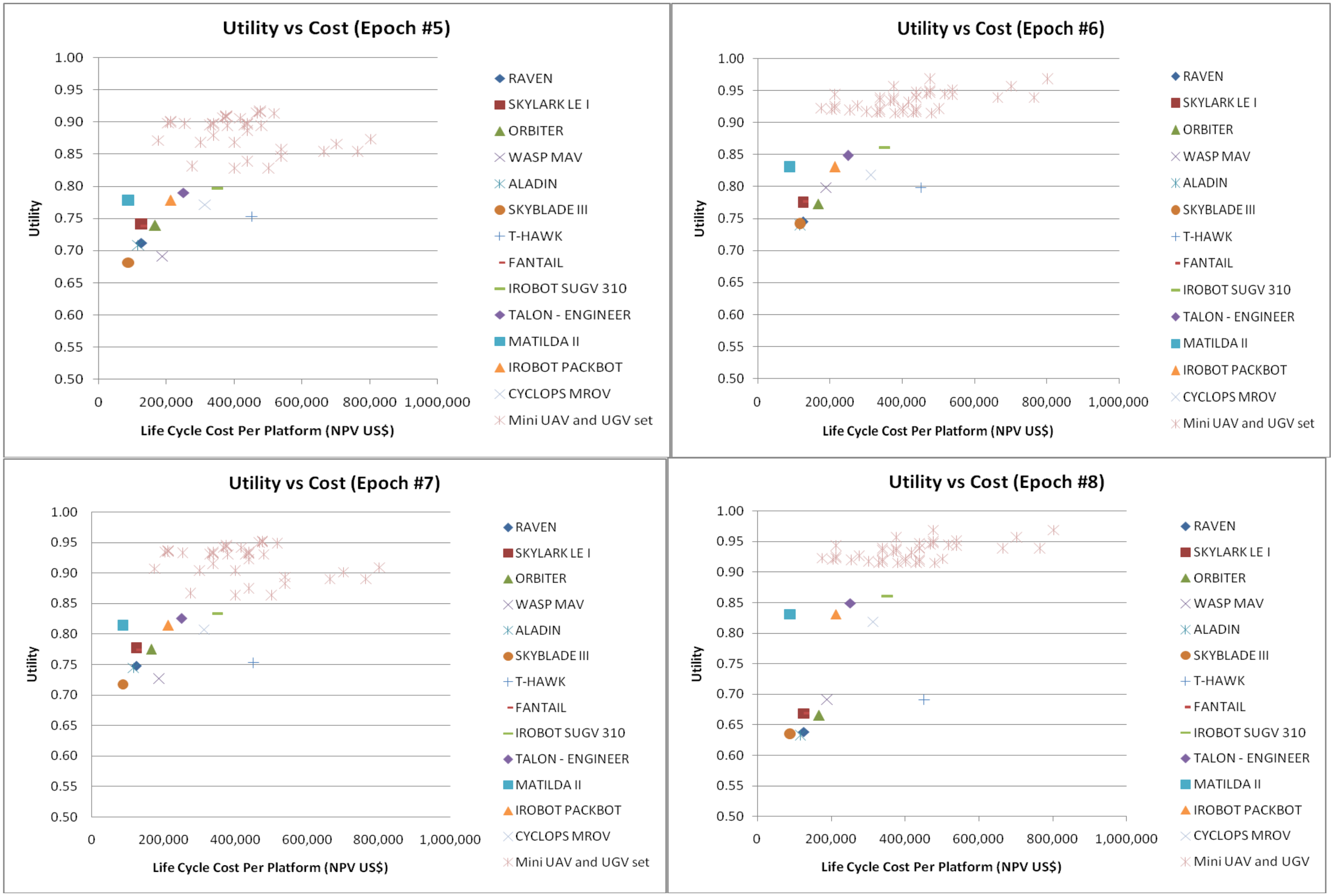


Figure 5-29: Tradespace Analysis of Combination of Systems across Epochs

Epoch #1 is chosen to facilitate in-depth analysis.

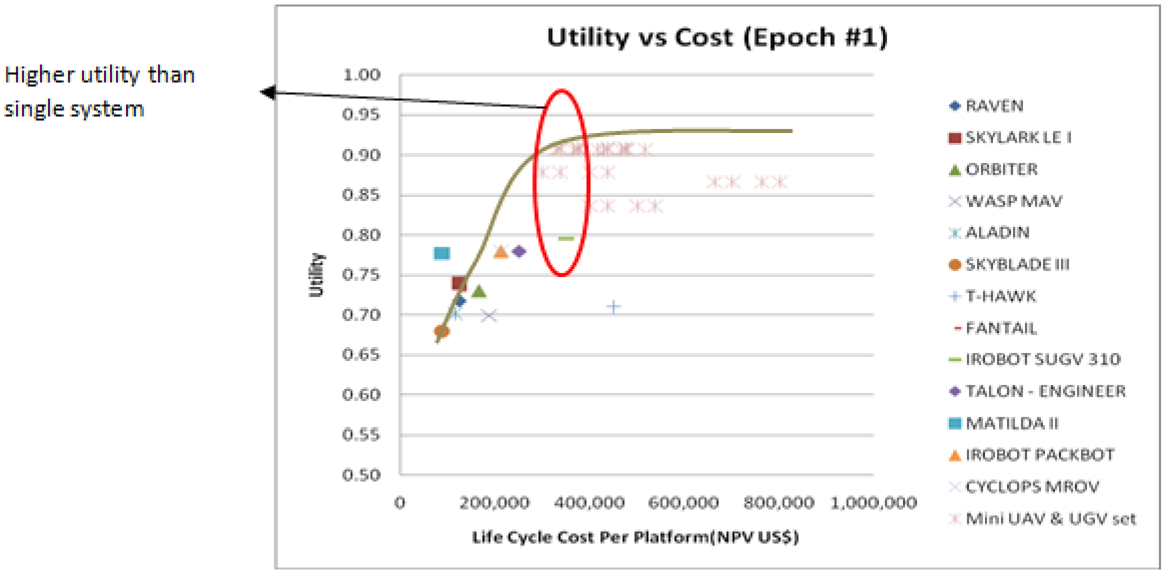


Figure 5-30: Epoch #1

Figure 5-30 shows that Pareto Front in this epoch is shifted upwards. The IROBOT SUGV 310, which was on the Pareto Front previously, will no longer be on the front as the ISR system that gives the stakeholder the highest utility at that cost. Various combinations, such as the ones below, provide higher utility (between 0.88 and 0.91 verses 0.72) to the decision maker at lower life cycle cost to the IROBOT SUGV 310 and they are as follows:

Combination Concept #1: mini-UGV and fixed wing mini-UAV

a. TALON ENGINEER and SKYBLADE III

b. IROBOT PACKBOT and RAVEN

c. IROBOT PACKBOT and SKYLARK LE1

d. IROBOT PACKBOT and ALADIN

e. IROBOT PACKBOT and SKYLARK LE I

And Combination Concept #2: mini-UGV and VTOL mini-UAV

f. IROBOT PACKBOT and FANTAIL

With this information, the decision makers have more options to choose from. They also provide clarity on the pros and cons of the attributes that a combination of systems verses a single system provides.

5.4.3.3 Active Value Robustness

Another way to maintain stakeholders' utility levels in all epochs will be to ensure that the design meets the minimum required utility level of the beneficiary but provides some form of flexibility that allows it to be modified to meet changing contexts in the future. Figure 5-31 shows the relationship between active value robustness strategy and the associated "ilities".

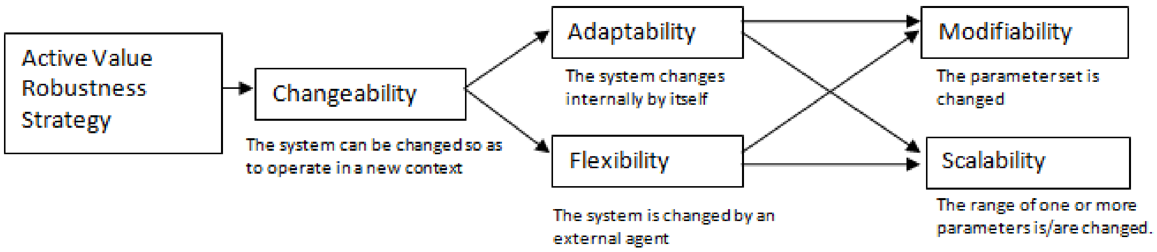


Figure 5-31: Active Value Robustness Strategy

To ascertain whether a design concept is active value robust, there is a need to calculate the number of paths across which the design can be changed. The design with the most number of changeable paths will be the most active value robust system. There is also a requirement to calculate the cost of the change. If the cost of the change is more than the cost of acquiring a new system to satisfy that particular need, the stakeholders will be less willing to invest in the changeable design. The quantification of changeability using the tradespace analysis is still a subject of intense research and will be looked into subsequently.

In the interim period, a semi-quantitative method presented by (Ross, 2006) is used to demonstrate the active value robustness strategy conceptually. The method is a simplified version of the Filtered Outdegree (FoD) calculation that is shown in Chapter 4. While the FoD calculation is being validated through extensive research case studies, the semi-quantitative method will suffice to demonstrate the thinking and methodology behind the FoD algorithm. This is in view of the low fidelity data used in this thesis to demonstrate the architecting approach. A simplified method is also advantageous because it can surface valuable insights about the changeability aspects of a concept quickly, without the need to use complex computational algorithms. The degree of changeability of the different ISR system concepts is evaluated using the simplified method and presented in Figure 5-32.

S/N	Change Configuration	Designs of ISR System																									
		RAVEN		SKYLARK LE I		ORBITER		WASP III		ALADIN		SKYBLADE III		T-HAWK		FANTAIL		IROBOT SUGV 310		TALON - ENGINEER		MATILDA II		IROBOT PACKBOT		CYCLOPS MROV	
		$	T	$	T	$	T	$	T	$	T	$	T	$	T	$	T	$	T	$	T	$	T	$	T	$	T
1	Add EO/IR Sensor	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	L	L	L	L	L	L	L	L	L	L
2	Add Accoustic Sensor	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	L	L	L	L	L	L	L	L	L	L
3	Add HAZMAT Sensor	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	M	L	M	L	M	L	M	L
4	Add manipulator	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	M	L	M	L	M	L	M	L	M	L
5	Add small arm weapon	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
6	Add batteries or increase fuel capacity to increase endurance of ISR system	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	M	M	M	M	M	M	L	L	M	M
	Max OD	6		6		6		6		6		6		6		6		6		6		6		6		6	
	OD [($:T) <= (M:M)]	0		0		0		0		0		0		0		0		4		5		5		5		5	

Legend:
$ - Cost to implement a change
T - Time to implement a change
L - Low
M - Medium
H - High
OD - Outdegree

Figure 5-32: Simplified Method to Identify Changeable ISR concepts

Six change configurations were identified in Figure 5-32. The change configurations were not exhaustive but they were adequate for the demonstration purpose. The decision rule to change an aspect of the design is dependent on the cost and time to change. The stakeholders will be unwilling to pay for the change if the cost of modification is above a threshold that the stakeholders can afford or deem fair to pay. Similarly, stakeholders will be unwilling to modify the design to meet their needs if the time to change is more than their threshold time to change. As there is insufficient information regarding the cost and time due to the low fidelity model used in the case study, the cost and time required to change are each classified qualitatively as “low”, “medium” and “high” and assessed qualitatively. High cost and high amount of time are required if the changes are difficult to implement in the current design configuration, especially in situations where the change is dependent on future technology improvements in other subsystems and large amount of effort is required to make the change. For example, a mini-UAV platform has limited payload capability. Hence, it will require further miniaturization of other subsystems within the mini-UAV to reduce overall weight so as to increase the payload to mount more sensors. A second example is the need to mount a weapon system to the ISR systems. Currently, none of the concepts can facilitate the need to mount a weapon because the payload capacity of their current chassis is insufficient for the purpose. On the other hand, the cost and time to change is low if the designs have additional capability add-ons, which can be performed with relative ease and short time. For example, the iROBOT PackBot’s product brochure has indicated that the design can accommodate a HAZMAT kit. This means that the designers have already considered the possible changes and growth. These add-on features allow designers to vary the system without undergoing wholesale modifications to meet a change in the stakeholders' mission need from an ISR to a HAZMAT detection operation. For the purpose of the demonstration, a change is considered acceptable and counted toward the Outdegree if the cost and time to change requires "medium" level of effort or less. The author would also like to note that the analysis was conducted with the use of information from product brochures and his own assessment. Detailed change information should be obtained from the manufacturers or the system designers.

Figure 5-32 showed that the TALON-Engineer, MATILDA II, IROBOT PackBot and Cyclops MROV had the highest Filtered Outdegree. They were the most changeable designs among the ISR design options and should be considered if the system architect would like to pursue an active value robust strategy for the ISR system.

Changeability considerations can be incorporated at the front end conceptual phase. Recall that one of the attributes in the ISR system pertains to the flexibility of the concept design to incorporate new, additional or different payload. Designs with modular payload or additional payload capacity are given higher utility than designs with integrated payload. Thus, the author has already incorporated this flexibility attribute into the selection criteria. However, to keep the analysis simple, the cost of an additional camera or payload will not be considered. The author considers only the extra cost of more payload pods or structural enhancement associated with the flexibility. In many cases, this extra payload capacity has been factored into the design already. For example, the mini-UGV has extra capacity that allows the end user to mount additional payload subsequently in the later stage of the lifecycle. Some ISR systems may be altered easily at a low modification cost to meet the changing needs of the end users.

The combination of flexibility considerations with the passive value robustness strategy can be a new approach towards selecting a concept design that is value robust. However, system architects must be able to convince decision makers that it is worth the upfront investment to incorporate the flexibility, as well as to select a passive value robust concept.

5.4.4 Representing Emerging Concepts in the Tradespace Analysis

One may ask whether it is possible to represent a potential design whose cost may be uncertain at the point of concept selection. It is possible but the system architect will have to estimate the maximum and minimum costs of the concept. The design concept will have a range of possible costs represented on the tradespace. This type of representation can also be applied to potential designs which have a Technology Readiness Level of 8. One example might be a mini-UAV or mini-UGV armed with munitions. While there are strategic UAVs armed with precision weapons such as the PREDATOR UAV, there is no proven mini-UAV design armed with munitions. There has been extensive research and development on mini-UAV armed with a weapon such as a bomb with the lethality of a hand grenade, but this can only happen if there are improvements in other supporting technologies, such as miniaturization of equipment (e.g. cameras, autopilot system), that comprise the UAV. Similarly, there are mini-UGVs which are integrated with weapons (e.g. TALON’s Modular Advanced Armed Robotic System (MAARS)). Figure 5.33 shows the MAARS.

Figure 5-33: MAARS (Liu, 2008)

However, the laden MAARS weighs between 300 to 400 pounds, which is too heavy for the ground troops to “back-pack” on their mission. As such, there is a need for significant improvement in other technologies to reduce overall weight so that the TALON’s chassis design can be considered suitable as a weapon platform, which serves as a dual function to the ISR system mentioned in the tradespace analysis. Nevertheless, potential designs can still be included in the tradespace for discussion with stakeholders regarding emerging technologies. The system architect must be able to articulate the difference and what the trade-off within are in the system. This is to allow a complete representation of possible concept designs.

5.5 Additional Comments about Passive and Active Value Robust Systems

Every product feature comes with a cost and a design may have too many real options which may be perceived as extra, wasted costs if they are not exercised. One strategy may be to seek a suitable design in the most likely context and develop a degree of flexibility for some of the most likely scenarios.

Secondly, in addition to the additional cost to the system in order to incorporate flexibility features, these features also come with a “design” cost. For instance, the mini-UGV may be a flexible design and might possibly accommodate end-user’s future additional payload requirements such as additional cameras or manipulator arm. However, there is also a weight penalty, which makes it less desirable for a back-packable design. As such, the crucial issue is for the architect to justify the trades among the attributes so as to allow the decision makers to make an informed decision.

Chapter 6 Value Robustness of System of Systems

6.1 Introduction

Chapter 5 has highlighted how the tradespace analysis can be used to compare different architecture concepts in the same space for meaningful and comprehensive comparisons in a static timeframe or period of time. The tradespace analysis is augmented by the Epoch-Era analysis, which helps system architects anticipate possible future changes in needs, expectations and contexts. This in turn allows system architects to view the lifecycle as a series of dynamic contexts. Armed with this analysis, the system architects can recommend a value robust concept system solution to the decision makers. Communications between stakeholders and decision makers are enhanced by referencing the dynamic tradespace and modeling additional analysis.

This analysis may be applied to a larger SoS context. However, it is challenging to represent different concepts of large scale SoS in a tradespace. Kaplan (2006) explains that this is because SoS is “a large complex, enduring collection of interdependent systems under development over time by multiple independent (or perhaps loosely coordinated) authorities to provide multiple, interdependent capabilities to support multiple missions”. As such, changes are inevitable and SoS may be evolutionary in the pursuit of capabilities. In addition, systems within the SoS may be undergoing change as well and since all the systems are coupled together, the SoS performance may not be representative of the whole capability at any point in time. To compound the complexity, systems “exit and enter” the SoS. It also requires long period of testing and evaluation to see how the SoS can perform. An Army SoS is used as a case study for the discussion on value robustness of SoS in this Chapter.

6.2 Case Study: Army SoS Architecture

Similar to the previous approach, the generic "Needs to Architecture" framework is applied at an Army SoS level. The intent of a defense force is to deter any potential aggressor or adversary from using military force to infringe on a defending country's land, air and naval territories. Looking from a narrow operational point of view, the need of the Army is to execute and achieve mission objectives of the defense force. One possible operational intent of the Army SoS is to capture an area of operation decisively within X hours, with Force Level Y and a Readiness Condition Status Z. The intent is preferably accomplished through comprehensive situation awareness of the battlefield condition and effective combat power.

There are many ways of configure a SoS to achieve the intent. Chen, Gori and Pozgay (2004) argued that the systems in SoS can be related in "structure, function, information, operation and generation". One common technique is to arrange by functions or capability (Kaplan, 2006). The Object Process Methodology (OPM) diagram in Figure 6.1 represents one way which Army SoS can be organized. While this is neither a comprehensive nor the "right" way to configure the Army SoS, it represents a generic, baseline SoS architecture concept from the perspective of the author.

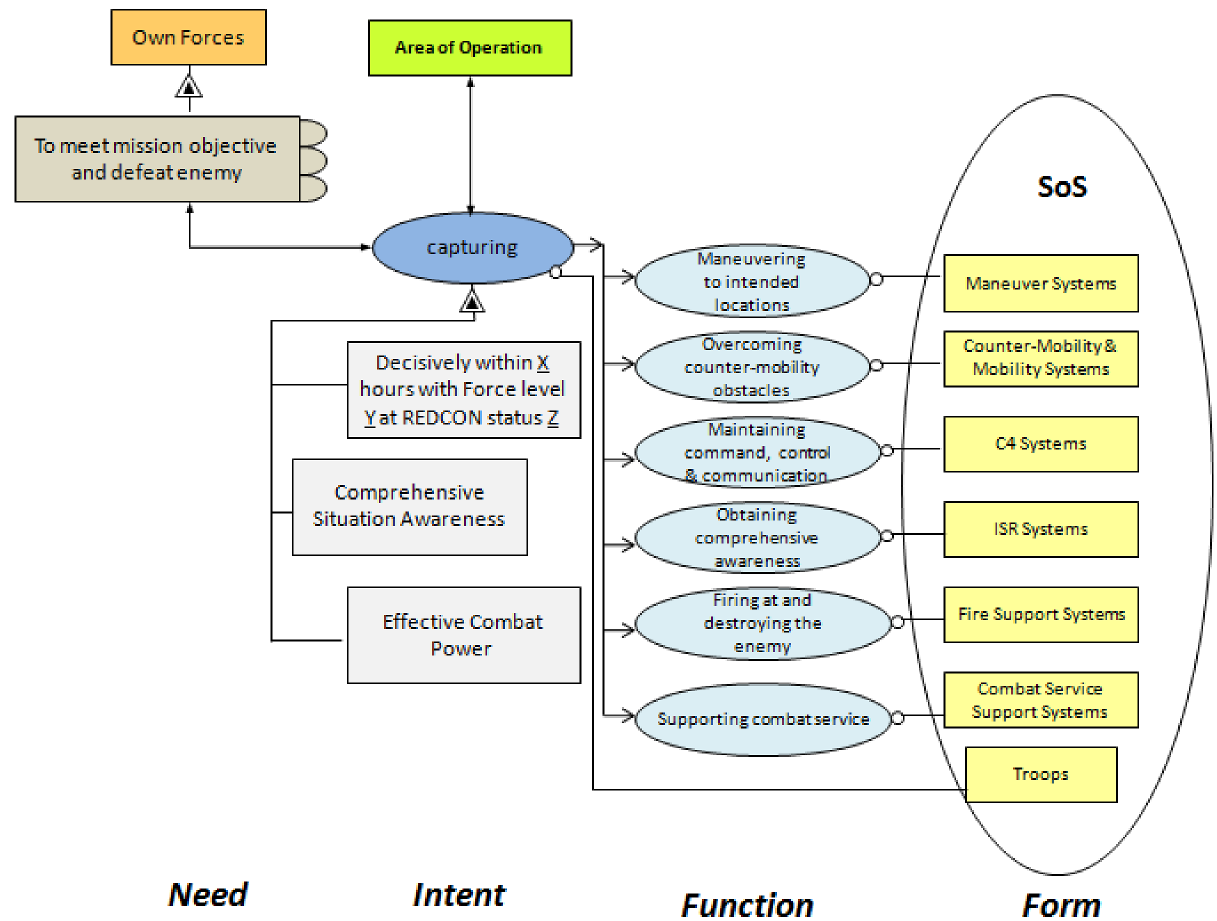


Figure 6-1: High Level Baseline Army SoS Architecture Concept

By adapting and modifying a typical SoS framework from (Ong, 2009), the six functions of an Army SoS are:

1. Maneuvering to the intended locations

   Armor and Infantry will need to maneuver and advance to the intended location to attack the enemy, delay the enemy's advance or defend the location against enemy's attack.

2. Overcoming counter-mobility obstacles

   Natural and man-made obstacles may impede own forces' movement. The obstacles include water bodies, soft grounds, damaged roads or bridges, and minefields. Capabilities that enable own forces to overcome these obstacles are desired.

3. Maintaining command, control and communication

   In order to maintain command and control of the troops to shape the battlefield situation, an effective and robust communication system must be established between all elements in the SoS so that they can communicate battlefield information and orders to each other.

4. Obtaining comprehensive awareness

   Information from sensors are collected, collated and disseminated to others in order to allow all elements within the SoS to understand the battlefield picture, know where the friends and foes are, and execute tasks decisively.

5. Firing at and destroying the enemy

   This function is to deter or destroy the enemy using munitions.

6. Supporting combat service

   Combat Service Support is required to sustain the troops' ability to engage in the current battlefield fight and to resupply the combat force to an adequate Readiness Condition Level to undertake the next mission task.

The high level functions are implemented by high level forms, which include maneuver systems, counter mobility and mobility systems, C4ISR (Command, Control, Communication, Computer, Intelligence, Surveillance & Reconnaissance) systems, fire support systems and combat service support systems. All these systems will be operated by troops, which form an integral part of the SoS. The C4ISR system serves as the "glue" of the SoS because it provides the network where information can be communicated between the various nodes, that is, the SoS's component systems. Figure 6-2 to 6-8 shows the decomposition of forms. Note that this is by no means comprehensive, and represents the high level decomposition of the various systems that form the Army SoS.

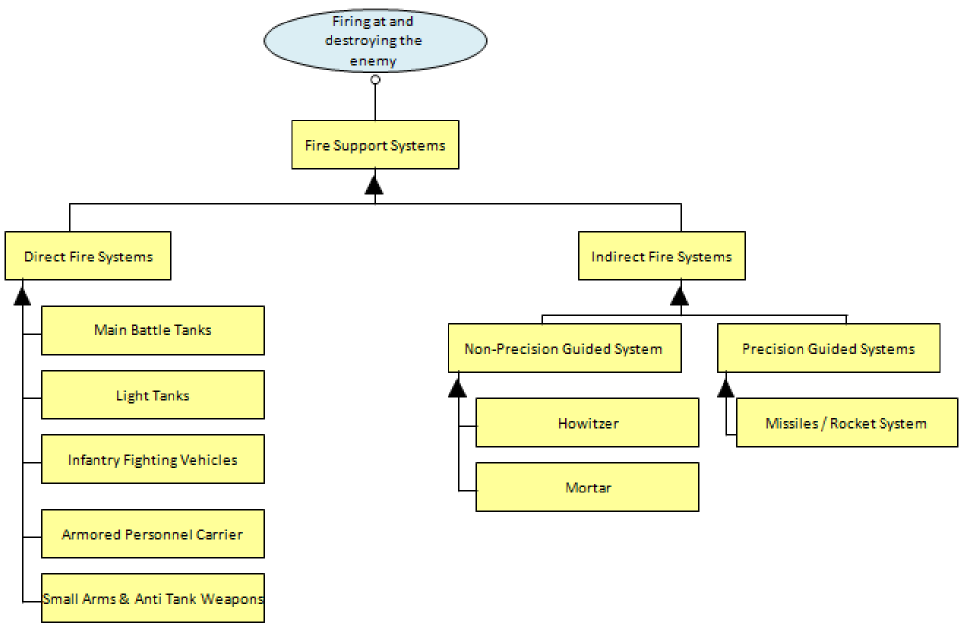


Figure 6-2: Fire Support Systems

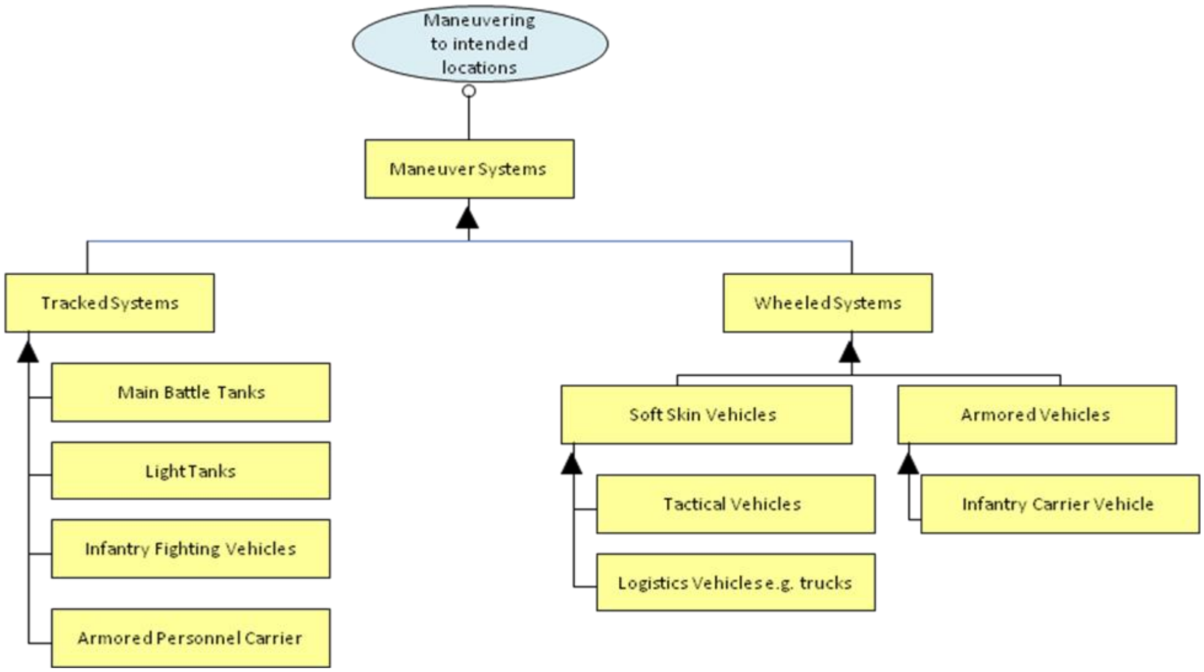


Figure 6-3: Maneuver Systems

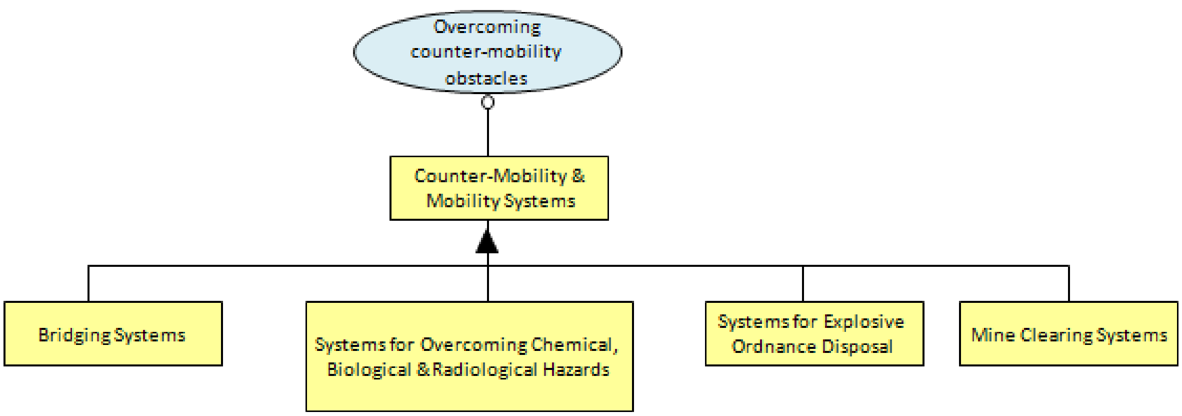


Figure 6-4: Counter Mobility and Mobility Systems

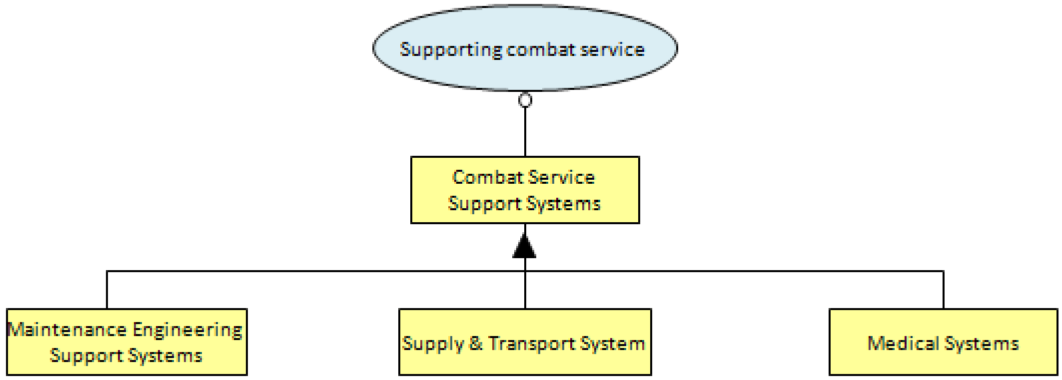


Figure 6-5: Combat Service Support System

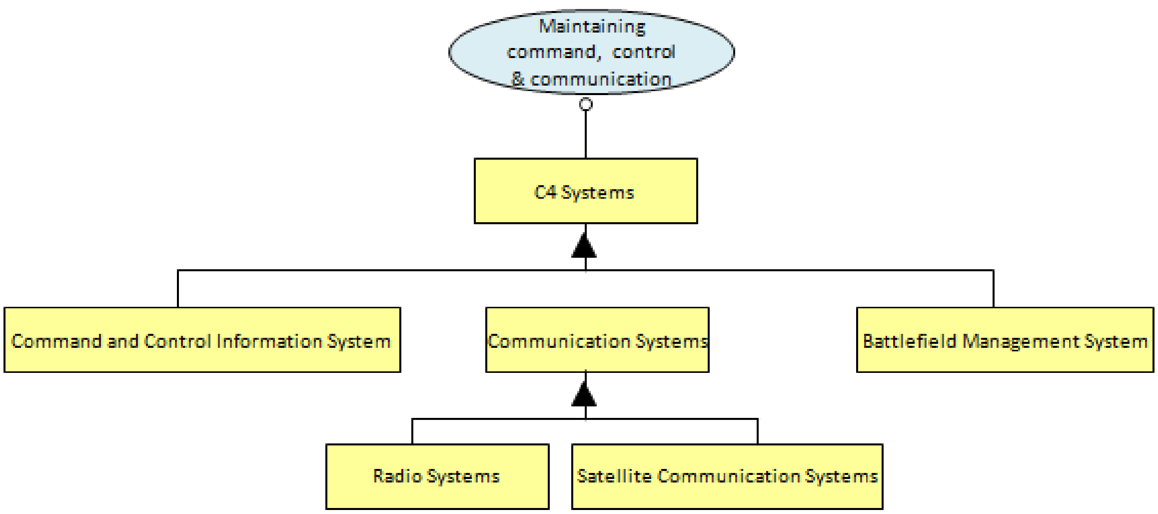


Figure 6-6: C4 Systems

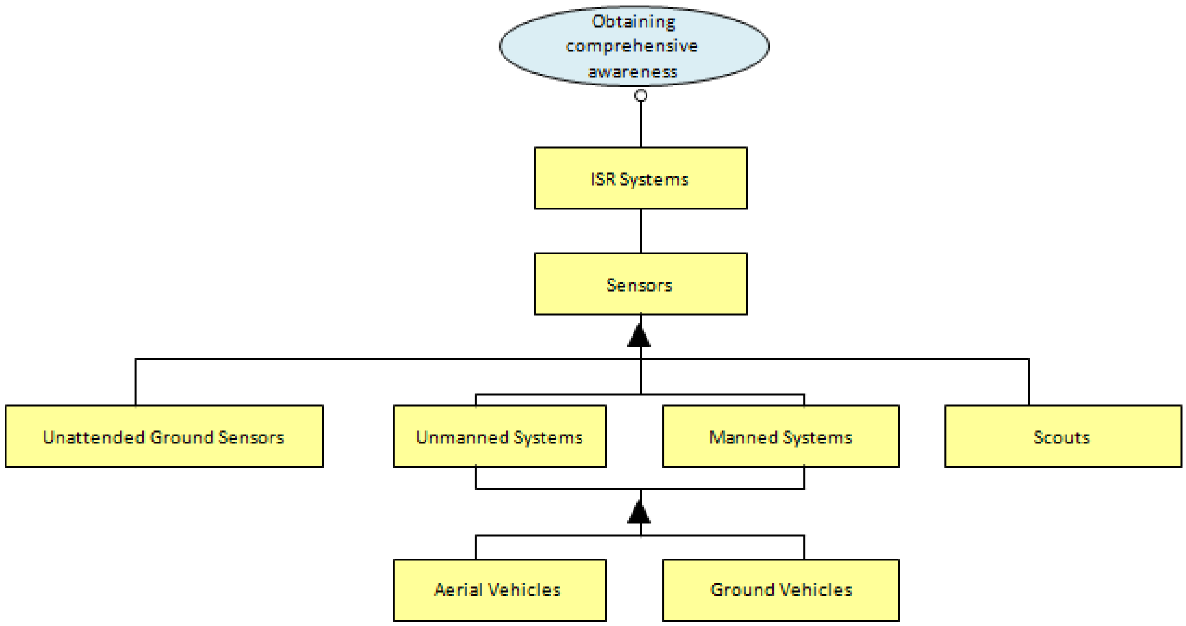


Figure 6-7: ISR systems

A SoS design that is designed from scratch is ideal because it allows a complete coherent set of requirements to be specified upfront and addressed in the SoS life cycle. Due to the large number of permutations among the SoS components, it can be envisaged that the tradespace architectural options for a SoS, which start from a "clean sheet", are abundant and extremely complex. As such, representing a large scale, new SoS such as an Army SoS, on a tradespace is a subject for future analysis.

Nevertheless, it is rare to establish a new, large scale Army SoS from scratch. In most instances, system architects are more likely to be given the task to reorganize and build up a SoS by using existing operating systems that the Army has. These current systems may contain legacy systems, which might be one generation older than the current operating system. This is because Army systems are built to last for many years because of the high investment in capital cost. As such, it is not possible for Army to write off the existing fleet of equipment and acquire new systems to develop SoS. In view of this, it is more cost effective to configure the current weapon systems of the Army to be part of the SoS while acquiring new systems to augment any capability gaps. The Army SoS's emergent effect will be obtained through incremental change and transformation to achieve the desired SoS.

6.3 Army SoS Characteristics

Before the SoS system can be evaluated for its value robustness, it is important to identify the characteristics of the SoS. The author has conducted interviews with five practicing defense system architects and senior acquisition managers of a defense agency spearheading the development of an Army SoS. One of the interview questions pertains to the key attributes of a successful Army SoS architecture. A common attribute quoted is a robust C4ISR system, which networks all the elements of the Army SoS. A robust C4ISR also facilitates the Army working together with the Air Force and Navy operating as an integrated force, that is, "holistically integrated capability". The integrated force should ideally be able to tap on the entire Armed Forces' resources to complete a mission effectively and efficiently. Scalability in quantity of component systems, capabilities and effectiveness in meeting mission objectives is a cardinal requirement also. Modular component systems and sub-systems are also another attribute identified by the interviewees. Finally, one respondent mentioned that a successful Army SoS should have strong modeling and simulation to guide front-end design of the component systems as well as the evolving SoS. With these responses in mind, the next section explores a case study, that is, Country Sierra's Army SoS, to investigate value robustness of SoS.

6.3.1 Type of SoS and Level of Control

Country Sierra's Army SoS, which the author intends to delve into, pertains to an Acknowledged SoS, meaning the SoS is centrally managed. Based on interviews with the relevant stakeholders, the Army leadership would articulate the operational concept. The Operational and Engineering Master Plans will be formulated to convey the intent of the operational concept. The specific functions and forms of the defense systems will be acquired and developed to realize the capabilities envisaged in the master plans. While the various developmental and acquisition programs are managed by the different program managers to meet the needs of the local stakeholders through the development of a component system of the SoS, the SoS architects will ensure that the component systems maintain coherence with the global goals of the Army SoS.

6.3.2 Participation Risk

The Army leadership has complete managerial control over the availability of its component systems to participate in the SoS configuration. Therefore, the participation risk of the component systems is zero. As such, the SoS architects have the authority to adopt strategies to influence the design of the component systems to meet the needs and goals of the SoS. In fact, the goals of the component systems are aligned to that of the SoS design due to the top-down requirements flow structure.

6.4 Example of the Army SoS

To aid the understanding of an Army SoS concept mentioned in Section 6.2 and 6.3, the author provides an illustration of a SoS operation in Figure 6-8. Figure 6-8 is originated from Chow (2008) and is adapted by the author to explain the operation.

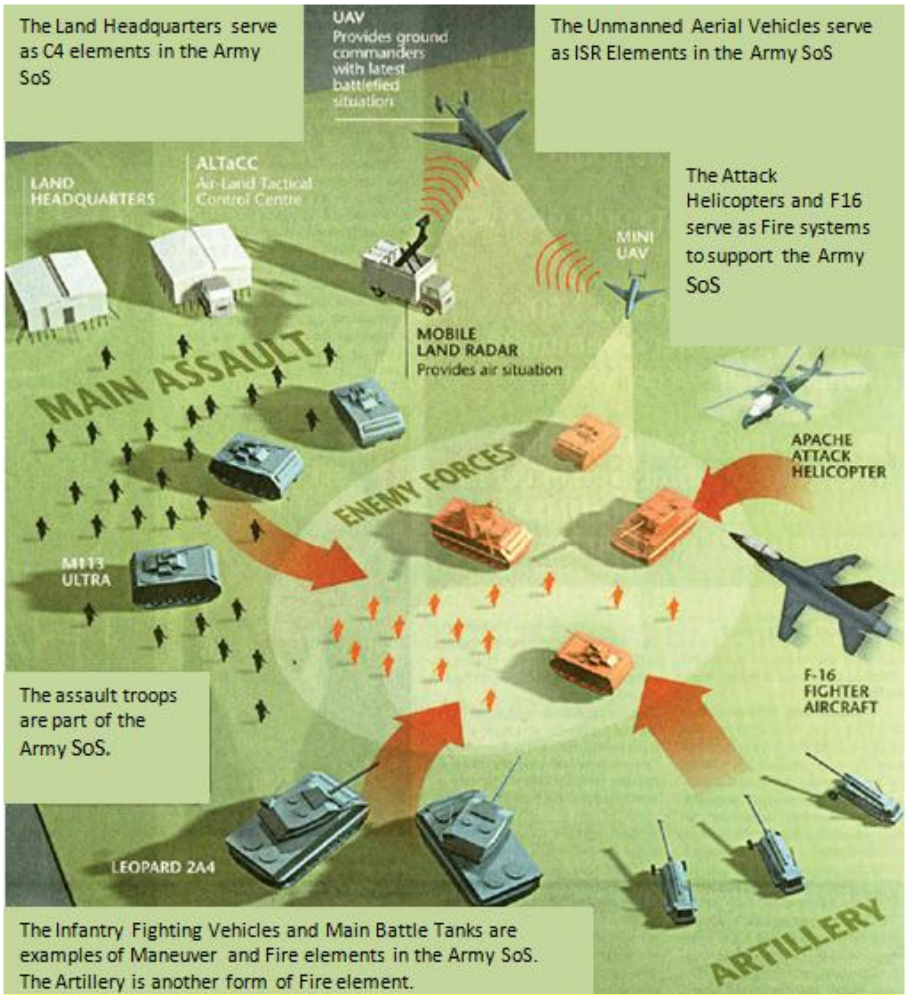


Figure 6-8: Adapted Graphics Illustration[12] of an Army SoS example (Chow, 2008)

In this specific example, ISR systems such as UAVs conduct surveillance on the enemy forces. The information is relayed to the Land Headquarters and all other

[12] According to Chow (2008), the source of the illustration is from Ministry of Defence, Singapore.

surrounding elements that need the information such as the ground troops. The Land Headquarters operates as a Command and Control operations hub that collates the sensors information to form a battlefield situation. The commanders will make sense out of all the information from the various sensors, make field decisions and coordinate the assault on the enemy forces. Fire elements (i.e. the shooters in the form of artillery, attack helicopters, fighter jets and main battle tanks) will provide fire support to attrite the enemy before the maneuver forces (the infantry fighting vehicles carrying the ground troops) move in to overcome the remaining enemy elements. Various component SoS elements can communicate with one another in a network and be able to know where the friends and foes are through a battlefield management system. The coordinated operation is made possible by using a robust C4ISR network to allow information sharing and fusion as well as faster decision making. The end result is the emergent effect of superior situation awareness for all elements of the networked SoS and an effective, coordinated completion of the mission.

6.5 Use of Epoch-Era Analysis

Changes within the systems in the SoS as well as change in context, expectation and new demands on the SoS will occur. Most of the changes may be beyond the span of control of the SoS architects. In addition, the changes may be happening concurrently. If the changes are left unchecked and are not managed properly, the overall performance of the SoS may be degraded or with its constituent systems unable to work together. Another advantage of anticipating changes is to seize an early opportunity to plan and integrate emerging, leading edge capabilities to the SoS. This section presents some early thoughts of what changes or epochs might occur to Country Sierra's Army SoS.

6.5.1 Epoch Category – Resources

The category of "Resources" is broken down into three sub-categories: defense budget, SoS component budget and people.

6.5.1.1 Epoch Variable – Defense Budget

Based on the interviews, there are long-term plans in place that guide SoS architects on the capabilities that the armed forces will want to acquire. Based on this operational and engineering master plan, the authority will phase in the development of capabilities and the development will be prioritized. A yearly budget based on a percentage of the country's Gross Domestic Product (GDP) will be allocated to maintain and upgrade current operational systems, invest in research and development of identified key technologies as well as acquire weapon systems to build up the capability of the Armed Force. In view of this, the defense budget is dependent on the country's economic growth. The SoS architects should plan for an epoch in which the country suffers from a sustained period of economic down-turn where spending on defense acquisition will decrease. When this situation arises, evolutionary development of the SoS will be slowed down. As such, the army must put in place mitigation plans when the capability cannot be developed or acquired as planned originally. One possible risk mitigation plan is to ensure that current systems are able to function as a SoS to fulfill the SoS operational objective. For example, if the C4 network digitalization program is delayed from the original schedule completion, the analog communication system in the form of existing radio systems should still serve as the backbone of information transmission within the Army while the upgrade is in progress. The Army continues to operate using its existing connectivity system. The analog communication system may serve as a backup mode when the upgrade is completed. This mitigation plan is synonymous to Maier's principle of stable intermediate forms (Maier, 1998). The SoS system must have stable intermediate forms, which enable the SoS to perform its functions and missions as a collective entity in parallel with its development and evolution.

6.5.1.2 Epoch Variable –SoS Component Budget

Chapter 5 has discussed briefly on the impact of the individual system's allocated budget on the concept design of the system. The budget constraint on each system will impact the value robustness strategy of the individual systems, which in turns affects the SoS concept. For example, it may not be possible to pursue a value robust system, which can meet the stakeholders' expectation in all epochs, if the budget is not adequate. The budget might only be sufficient to design a system that meets the current need.

As the SoS will evolve with time, changes might be required in the legacy and current systems of the SoS. When this happens, the overall cost of a SoS concept will increase because there is a need for these systems to interoperable with the new "entrants" to a SoS at a cost. As such, a SoS concept will be less desirable if there is a need to modify the component systems as compared to one where the component systems do not need to change to participate in the SoS.

6.5.1.3 Epoch Variable – People

One of the resources of the SoS is the people or troops. The perceived future size of the Army may be an important factor in determining the Army SoS concept. This is especially important for small conscript armies, which may not have the huge manpower to pursue an Army SoS concept that requires a large troop presence to secure an Area of Operation. Alternative SoS concepts that utilize unmanned technologies to bolster a small force in the military operations may provide high value to the decision makers for the SoS design.

Similarly, the perceived education level of the troops in the future will also be a consideration in formulating the SoS concepts. If the troops' education level is high and are adept in operating high-tech, complex weapon systems, a SoS concept that leverages on technology as the force multiplier may confers high value to the decision makers in the Army leadership. On the other hand, if the troops are not highly educated, skillful or resistant in handling technology, a SoS concept with complex systems will not be suitable for this type of Army.

6.5.2 Epoch Category – Capital

The category of "Capital" is broken down into two sub-categories: emergence of new technology and availability of technology.

6.5.2.1 Epoch Variable – Emergence of New Technology

Technology trend is one area where the system architects have to keep a constant watch. An architect should study which technologies or systems are emerging and will serve as a force multiplier to the Army. One of the most important fields of technology is C4ISR. As mentioned previously, the C4ISR systems connect all the systems in a networked defense SoS. Information is transmitted and shared between the nodes of the SoS. With this in place, situation awareness of the entire force is enhanced. This emergent effect facilitates faster and better decision making so that actions can be taken swiftly to mitigate the threats posed by the adversary in the battlefield. A robust C4ISR system is critical to a successful SoS architecture and provides the foundation for further increase in capabilities of the SoS. As such, technologies that serve to improve the reliability of the C4ISR systems should be factored in upfront in the early design phase.

Similarly, there is also a need to increase the communication bandwidth. Increasingly, high bandwidth transmission such as videos from UAVs will be streamed to other forces within the SoS for situation awareness. As such, it is envisaged that a high bandwidth network has to be established to satisfy future needs. Network equipment must increase in tandem in capacity. This demand for high speed and high capacity information network is increasing rapidly and system architects will be well served to keep abreast of communication technologies so as to implement a network infrastructure that is scalable, instead of making changes to the network and buying costly new equipment when the demand surges.

The surge in the use of more electronic equipment and the need for more bandwidth has an implication on the power supply. The power capacity has to be increased as well in the field. However, an increase in the size of the generators should not be the only answer to solve these problems. There are logistical, signature and “real estate” issues when the number and size of the generators are increased in tandem with the power requirements. Innovative, emerging energy storage solutions, new sources of power and advancement in power distribution may change the logistics arrangement of the Army as well as its operational concepts. There is thus a need to keep a technology watch on these supporting technologies as well.

In today's context, there are some emerging promising fields that may be dominant in the battlefield of tomorrow. For example, robotics and unmanned, autonomous and networked systems are the next "technology S curves", which the SoS architects must embrace and look out for its trends. In fact, Levinson (2010) reported that the Israeli defense industry is "one of the world's leading innovators of military robots" and they believed that the next phase of development will be transit into the "robotics era". This should be factored in the design of the SoS as a force multiplier.

Similarly, there has been research on electronics bombs to knock out all the electronics and communication systems. If this scenario materializes, there must be risk mitigation plans in place to protect the critical command and control systems, from this disruption in order for the own forces to continue to operate in the same or degraded mode. It should not be a mission failure risk. While it may not be necessary to put risk mitigation plans in place if the threat level is not available in the near future, it is still valuable to deliberate and identify critical areas of the SoS which need to be protected against such threats.

Lastly, there is also an emergence of software defined radios. Software radios can be used to transmit and receive communication from different radios protocols in real time by changing the software. There is a huge potential and interest in this technology because it can reduce the number of radios and the number of interfacing “frequency patching” systems that allow different types of radios to “communicate” with one another.

One may ask “what is the impact of this epoch sub-category on the value robustness of SoS?” First, the architect might design the SoS in anticipation of the emergence of the technology in terms of its Technology Readiness Level. He can factor this into future development plans of the SoS if the technology is ready in the near future for implementation. This can be in the form of compatible interfaces or adopting an open coupling architecting concept to integrate this technology. Software defined radios is one example whose development is currently in progress and might be close to maturity in the near future. As such, the communication protocol might be designed such that the new radios are able to communicate seamlessly with the current operational Very High Frequency (VHF)/ High Frequency (HF) radios.

6.5.2.2 Epoch Variable – Availability of Technology

Another area of concern may be the availability of technology. Issues concerning this might be a freeze in technology transfer from a strategic partner, who has the know-how to a critical technology that Country Sierra wants to acquire. To mitigate this risk, the SoS architects may attempt to develop technology collaboration agreements with a diverse pool of strategic partners. Another strategy may be to selectively invest in research and development activities for high pay-off technologies that may provide a quantum leap in capability. This strategy is also applicable in cases where certain strategic technologies or systems are not available for sale and the Army has to nurture its defense ecosystem to perform research in that indigenous capability. Electronic warfare technologies and computer security are two such examples.

6.5.3 Epoch Category - Strategy/ Mission

The category of “Strategy/ Mission” is broken down into two sub-categories: changes in the threat level to SoS and multi-spectrum operations.

6.5.3.1 Epoch Variable – Changes in Threat level to SoS

The evaluation of the capability against potential adversaries is important. It allows defense strategists to determine if the current SoS capabilities are sufficient to mitigate the threat level. As SoS development is never static, the SoS design must be kept relevant and continue to deliver high in value to the stakeholders. As the threat level of the potential adversary changes, the SoS capabilities have to be reviewed periodically. This is to ensure that the army is constantly equipped to deal with the latest threats. New capabilities may be required to enhance the SoS. The implication for SoS architects is to ensure that the interfaces between new entrants into the SoS and the rest of the SoS elements are compatible. They also have to ensure that the value of the SoS to the stakeholders is maintained or enhanced over the years.

One possible threat to an army may be cyber warfare. As many modern armies configure their SoS to mirror the US Military’s Network-Centric Operation concept, there is a potential threat that an adversary will try to disrupt the network communication system to destroy the strategic advantage of sharing information within the network to enhance battlefield situation awareness. Information may be intercepted and amended by enemies. These will put the troops at risk if the information cannot be received or modified. Possible states of this epoch include a secure communication network, a degraded network and a shut down network in the worst case scenario. SoS architects have to consider these states when comparing between the SoS concept alternatives. One mitigation action in the system design concepts might be to provide redundant, back-up systems such as the current VHF/HF radios, which provide voice communication and limited data communication. This may complement future high bandwidth, digitalized networks such as US's Joint Tactical Radio System (US Army, 2009b).

6.5.3.2 Epoch Variable – Multi-spectrum Operations

Although the Army SoS is designed primarily to prepare for war, its value will be greatly enhanced if they can be deployed for other operations. For example, certain elements of the SoS may be deployed for operations in a national event such as providing security and support for international conferences such as International Monetary Fund (IMF) / World Bank events. Ideally, the Army SoS is envisaged to have component systems which are value robust. The component systems can be configured using a "plug and play" concept to meet new operation objectives. The component systems can be easily "retrieved" from the SoS design and "configured" with other SoS elements to perform a new role. One example is that combat service support elements can be used to provide humanitarian assistance and disaster recovery. For example, medical systems and command centers, which are used to provide medical services to injured troops in war, can be transported and set up in a disaster zone to help civilian authorities treat injured people. The 2004 Indian Ocean Tsunami Disaster was an example where international armed forces utilized their military assets to help affected nations such as Indonesia and provide immediate aid relief to save the injured and stranded people (UN OCHA, 2006). Ships, aircrafts, and military logistical vehicles were some of the equipment utilized.

6.5.4 Epoch Category – Product

The author will emphasis one sub-category of “Product”: Missing system nodes in the network.

6.5.4.1 Epoch Variable – Missing system nodes in the network

It is possible that the C4ISR network may be degraded during its operations. This epoch is very real and affects a networked force. As such, the SoS architect has to ensure that there is a strategy in place to harness the suite of weapons or systems available in the whole integrated force to temporarily overcome the deficiency in the network operations. For example, if a command post is unable to transmit information to other units, there must be supporting nodes or systems in the neighboring area to transmit the information until the command post’s communication system is functional. In another instance, if the shooters, such as artillery, are not available to provide far fire support, the maneuver forces might use its long range gun systems to provide fire base support to support the ground troops in overcoming the adversary at an objective.

6.6 Suggested Emerging Principles for Designing Value Robust SoS

The Epoch-Era Analysis has been shown to be a powerful tool to help system architects think about potential situations that can affect the SoS. While the tradespace analysis is very promising and may eventually be used to determine a value robustness concept as seen in Chapter 5, the author deemed that more research has to be done in this area so that a comprehensive SoS concept evaluation of large scale SoS can be performed effectively. In the interim, the author contends the following emerging principles can be used to help SoS architects formulate a value robustness strategy for the design of the SoS. These emerging principles are mostly based on literature review and the author would like to highlight the following:

6.6.1 "Focus on the design strategy and trades both when the formal SoS is first established and throughout the SoS evolution" (System Engineering Guide for Systems of Systems, 2008)

A SoS architecture involves concurrent and phased development of component systems over years to reach the desired capability goals of the SoS In view of the long development cycle, dynamics changes within the SoS and beyond the system boundary of the SoS is bound to occur. In order for the SoS to remain relevant and deliver consistent high values to the stakeholders, the SoS architecture has to evolve to match the dynamic changes in context and expectations that will inevitably take shape. As such, the SoS architecture must be reviewed periodically and remain adaptable to anticipatory changes. Epoch-Era Analysis is therefore a valuable fundamental framework to aid SoS architects in thinking about changes and it provides the impetus for strategizing value robust SoS.

6.6.2 "Use an architecture based on open systems and loose coupling" (System Engineering Guide for Systems of Systems, 2008)

The US DOD recommends an SoS architecture that is based on "open systems and loose coupling" whenever possible. This approach can facilitate the ease of trades among component system alternatives without affecting the global goals of the SoS architecture and vice versa. A strong informational and structural coupling among component systems might not be ideal because the absence of a particular system will affect other component system and degrade the overall capability of the SoS. It might also make it difficult for an SoS architect to infuse new capabilities into the SoS by introducing new systems, because this might involve changes in other systems that will escalate the SoS cost. On the other hand, an approach of "open systems and loose coupling" will facilitate the implementation of a decomposition strategy of "structure and behavior". There are clear goals of what each component system is supposed to achieve. This concept allows the SoS architect to pursue a flexible and scalable design approach based on stakeholders' needs, and maximize their utility in the SoS concept over time.

In line with this emerging principle, Ross and Rhodes (2007) presented a "system shell" methodology as a means of preserving the value of the SoS in the face of changing contexts. They introduced the concept of system shell that would consist of the inner "shelter" and the outer "mask". The "shelter" protects the system from external context changes, and makes it insensitive to external changes while the "mask" preserves the perceived value of the system as seen from within the context. This concept exemplifies the benefit of having an open system and loose coupling in a SoS.

If the design of every component system in the SoS is decoupled from the design of the other component in the SoS, a “shelter” is being built across the component systems whereby the removal or addition of other component systems will not affect the performance of the systems that remains in the SoS. This allows design trades of the component systems without affecting the overall global SoS. In addition, these concepts allow legacy systems to participate in the SoS without being obsolete or require huge modification costs whenever the SoS context changes.

6.6.3 “Leverage at the Interface” (Maier, 2009)

Maier (2009) has advocated that SoS architects should leverage the interfaces of the SoS. The “system shell approach”, specifically the “mask” method, is also built on this principle. The interfaces of a SoS can be designed to be flexible and changeable in order to preserve value of the component systems in changing contexts. For instance, legacy defense systems can continue to provide value and operate in a network-centric SoS by designing gateways, which serve as “adapters” to the rest of the component systems in the network centric SoS.

6.6.4 Focus on the glue: the Command, Control and Communication Network

A robust communication network is also a key success factor in a network-centric Army SoS. It is cornerstone of network-centric operational concept of the US Army. A robust communication system can allow battlefield information to be disseminated among battlefield units securely. Information superiority is a strategic capability as it magnifies the situation awareness of all combat units in the SoS. As such, in order to provide high value to the stakeholders of the Army SoS, the communication systems must remain robust, be scalable in design to accommodate the growth of the SoS and interoperable with each other.

6.6.5 Focus on the "ilities"

Tang (2009) argued that one of the SoS's designs pertains to the management of "ilities" as a "value multiplier". However, it is important to distinguish the different "ilities" that are often used in a confusing way. Ross, Rhodes and Hastings (2008a) attempted to clarify robustness, scalability and modifiability as possible "effects" of a system change. On the other hand, "flexibility and adaptability" describe a change of the system that is made by an external agent or internally by the system itself. As an adaptation of Ross and Rhodes (2008) research findings, there are two possible value robustness strategies, passive value robustness and active value robustness corresponding to robustness and changeability of the systems. Refer to Figure 6-9.

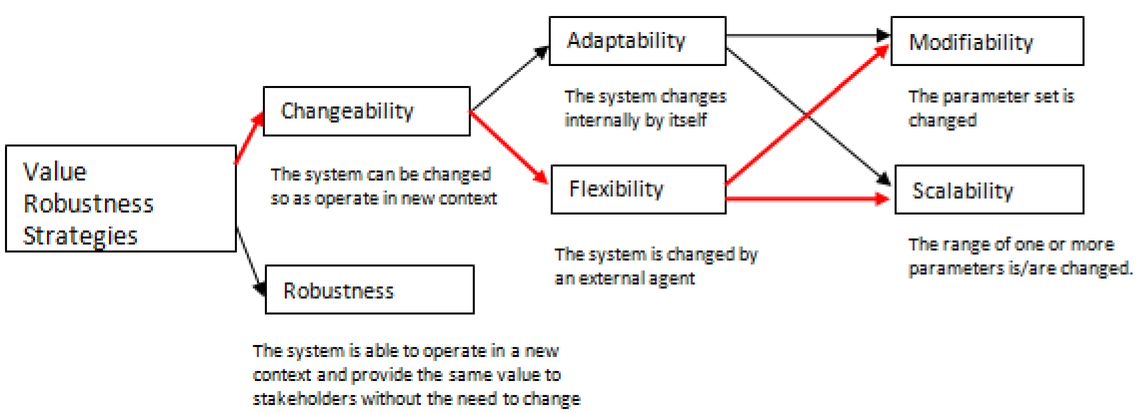


Figure 6-9: Value Robustness Strategies

However, a defense SoS is likely to evolve because there is a constant need to review and improve the capabilities to fulfill operational needs to mitigate the threats posed by potential adversaries. In the face of uncertainties in the future, modifiability and scalability are desired outcomes of the SoS as illustrated by the SoS.

On the other hand, value robustness of an Army SoS is also associated with outcomes of interoperability. Chen, Gori and Pozgay (2004) asserted that defense SoS architects are especially concerned with “joint effects, interoperability levels and analysis, information sharing as well as planning, coordination and management of system evolution”. The ability to communicate and disseminated information to battlefield units, regardless of services, platforms, and force level, to appreciate the battlefield situations and take decisive actions to defeat the enemy is strategic. This is facilitated by a robust network communication system.

Finally, modularity is a key principle in the SoS architecture concept. Fricke, et al. (2005) asserted that a modular architecture facilitates changes, and a changeable architecture is desirable for highly connected systems with the need for future growth (i.e. SoS). Similarly, a modular architecture is also useful in integrating legacy systems into the SoS, so that these systems can continue to provide value under the new SoS context.

6.7 Value Robustness of the Baseline SoS

After the discussion in Section 6.3 and 6.4, one may ask the following question:

a. Is the current configuration of Country Sierra’s Army SoS value robust?

The author believes that the Army SoS is value-robust based on the following perspective:

The Army SoS has undergone three distinct eras. The first era occurred when the Army had functional formations of Infantry, Armor, etc and they operated in silos. The second era occurred when the Army was organized as a Combined Arms force, which brought together the elements of the various formations to operate as a team. The force harnessed the different capabilities of the elements of each formation and was centrally controlled by the force commander. As a result, the commander had a variety of resources to help him meet the mission objectives. There was also better coordination and synergy between the elements of the Combined Arms force as compared to the situation where the Army operated in separate functional teams. The third and current era takes place when the Army harnesses the capability of information technology to build a network force. According to Chen et al. (2008), the general characteristic of the network force is the ability of the force to work as an “integrated team”, “achieving information superiority” and “leveraging precision fire and maneuver”. In this vision, the communication network links every element of the Army together and also connects to the Air Force and Navy elements to function as an integrated force. The characteristics also meant that the Army is also capability centric as compared to platform centric Army of the second era.

As such, the SoS is utilizing the active robustness strategy to preserve value for the stakeholders. Using modeling, simulation and experimentation, the Army SoS is evolving in the present era. Different operating concepts and capabilities are trialed and experimented. Spiral developments are also being carried out concurrently with the development of the Army SoS to realize the vision. At the same time, strategic investments in indigenous technology were also hedged in order to provide the next quantum leap in SoS capability. Successful capabilities will then be integrated into an Army SoS. The interviews from the stakeholders revealed that the Army SoS is envisaged to be an integrated force, tapping on all the SoS resources and augmented by the communication network system, that is, battlefield management system. “Ilities” such as flexibility, scalability and evolvability are central to the theme of the Army systems and are also consistent with the changeability paradigm in active value robustness literature.

However, more research is required to determine the degree of value robustness in the current SoS. Quantification of value robustness of a SoS is an active area of research. Two important sets of information are required to facilitate the discussion. First, there is a need to determine the number of paths to change and evolve for each of the SoS architecture concepts. Second, there is also a need to determine the cost of changing along each network path from the current SoS design to the next desired SoS concept. In view of the large number of systems within the Army SoS and design parameters of each system, it is challenging to use tradespace analysis to select an active value robust SoS. In the meantime, the author would like to propose decomposing the SoS into smaller groups of SoS for analysis for value robustness. This will be discussed in Chapter 7.

In order for the current SoS to continue to provide value to the stakeholders, system architects have begun to develop capabilities in emerging technology fields. Unmanned and autonomous technologies have proven their usefulness in ISR systems. They will continue to evolve and expand in applications. The use of precision weapons has added an extra edge to the capabilities of Country Sierra’s Army. Precision weapons such as the High Mobility Artillery Rocket System (HIMARS) allow the forces to pin point and destroy an enemy target with better precision than the convention artillery and mortar guns. As such, continued investment and development in the sensor-shooter configurations will provide high value to the stakeholders in the foreseeable future. Lastly, the robustness of the C4ISR system is critical and has been deliberated at length in the earlier sections.

6.8 Conclusion

Epoch-Era Analysis has been applied at a conceptual level to the baseline Army SoS described in Chapter 6. The analysis has provided insights into the exogenous factors that will affect the stakeholders' perception of the value of the Army SoS over time and assist the SoS architect to shape the SoS to maintain or improve its value robustness. Emerging principles are also proposed by the author to help SoS architects to design a value robust SoS under dynamic contexts.

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Chapter 7 Discussion and Recommendations

7.1 Introduction

Chapter 7 summarizes the contributions of this thesis. It also discusses the strengths and usefulness of the proposed methods for architecting value robust defense systems and SoS. The methods are still being refined and will require further validation at the SoS level before being ready for implementation. In view of this, the author will provide recommendations on areas of enhancement to make the methods comprehensive for future applications.

7.2 Overall contributions

The primary contribution of this thesis is a demonstration of an approach to formulate a value robust defense system or SoS architecture at the front-end concept planning stage. The proposed approach provides a systematic means to brainstorm, synthesize, screen and select architecture concepts. The methods used in this approach include the “Needs to Architecture” framework, MATE, and Epoch-Era Analysis. The proposed approach also facilitates a complete architecting process for gathering the needs and selecting a concept that is value robust to the stakeholders. In addition, system architects are able to use a common baseline (i.e. utility level) to compare between concept alternatives and assess if they are value robust. This is a key advantage that is not available to the architects using existing architecting methodology that relies strongly on heuristics and experience, whereby validation of value robustness can only be performed after the system or components of SoS are developed.

The proposed architecting approach is also compared against existing complex architecting methods such as Operational Analysis (OA), Modeling and Simulation (M&S), and Experimentation, which are used to develop and evaluate architectural options. These architecting methods require significant time and modeling resources to model the behavior of the SoS. While the proposed value robustness approach is not meant to replace OA, M&S and Experimentation, it serves to complement these methods by providing a quick exploration of all possible tradespace options and down-selecting to a few value robust design options. The value robust concept options can then be modeling using OA and M&S to further validate and optimize the SoS concepts. As such, the time and effort to evaluate the design options can potentially be reduced. The Epoch-Era Analysis also provide the additional advantage in allowing the SoS architect to postulate future changes and mitigate these changes through the design of the constituent systems or SoS. While the proposed approach are still being refined, it has the potential to satisfy stakeholders' needs in the long run under possible changing needs, contexts and expectations.

In addition, the overall architecting methods involving "Needs to Architecture" framework, MATE and Epoch Era Analysis, are thought to be intuitive and easy to use. This is important to defense system architects, acquisition project managers, stakeholders and decision makers. The ease of use of the methods will spur their adoption within the defense community. Lastly, the case studies in this thesis provide further validation on the usefulness of the methods towards architecting a system or SoS for value robustness.

7.2.1 MATE

MATE is a method that utilizes parametric modeling to assess different concepts of a system or SoS quantitatively on a common utility-cost basis. Maximizing stakeholders' utilities and minimizing the system or SoS cost is the typical goal of the MATE analysis. MATE is a good alternative to the method where concepts are proposed through brainstorming and a participative method is used to select the concept. If the concepts are not explored comprehensively in the system architecting phase, the number of concepts might be artificially constrained early in the system's development. A single-point design might be selected based on the few concepts offered in the concept formulation stage. This is in contrast with MATE, which allows many architectural concepts to be considered in the same tradespace. Chapter 5 demonstrates the method through the selection of an ISR system in the defense context. There are three architectural concepts: fixed wing miniature flying platform, rotary wing miniature flying platform and rolling miniature land platform. Their performance was benchmarked to the system's goals and the comparison done using utility and cost. The utility level of the stakeholders towards the system's attributes belies the stakeholders' perceived preferences and serves as a quantifiable measure for comparison, instead of articulating the preferences qualitatively with no common denominator. Another benefit of MATE over a traditional concept screening and selection stage is the tradespace (i.e. utility-cost plots) provides a good visualization tool of the preferences of the stakeholders' concept, and helps as a starting point for deliberation. Supported by the "Needs to Architecture", it provides traceability on how the concepts meet the system goals and how the trades among the attributes can be performed.

For more complex SoS, MATE holds great potential as a tool to select different SoS architectures. Using computer modeling and simulation, SoS concept performances may be simulated and utility levels are found by benchmarking to SoS's goals and attributes. However, this requires a substantial modeling effort and this is especially true when SoS are built from scratch. While there are challenges to acquire proprietary information on the different defense systems' performance, the simulation using low fidelity information from product brochures, look up tables of performance statistics and proxy systems' technical information, can still provide valuable assessment on whether a SoS architecture concept can meet the SoS attributes. The SoS tradespace analysis is extremely useful when used in conjunction with Epoch-Era Analysis where the long term vision, capability needs, operating environment and mission contexts are assessed and postulated. Specific to SoS, tradespace analysis is also beneficial in situations where the baseline SoS is made available already. Evaluation is only required for changes in constituent systems, with all else held constant. The capability change will be evaluated in a SoS context, and the tradespace exploration will be simpler than the case where the whole SoS is initiated or revamped from scratch.

Take for example, a precision strike and sensor system required to augment the sensor-shooter capability of an established Army SoS, as described in Chapter 6. Tradespace exploration can be performed using numerous sensor-shooter concepts with the rest of the Army SoS's Maneuver, Combat Service Support and Counter

Mobility & Mobility systems intact. This type of tradespace exploration is meant for selecting SoS concepts where “gap-fillers” are required to supplement the rest of the SoS elements in place. An example of the sensor shooter system concept may be a UAV (e.g. HERMES 450) system relaying information about an enemy target to a land based Mobile Command Post, which in turn issues command orders to strike at the enemy using a precision strike weapon such as High Mobility Artillery Rocket System (HIMARS) in a networked centric operation. The rest of the SoS constituent systems remain the same. These new SoS concepts with the different sensor-shooter architecture concepts may be modeled using simulations, and the overall performance of the SoS is evaluated based on the success of the missions of the Army SoS. They are then represented in the tradespace and the concept is selected with the support of MATE. In addition, small scale actual field testing may be performed to ascertain its capability performance of the sensor shooter concept. More research remains to be carried out to combine the computer and parametric simulation, with tradespace exploration, that is, using MATE to select value robust concepts in the SoS domain.

7.2.2 Epoch-Era Analysis

Epoch-Era Analysis involves dividing the system or SoS’s lifecycle into a series of epochs with fixed needs and contexts. The epochs are joined together to create an era that shows a long term picture of evolution of the system’s context. This method is useful because system architects can think ahead and devise strategies at the front end concept design stage to mitigate the risk of the system’s being obsolete when dynamic changes in needs, context and expectation occur. It can provide valuable insights of new technologies or systems that will be available in future, and prompt system architects to plan for their inclusion at the design stage or during upgrades in future. This is more cost effective as compared to developing a new system in future.

Epoch-Era Analysis is found to be useful in defense system and SoS architecting as shown in Chapter 5 and 6. It is a promising tool in the area of SoS development, which takes on a longer horizon. As a SoS evolves to incorporate new capabilities, Epoch-Era Analysis can be repeated to reassess conditions in the future and calibrate strategies to sustain value to the stakeholders. Chapter 6 shows several exogenous categories, such as strategy/policy, capital, resources and product, which can impact the design of the Army SoS. These factors are beyond the span of control of system architects, but they do affect the success of an architecture. By considering technical and enterprise factors, the SoS architects are able to assess the effect of these changes on Army SoS and intervene early in the development stage.

Chapter 6 also highlights a generic high level Army SoS's form and function. As mentioned previously, the information about the specific forms are incomplete due to the sensitivity in revealing defense capabilities. The information is also not exhaustive as much of the information is obtained from public domains. Therefore, in the real scenario, a complete picture will reveal the full extent of the Army SoS and identify opportunities for the continued evolution of the SoS. However, the system architects will still be able to obtain important insights even with the low system model fidelity. Through multi-epoch analysis, the author is able to obtain insights regarding the critical Army assets as well as future capabilities which might be decisive in the battlefield. The semi-structured interviews also offer collective insight from participants with regards to the possible epochs and their effects on the Army SoS.

7.2.3 Value Robustness Strategies

This thesis also sharpens the focus on value robustness strategies being designed upfront in the concept stage. Passive and active value robustness strategies are discussed for the concept stage. Coupled with the multi-epoch analysis that offers a possible long term view of what might happen in future, the concept selection will have taken into account these strategies through the use of metrics such as Pareto Trace and Filtered Outdegree. The stakeholders and decision makers will have to deliberate and decide if they should pursue a robust or changeable design. The value robustness strategies would provide a clear direction and justification for the resources. For example, the use of a flexible strategy would provide architects with the justification for additional resources to incorporate design features that enable changes to be done more easily at a later stage. It also means that there must be subsequent budget to allow the changes to be made when a future epoch arrives. Chapter 5 shows how passive robust defense system designs can be identified through the Pareto Trace. A semi-quantifiable method to identify active value robust designs is also demonstrated. This method is advocated as a quick assessment tool, which is useful to defense system architects and project managers to evaluate concept designs in acquisition management projects. The Filtered Outdegree metric is a comprehensive analysis to discover active robust designs, but it requires more elaborate analysis and information.

Extensive research work in the Filtered Outdegree metric to identify flexible, value robust design is currently on-going.

7.2.4 Enterprise Considerations in Epoch-Era Analysis

Increasingly, the technological solutions of the SoS are intrinsically linked to the evolution of the enterprise of the SoS. The enterprises of the constituent systems that make up the SoS have an impact on the SoS architecture and vice versa. Hence, it is critical for the architect to capture the influence of the enterprise view on the technical SoS architecture concept at the front-end stage in order to deliver sustained value to its stakeholders. Chapter 4 and 6 highlighted several factors from the Value-Based Enterprise Model, such as resources and strategy that can shape the evolution of SoS. By considering enterprise and technical views in a holistic manner, the Multi-Epoch Analysis or Epoch-Era Analysis enables a powerful conceptualization tool of the evolution of the technical aspects of the SoS that are moving in tandem and interconnected with the changing landscape of the SoS enterprise. The enterprise and technical views will only enrich the concept screening process. In addition, these views provide a rigorous assessment on the value robustness of the SoS architecture concepts in the tradespace analysis.

While there is immense potential in using the epoch-based analysis at the technical and enterprise level, considerable research work is still ongoing to validate its applications through additional case studies. There is also extensive research work in the field of enterprise architecting, that is, the use of epoch analysis to shape and transform large scale complex enterprises involving multiple SoS stakeholders.

7.3 Possible Improvement and Future Research

While the proposed value robustness approach provides immense value to the field of system architecting, the author would like to provide input on the limitations and propose suggestions for future research. They are discussed as follows:

7.3.1 Chance of Epoch Occurrence

When a passive value robust strategy is pursued, all the concept designs are evaluated across all epochs. The concept design that has the highest frequency of occurrence on the Pareto Front across all epochs will be the concept that is most likely to satisfy stakeholders' needs in the future. However, a passive value robust concept design may not necessarily be on the Pareto Front in the epoch that matters most to the stakeholders. Take, for example, a hypothetical case in Chapter 5 where an ISR concept design that provides high value to stakeholders across other epochs such as peacekeeping, counterterrorism, humanitarian assistance and disaster recovery operations may not be a design on the Pareto Front in operational environment of "war. However, the system is being developed for defense operations in war and it is this context that the decision makers are most willing to pay for. Under such scenarios, it might be difficult to convince the decision makers that the selected value robust design meets their needs in the most pressing context. While the Epoch-Era Analysis anticipates that an epoch will occur in the future, there is no certainty that the particular epoch will take place. By investing in an ISR system that provides lower utility to the stakeholders in the epoch (i.e., war operation), that matters most to defense forces, but has capability that provides high utility in other epochs that might happen in future, strong justifications will have to be made by spending effort to assess the probability of occurrence of the rest of the epochs. This is especially the case if the acquisition is made with public funds (i.e. tax payer’s money), and there is scrutiny towards how the funds are used. Therefore, decision makers and stakeholders may not be willing to develop a system that is deemed high value for many future contexts. To tackle this issue, future work may involve the need to estimate the likelihood of occurrence of the epochs, or separate multi-epoch analysis across high importance epochs as well as across all other epochs. In the meantime, qualitative assessment might be required to gauge if the likelihood of certain epochs occurring. If certain epochs have low probability of occurrence in the future, considerations may be made to eliminate the epochs from the Pareto Trace or Filtered Outdegree calculation. However, the system architects have to think of other systems that may be used to perform the same role when the epoch occurs in future. Lastly, another solution is to use the Fuzzy Pareto Trace metric. It involves introducing a fuzziness factor into the Pareto Front for each epoch so that designs that are “close” to the Pareto front are also considered (Ross, Rhodes and Hastings, 2009). The system architects can estimate how much fuzziness or the rate of change of the system cost in order to include a solution near the Pareto Front of the epoch that stakeholders are concerned with. This fuzziness can reflect the level of uncertainty in the utility levels of the stakeholders or cost. However, further research is required to determine the impact of fuzziness to passive robustness of the selected concept as well as being in the Pareto Front in the epoch that stakeholders care about.

In the case of a situation where there are multiple epochs, numerous eras can evolve due to the different combination set of epochs. When this happens, there is a concern as to which era is likely to occur because the epochs in the selected era will be used for the active and passive value robustness analysis. The selection of the most likely era is still an area of future research.

While the tradespace analysis and Epoch-Era Analysis are useful methods for evaluating front-end design concepts, the sheer number of parameters in the design and epoch vectors makes it extremely challenging for system architects to analyze and elicit information for visualization and communicating the trade-space analysis to decision makers. Ross et al. (2008) proposed a Responsive Systems Comparison method (RSC) which enabled an ordered arrangement of the epochs to reflect possible future changes. This reduces the number of possible future scenarios for evaluation. Alternatively, the system architects can choose to restrict the amount of changes that a system can undergo because it is impossible for the system to be so versatile to be robust or changeable to meet all possible future scenarios. One possible way that the system architects can think about is the characterization of changes that is, (a) high impact, high probability (b) high impact, low probability, (c) low impact, high probability and (d) low impact, low probability changes. Those changes that are low impact, low probability of occurring should be eliminated from evaluation. By considering those possible changes which will bring about high switching or change costs, the number of possible future scenarios can be further reduced, the tradespace appeared pruned and less cluttered.

7.3.2 Tradespace Exploration of SoS

Although tradespace exploration can be used to assess SoS architectures, more extensive research has to done in this area. Defense SoS might consist of multiple, independently managed, networked systems working together to fulfill missions to defend a country against adversaries' attack. As such, the design vector of the SoS will consist of multiple design variables. There are two challenges associated with this large design vector. First, extensive modeling will be required to replicate the performance of all the individual systems in the SoS in order to ascertain the SoS attributes. However, there are many permutations and design variations in each system. For example, there are many versions of Main Battle Tanks (MBT) in the Fire Support System category. All these have different performance parameters. Unlike a system, SoS involves all the constituent components working together to perform a mission. As such, while the performance of individual systems can be gauged using the performance specifications, the performance of the SoS, as a whole, will have to be validated through modeling. This challenge is compounded by the difficulty of obtaining a database of all possible versions of defense systems available in the market.

As such, more research work has to be conducted before MATE is useful as a screening tool for SoS architecture selection. MIT System Engineering Advancement Research Initiative (SEAri) has started work on the creation of a laboratory environment equipped with computing systems to undertake the tradespace exploration of complex, large scale systems. With the set up of this laboratory, the time to perform complex tradespace analysis can be reduced. At the same time, SEAri will continue to build on and develop Chattopadhyay (2009)'s initial work on a conceptual SoS Tradespace

Exploration Methodology (SoSTEM) to compare multi-SoS concepts. When the SoSTEM is fully developed, it has the potential to assist system architects to identify value robust SoS in the front end, conceptual design phase. Separately, there are also plans to complement tradespace analysis with modeling and simulation analysis so that performance and behavior of SoS architecture can be predicted with accuracy. The emergence of the Model Based System Engineering (MBSE) Approach may also complement the tradespace analysis in the future. The System Modeling Language (SysML) is one possible MBSE tool where the behavior of systems may be modeled in its State Machine, Sequence and Activity Diagrams. Its Parametric Diagram can depict the constraints and critical design parameters. All these information can be ported over to simulation software for validation of the performance of a single system. A fully developed MBSE approach might be used in conjunction with tradespace analysis for SoS. MBSE is currently an area of intense research within the INCOSE community. All the above mentioned work are in progress and can address the current limitation of the SoS tradespace analysis.

In the meantime, the author has proposed that the SoS's concept selection be performed in a staged deployment manner. The SoS can be broken up into small scale SoS, for example, the Mobile Command Post, the soldier, ISR system and Infantry Fighting Vehicle can form a surveillance SoS as part of the bigger Army SoS. They are networked together using the Battlefield Management System. Tradespace Exploration can be performed in a manageable permutation. Their performance can be validated using simulation software and validated on the field using field trials of proxy equipment to gauge the overall effect. Once the selected concept is validated as a value robust

SoS, the SoS is scaled and more system or smaller SoS can be added to assess the overall performance.

Similarly, there are significant challenges to incorporate systems that have the potential to be dominant in the near future into the tradespace for concept selection. In the SoS domain, new, “big bet” technological systems are often included into the defense SoS over time to increase its capability. However, it might not be easy to pin-point its performance with a fair degree of confidence at the front end development stage where the tradespace analysis is being conducted. This is because the technologies (e.g. TRL 5, 6 or 7 technologies) might not be proven at the point of concept selection. If the high payoff, new technology is incorporated as part of the operating concept of the selected SoS design, there is an associated risk that this technology may not be ready in future and hampers the simultaneous development of other SoS constituent systems or the success of the mission concept. In view of this, the author will propose risk mitigation strategies to be put in place into the concept which incorporates future, uncertain emerging technologies. There must be back up, proven systems or mission concept fragments that will facilitate the viability the SoS mission concept even if the new technologies are not realized in future. When the high payoff technologies did not materialize, the stakeholders and decision makers must accept that the backup solutions will result in a lower utility level and possibly a less passive value robust SoS design. The system architects might have to intervene to evolve the development of the SoS such that stakeholders’ values are maintained in the long run. The dynamics are fluid and more research work might be required to offer possible solutions or strategies to deal with such situations.

Lastly, tradespace exploration might not be able to take into account the “emergence” effect of the SoS. This emergence effect is only possible through a unique combination of constituent systems working together to perform a role that is not possible with the individual systems and it is a challenge to assess emergence effects in the SoS tradespace exploration. While it is hard to model the positive emergent behavior, one possible way to view the use of tradespace exploration is that it can potentially help to identify and sieve out SoS architectural options that have negative emergent behavior. The incompatibility of certain constituent systems in the SoS (e.g. two constituent systems might not be interoperable with one another or significant changes are required in the constituent system’s designs in order for them to work together) might be identified and this might help to prune the numerous SoS architectural concepts at the front end stage.

The author also opines that the emergence effect of the SoS can be studied through the “ilities” associated with the SoS. Flexibility, scalability, evolvability and survivability are some of the key SoS related “ilities”. While “ilities” research has been on-going in the system engineering field, more research is suggested into the assessment of emergence effects in tradespace exploration.

7.3.3 Real Options and Active Value Robustness

Epoch-Era Analysis can be used in conjunction with “Real Options Thinking”. A real option is the right but not the obligation to utilize. Real Option embodies the concept of flexibility (Spinler, 2009). Epoch-Era Analysis is able to identify the system or SoS’s performance in different scenarios representing different contexts. Some of the system’s requirements may not be required under the present epoch but will be useful in other epochs. As such, one strategy is to introduce flexibility in the design by incorporating desirable design attributes in the system design and utilize it when the need arises. An example is shown in the case study in Chapter 5. One of the attributes is to assess the design if there is flexibility to mount payload. Stakeholder's utility will increase if the ISR system's payload design is modular and able to mount additional sensors. While the current mission requires the ISR system to carry one sensor for surveillance, there might be a need to carry other type of payload in future. The excess payload capacity might be use to mount a different payload such as acoustic or HAZMAT sensors. The additional, built in, payload capacity is a real option. Should the need arise in future; the system can be adapted easily to meet new mission need instead of acquiring a new platform for the mission. In addition, a modular design is a strategy that builds in flexibility in the design. Having modular payload ports may allow different sensors to be fitted into the ISR system. It is a strategy that is associated closely with real option to mitigate uncertainty of needs that might only be defined in future epochs. As such, the author advocates a more in-depth research into the combination of real option into tradespace analysis evaluation and active value robustness strategy.

7.3.4 Risk Assessment

The concept screening and selection has utilized the concept of utility or benefit and cost for all the concepts. However, risk has not been considered in the framework. The risk may come in the form of technical, schedule and cost risk. Some of the risks are shown in Figure 7-1.

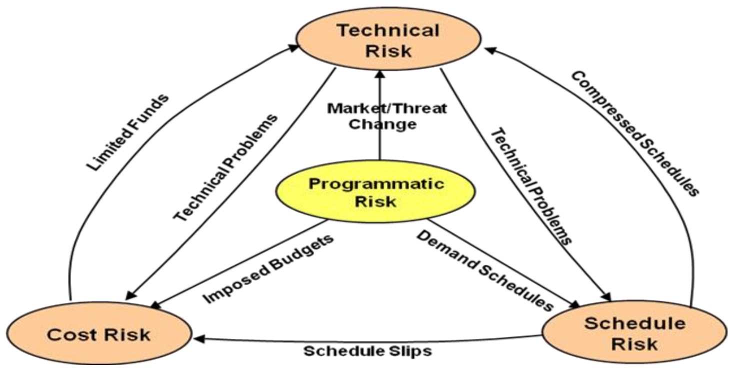

Figure 7-1: de Weck (2009) representation of risks and their inter-relationship

The cost risk of a system might be represented by a range of utility-cost data to reflect the uncertainty in its cost. However, there is no framework to take into account the technical and the schedule risk of the concepts. Certain architectures may be riskier than the rest of the concepts as some of these technologies may not be proven yet. Similarly, there may be concerns regarding delivering the system or SoS capabilities on-time based on needs. Defense needs are correlated to threats analysis and are therefore time critical. In view of this, there is a need to perform risk analysis for each concept in addition to the tradespace exploration that stresses utility and cost. A study may be required to integrate a risk framework with the tradespace exploration.

7.4 Summary

This chapter provides a discussion of the strengths and limitation of the methods used in the proposed value robustness approach. The author explains that the methods are able to assist system architects to systematically explore the design concept tradespace, analyze the tradeoffs between alternatives in different epochs, and converge on a solution that is able to provide sustained high value to the stakeholders. Future works are also proposed to make this approach robust.

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Chapter 8 Conclusion

Architecting systems and SoS for value robustness is a new approach in system architecting. This approach explores the notion of value robustness in the front-end system design phase as compared to traditional system architecting approaches, which do not consider explicitly whether the selected concept design is the best design among all possible alternatives in satisfying current and future stakeholders' needs. The approach emphasizes the use of "tradespace exploration" and "epoch-based thinking" to guide system architects to investigate value robustness in system design. Appropriate selection strategies will be adopted to ensure that the concept design remains robust under future postulated scenarios or is able to be changed easily to meet anticipated changes in needs, contexts and environment.

This thesis has met the three objectives stated in Chapter 1. The proposed approach, utilizing the "Needs to Architecture" framework, MATE and Epoch-Era Analysis, has the potential to ensure that the defense systems and SoS are passively or actively value robust. While the MATE analysis for SoS, that is SoSTEM, requires further research validation, the Epoch-Era Analysis has shown to be useful to conceptually identify areas in defense SoS where there are opportunities to guide a baseline SoS into a value robust SoS. Emerging principles derived from practitioners in the System Engineering community (e.g. INCOSE and US DOD) further help to shape the system architects' thinking towards incorporating ilities features (e.g. flexibility and interoperability) or design strategies (e.g. modularity) that enhance value robustness in the SoS. Lastly, enhancements to the approach and methods are required to address the limitations highlighted in Chapter 7. Several suggestions are also proposed to further the research.

In conclusion, the author hopes that the approach and methods proposed in this thesis can be further refined to ensure their robustness so that they can better support system architects as they design and select complex defense SoS in future. A combination of passive and active value robustness strategies will ensure that the defense SoS will continue to improve and evolve in its capabilities in a sustained, cost efficient manner. Designing for value robustness is thus a critical proposition that a system architect must consider at the front end phase of system design.

Appendix A: Data Analysis of ISR Systems

Annex A will show the assumptions and key data used in the ISR system case study in Chapter 5.

A.1 Assumptions

1. All the cost information of the ISR systems was obtained from public literatures, product brochures, market research reports and surveys. As mentioned in Chapter 1, Section 1.5, the cost estimates and comparisons were inferred for the purpose of demonstrating the proposed value robustness approach. Section 1.5 also highlighted the challenges in obtaining the cost information. As such, the cost information should not be viewed as comprehensive and reflective of the ISR systems' prices in the commercial environment.

2. The costs of one ISR system was obtained by using a known contract price divided by the number of ISR systems acquired. As an example, TEAL's market report on UAV mentioned that an Oct 2007 contract price for the sale of 36 RAVEN mini-UAVs to Denmark was US$3.6million (TEAL Group Corporation, 2009). As such, the estimated price of one RAVEN mini-UAV was US$100,000. This method of calculation was the same approach taken by TEAL Group Corporation for its report.

3. The technical information for each ISR system was inferred from product brochures and information from public domain. The sources of information were shown in the bibliography section specific to ISR systems.

4. Most technical brochures did not mention the weight of the Ground Control Station whose function is to control ISR systems in operation. However, there is a need to estimate the weight of the Ground Control Station because it is part of the system weight and determines whether the overall ISR system concept is portable. In this thesis, the author had made an assessment to estimate the weight of the Ground Control Station at 10kg. This weight was added to the individual ISR platform weight to obtain the overall system weight. This was applied consistently to all the ISR systems mentioned in Chapter 5.

5. The system life cycle cost would include the system's acquisition cost in the first year, followed by an annual maintenance cost estimate of 8% of the acquisition cost in the next 4 years. The life cycle cost was calculated using Net Present Value with the discount rate being assumed to be 10%.

6. Section 5.3.2 had highlighted that the role playing technique was used to obtain stakeholders' input on the mission and needs. Two military officers, who serve in armed forces, were asked to role play as infantry battalion officers (i.e. Stakeholder#1 and Stakeholder#2). The inputs were based on their personal preferences and were not reflective of their respective organization's ISR requirements. As the intent was to demonstrate the working of the proposed value robustness approach, their preference inputs would suffice.

A.2 Additional information on the calculation of weights of attributes

One of the first steps in the computations was to determine the weights of the attributes. As explained in Section 5.3, the weights of the attributes would be obtained through the House of Quality. Essentially, the weights had to be calculated for all the epochs affecting the selection of the system because each epoch might represent a different mission or use context that would affect the prioritization of the attributes. In the case study example shown in Chapter 5, the stakeholders deemed that the weights remained the same for the mentioned operational environments in Table 5-6. However, the weights would differ slightly between the mission purposes of surveillance and dual usage. If the ISR platform had the flexibility to mount and integrate a variety of sensors or other accessories for operations other than surveillance, it enhanced the capability of the stakeholders of the ISR system to carry out a variety of operations. The flexibility attribute would have a strong correlation to the VOC “Able to use in full spectrum of operations”. A strong correlation and impact would give rise to changes to the attributes’ weights as shown in Table A-1 and A-2. Table A-1 and A-2 showed Stakeholder #1’s House of Quality under different sets of epochs.

Table A-1: House of Quality of Stakeholder #1 in Epoch #1, 3, 5 & 7

Mission Purpose - Surveillance function (Epoch #1, 3, 5 & 7)

Normalised Weights	Weights by Users	VOC\ Technical Attributes	ECO / NUD	Coverage Range (in km) (+)	Flexibility to mount different cameras payload such as EO or IR cameras (+)	System Weight (-)	Time to deploy (-)	Endurance (minutes) (+)	Resource Availability any time any where (+)	Technology Readiness (+)	Ability to survey an object (+)
0.13	5	Able to perform surveillance over an area or object	NUD	9	9	0	0	3	3	9	9
0.10	4	Able to use in full spectrum of operations	NUD	9	3	3	3	3	1	3	9
0.05	2	Prefer to be Manportable	NUD	0	0	9	1	1	9	0	0
0.08	3	Easy to deploy within half an hour	NUD	0	0	3	9	0	3	0	0
0.13	5	Sufficient operating time within a mission profile	NUD	3	0	1	0	9	0	1	0
0.13	5	Prefer On Demand, Real Time Intelligence Information	NUD	0	1	1	3	0	9	3	0
0.08	3	Prefer to be fielded as soon as possible	NUD	0	0	0	0	0	0	9	0
0.13	5	Obtain clear videos and pictures on object of surveillance	ECO	0	9	0	0	0	0	1	3
0.10	4	Able to operate in day and night conditions	ECO	0	9	0	0	0	0	9	3
0.08	3	Provide Safety Cover for soldiers in operation	ECO	3	0	0	0	0	0	0	3
		Relative Weights		2.69	3.67	1.26	1.44	1.90	2.33	3.72	3.00
		Normalised Weights		0.13	0.18	0.06	0.07	0.09	0.12	0.19	0.15

Table A-1 showed the House of Quality of Stakeholder #1 for Epochs #1, 3, 5 and 7. The descriptions for Epoch #1, 3, 5 and 7 were in Table 5-6. In summary, these four epochs represented the state scenarios where the mission purpose was to conduct surveillance under four operational environments of war, peacekeeping, counter-terrorism and humanitarian assistance & disaster recovery.

First, Stakeholder #1 was asked to provide weights of 1 to 5 to every VOC, where 1 represented least important and 5 represented very important to him. Subsequently, the weights given by Stakeholder #1 were normalized. Concurrently, the system architect would determine how the engineering characteristics or attributes would affect the

VOC. Four ranks were given, where 0 represented no correlation, 1 represented weak correlation, 3 represented medium correlation and 9 represented strong correlation. After the correlation was assessed, the relative weight of each attribute would be obtained by multiplying the normalized weights of every VOC with the correlation figures between every VOC and the said attribute. The weight of each attribute was subsequently normalized. Table A-1 showed the detailed computation.

The weights of the attributes would also be obtained for Epoch #2, 4, 6 and 8 as shown in Table A-2.

Table A-2: House of Quality of Stakeholder #1 in Epoch #2, 4, 6 & 8

Mission Pupose - Dual function such as augmenting EOD operation, HAZMAT detection or striking the target using munitions (Epoch #2, 4, 6 & 8)												
Normalised Weights	Weights by Users	VOC\ Technical Attributes	ECO / NUD	Coverage Range (in km) (+)	Flexibility to upgrade and mount other payloads such as sensors or weapons (+)	System Weight (-)	Time to deploy (-)	Endurance (minutes) (+)	Resource Availability any time any where (+)	Technology Readiness (+)	Ability to survey an object (+)
0.13	5	Able to perform surveillance over an area or object	NUD	9	9	0	0	3	3	9	9
0.10	4	Able to use in full spectrum of operations	NUD	9	9	3	3	3	0	3	9
0.05	2	Prefer to be Manportable	NUD	0	0	9	1	3	9	0	0
0.08	3	Easy to deploy within half an hour	NUD	0	0	9	9	0	0	0	0
0.13	5	Sufficient operating time within a mission profile	NUD	1	0	3	0	9	0	1	0
0.13	5	Prefer On Demand, Real Time Intelligence Information	NUD	0	1	1	3	0	9	3	0
0.08	3	Prefer to be fielded as soon as possible	NUD	0	0	0	0	0	0	9	0
0.13	5	Obtain clear videos and pictures on object of surveillance	ECO	0	9	0	0	0	0	1	0
0.10	4	Able to operate in day and night conditions	ECO	0	9	0	0	0	0	9	0
0.08	3	Provide Safety Cover for soldiers in operation	ECO	1	0	0	0	0	0	0	3
		Relative Weights		2.28	4.28	1.97	1.44	2.00	2.00	3.72	2.31
		Normalised Weights		0.11	0.21	0.10	0.07	0.10	0.10	0.19	0.12

A.3 Explanation on the utility level of the attributes

Figure 5-19 had shown the utilities curves of the attributes in Epoch #1. This section would provide additional information on the utility calculations of the attributes in the rest of the epochs. While the maximum and minimum acceptable values of coverage range, system weight, endurance and technology readiness are interpolated to reveal the linear utility curves, more information has to be provided for the remaining attributes, namely flexibility, time to deploy, resource availability and ability to survey the object. They were as follows:

A.3.1 Flexibility

Section 5.3.3.2 explained the three states in single tradespace of Epoch #1. In the following section, the author explained the different states and their corresponding utility levels in each Epoch. For Epoch #1, 3, 5 and 7, the mission purpose of the system was to provide surveillance over an object or area. As such, there were three desired states highlighted by Stakeholder #1 as shown in Table A-3. The highest utility was obtained if the platform had additional payload to mount and integrate at least two onboard EO sensors for surveillance. The least desired State #1 corresponded to a design which had only one camera (EO and/or IR sensor) integrated to the platform. When the platform malfunctioned, the camera could not be removed for other uses (i.e. the payload design is not modular). State #2 corresponds to a design whose sole camera was modular and could be removed if the platform is no longer functional.

On the other hand, Epoch #2, 4 and 6 pertained to the epoch where the ISR system might be used for other mission purposes in war, peacekeeping and counter-terrorism. It would be advantageous if the payload of the ISR system was sufficient to allow the integration of other equipment such that the system could be of dual use in these epochs. State #1 represented the case where the payload of the platform was only sufficient to mount cameras for surveillance. State #2 represented the scenario where the payload was sufficient to integrate other equipment such as manipulator, acoustic sensors etc. A real option was available to configure the system for other mission contexts in State #2. State #3 represents the desired scenario where weapons could be integrated on the platform and would present the highest utility. However, the ISR systems used in the case study did not have sufficient payload currently to mount a weapon.

Epoch #8 represented a scenario where the system was deployed for humanitarian assistance and disaster recovery. As such, there was no desire to integrate a weapon for such operational environment now and in future. In view of this, there would only be two states in this epoch as shown in Table A-3.

A.3.2 Time to deploy

Ideally, the utility level should be linearly interpolated within the desired thirty minutes of deployment desired by the Stakeholder #1. However, there was little, exact information on the ISR systems' deployment time for meaningful comparison. Since the Stakeholder#1 required the ISR system to be deployed within thirty minutes so as to obtain on-demand intelligence information, the author had indicated that any ISR system with an estimated set up time of less than thirty minutes would be given a utility level of 1 for the purpose of demonstrating the proposed value robustness approach. The utility levels were shown in Table A-4.

Table A-3: Utility levels of Attribute "flexibility"

	Attribute: Flexibility to mount different cameras payload such as EO or IR cameras		
	Applicable in Epoch #1, 3, 5 and 7		
	State #1	State #2	State #3
Description	Payload is integrated with the platform	Modular payload design	The platform has additional payload to mount at least two modular sensors
Utility Level	0	0.5	1

	Attribute: Flexibility to mount other payloads such as sensors or weapons		
	Applicable in Epoch #2, 4 and 6		
	State #1	State #2	State #3
Description	Only EO sensors/cameras can be integrated to the platform only	Accessories for EOD or HAZMAT operations can be integrated to the platform	A weapon system can be integrated to the platform
Utility Level	0	0.5	1

	Attribute: Flexibility to mount other payloads	
	Applicable in Epoch #8	
	State #1	State #2
Description	The platform can only mount EO sensors/cameras only	Accessories for EOD or HAZMAT operations can be integrated to the platform
Utility Level	0	1

Table A-4: Utility levels of Attribute "Time to deploy"

	Attribute: Time to deploy	
	Applicable in all epochs	
	State #1	State #2
Description	more than 30 minutes	less than 30 minutes
Utility Level	0	1

A.3.3 Resource availability

Two states were indicated in Table A-5. If the ground commander has control of the ISR system (e.g. his soldiers have a portable ISR system, which can be deployed any time), the maximum utility of 1 will be obtained because the ground commander can obtain timely, accurate intelligence information by activating the use the ISR system as and when he requires the intelligence information. However, the utility level was zero if the commander has no direct control over the system (i.e. strategic or tactical assets, whose control is with the higher headquarters). In this scenario, the ISR system might not be available to the ground battalion commander when he requires information of what lies ahead of his battalion during a mission because the strategic or tactical ISR system might be deployed or prioritized for other usage.

Table A-5: Utility levels of Attribute "Resource Availability"

	Attribute: Resource availability at any time required by the ground commander	
	Applicable in all epochs	
	State #1	State #2
Description	No (Ground Commander cannot dictate control over the platform)	Yes (Ground Commander has control over the platform)
Utility Level	0	1

A.3.4 Ability to survey an object

Stakeholder #1 would obtain a higher satisfaction if the ISR system is able to survey an object or a point. As such, he deemed that a hovering platform would be useful to him to survey an object closely. He had a slightly lower preference for ground platform as compared to a hovering platform because he believed that a hovering platform could provide an all round view of the object while a ground platform might not be able to survey the top surface of an object if the object is at an elevated height from the ground. A lower utility was attributed to a flying ISR platform because there was a need to circle an area a couple of times in order to survey a point object (i.e. the platform is unable to stay stationary at a point to investigate the object). The state scenarios are given in Table A-6.

Table A-6: Utility levels of Attribute "Ability to survey an object"

	Attribute: Ability to survey an object			
	Applicable in all epochs			
	State #1	State #2	State #3	State #4
Description	Unable to survey object	Survey an object from a flying platform (i.e. need to circle the object)	Survey an object from a stationary ground platform	Survey an object from a hovering platform
Utility Level	0	0.4	0.8	1

A.4 Stakeholder #1's Utilities and Costs of ISR systems in all Epochs

Table A-7 to Table A-14 showed Stakeholder#1's utilities in using the different ISR systems in each epoch. The tables also showed the cost of each system over a five year period. The utility-cost data was used to create the tradespace plots in Figure 5-25 in Section 5.3.7.

Table A-7: Stakeholder #1's utility-cost data in Epoch #1

	Stakeholder 1: Ground Infantry Troop Battalion Commander															
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	10	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	[1,2,3]	2	2	2	2	2	2	2	2	3	3	3	3	3
System weight (kg)	20	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	30	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	6	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	4	4	3	3	3	3	3

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	Aladin	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	10	0.13	1.00	1.00	1.00	0.47	1.00	0.79	0.47	0.79	0.05	0.05	0.03	0.05	0.00
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	0.18	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00
System weight (kg)	20	0	0.06	0.40	0.25	0.10	0.45	0.15	0.25	0.15	0.15	0.25	0.00	0.00	0.00	0.00
System deployment time (minutes)	State #1	State #2	0.07	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	30	120	0.09	0.33	0.67	0.67	0.86	0.33	0.33	0.22	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability at any time required by the ground commander	State #1	State #2	0.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	6	9	0.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.15	0.40	0.40	0.40	0.40	0.40	0.40	1.00	1.00	0.80	0.80	0.80	0.80	0.80
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.72	0.74	0.73	0.70	0.70	0.68	0.71	0.73	0.80	0.78	0.78	0.78	0.77
			Estimated Cost (US$)	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-8: Stakeholder #1's utility-cost data in Epoch #2

Attributes of ISR System	Stakeholder 1 : Ground Infantry Troop Battalion Commander															
	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	5	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	[1,2,3]	1	1	1	1	1	1	1	1	2	2	2	2	2
System weight (kg)	20	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	30	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	6	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	4	4	3	3	3	3	3

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	Aladin	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	5	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.11	0.11	0.07	0.11	0.00
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50	0.50
System weight (kg)	20	0	0.10	0.40	0.25	0.10	0.45	0.15	0.25	0.15	0.15	0.25	0.00	0.00	0.00	0.00
System deployment time (minutes)	State #1	State #2	0.07	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	30	120	0.10	0.33	0.67	0.67	0.86	0.33	0.33	0.22	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability	State #1	State #2	0.10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	6	9	0.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.12	0.40	0.40	0.40	0.40	0.40	0.40	1.00	1.00	0.80	0.80	0.80	0.80	0.80
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.59	0.61	0.59	0.65	0.57	0.58	0.62	0.60	0.69	0.67	0.66	0.67	0.66
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-9: Stakeholder #1's utility-cost data in Epoch #3

Attributes of ISR System	Stakeholder 1: Ground Infantry Troop Battalion Commander																
	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	10	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	[1,2,3]	2	2	2	2	2	2	2	2	3	3	3	3	3
System weight (kg)	40	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	30	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	6	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	4	4	3	3	3	3	3

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	10	0.13	1.00	1.00	1.00	0.47	1.00	0.79	0.47	0.79	0.05	0.05	0.03	0.05	0.00
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	0.18	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00
System weight (kg)	40	0	0.06	0.70	0.63	0.55	0.73	0.58	0.63	0.58	0.58	0.63	0.33	0.00	0.00	0.00
System deployment time (minutes)	State #1	State #2	0.07	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	30	120	0.09	0.33	0.67	0.67	0.86	0.33	0.33	0.22	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability at any time required by the ground commander	State #1	State #2	0.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	6	9	0.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.15	0.40	0.40	0.40	0.40	0.40	0.40	1.00	1.00	0.80	0.80	0.80	0.80	0.80
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.74	0.76	0.76	0.72	0.73	0.70	0.74	0.76	0.82	0.80	0.78	0.78	0.77
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-10: Stakeholder #1’s utility-cost data in Epoch #4

	Stakeholder 1 : Ground Infantry Troop Battalion Commander															
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	5	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	[1,2,3]	1	1	1	1	1	1	1	1	2	2	2	2	2
System weight (kg)	40	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	30	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	6	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	4	4	3	3	3	3	3

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	5	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.11	0.11	0.07	0.11	0.00
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3 =	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50	0.50
System weight (kg)	40	0	0.10	0.70	0.63	0.55	0.73	0.58	0.63	0.58	0.58	0.63	0.33	0.00	0.00	0.00
System deployment time (minutes)	State #1	State #2	0.07	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Endurance (minutes)	30	120	0.10	0.33	0.67	0.67	0.86	0.33	0.33	0.22	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability at any time required by the ground commander	State #1	State #2	0.10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	6	9	0.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.12	0.40	0.40	0.40	0.40	0.40	0.40	1.00	1.00	0.80	0.80	0.80	0.80	0.80
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.58	0.61	0.60	0.64	0.57	0.58	0.63	0.61	0.70	0.67	0.63	0.63	0.62
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-11: Stakeholder #1’s utility-cost data in Epoch #5

Attributes of ISR System	Stakeholder 1: Ground Infantry Troop Battalion Commander Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	10	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	[1,2,3]	2	2	2	2	2	2	2	2	3	3	3	3	3
System weight (kg)	100	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	30	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	6	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	4	4	3	3	3	3	3

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	10	0.13	1.00	1.00	1.00	0.47	1.00	0.79	0.47	0.79	0.05	0.05	0.03	0.05	0.00
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	0.18	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00
System weight (kg)	100	0	0.06	0.88	0.85	0.82	0.89	0.83	0.85	0.83	0.83	0.85	0.73	0.60	0.55	0.55
System deployment time (minutes)	State #1	State #2	0.07	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	30	120	0.09	0.33	0.67	0.67	0.86	0.33	0.33	0.22	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability at any time required by the ground commander	State #1	State #2	0.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	6	9	0.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.15	0.40	0.40	0.40	0.40	0.40	0.40	1.00	1.00	0.80	0.80	0.80	0.80	0.80
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.75	0.78	0.78	0.73	0.74	0.72	0.75	0.77	0.83	0.83	0.81	0.81	0.81
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-12: Stakeholder #1's utility-cost data in Epoch #6

Attributes of ISR System	Stakeholder 1 : Ground Infantry Troop Battalion Commander Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	5	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	[1,2,3]	1	1	1	1	1	1	1	1	2	2	2	2	2
System weight (kg)	100	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	30	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	6	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	4	4	3	3	3	3	3

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	Aladin	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	5	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.11	0.11	0.07	0.11	0.00
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50	0.50
System weight (kg)	100	0	0.10	0.88	0.85	0.82	0.89	0.83	0.85	0.83	0.83	0.85	0.73	0.60	0.55	0.55
System deployment time (minutes)	State #1	State #2	0.07	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	30	120	0.10	0.33	0.67	0.67	0.86	0.33	0.33	0.22	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability at any time required by the ground commander	State #1	State #2	0.10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	6	9	0.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.12	0.40	0.40	0.40	0.40	0.40	0.40	1.00	1.00	0.80	0.80	0.80	0.80	0.80
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.64	0.67	0.67	0.69	0.63	0.64	0.69	0.67	0.75	0.74	0.72	0.72	0.71
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-13: Stakeholder #1's utility-cost data in Epoch #7

	Stakeholder 1: Ground Infantry Troop Battalion Commander																
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	10	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	[1,2,3]	2	2	2	2	2	2	2	2	3	3	3	3	3
System weight (kg)	100	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	30	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	6	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	4	4	3	3	3	3	3

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	Aladin	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	10	0.13	1.00	1.00	1.00	0.47	1.00	0.79	0.47	0.79	0.05	0.05	0.03	0.05	0.00
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	0.18	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00
System weight (kg)	100	0	0.06	0.88	0.85	0.82	0.89	0.83	0.85	0.83	0.83	0.85	0.73	0.60	0.55	0.55
System deployment time (minutes)	State #1	State #2	0.07	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	30	120	0.09	0.33	0.67	0.67	0.86	0.33	0.33	0.22	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability at any time required by the ground commander	State #1	State #2	0.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	6	9	0.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.15	0.40	0.40	0.40	0.40	0.40	0.40	1.00	1.00	0.80	0.80	0.80	0.80	0.80
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.75	0.78	0.78	0.73	0.74	0.72	0.75	0.77	0.83	0.83	0.81	0.81	0.81
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-14: Stakeholder #1's utility-cost data in Epoch #8

	Stakeholder 1 : Ground Infantry Troop Battalion Commander															
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON-ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	5	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #2	[1,2]	1	1	1	1	1	1	1	1	2	2	2	2	2
System weight (kg)	100	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	30	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	6	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	4	4	3	3	3	3	3

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	0.5	5	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.11	0.11	0.07	0.11	0.00
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00
System weight (kg)	100	0	0.10	0.88	0.85	0.82	0.89	0.83	0.85	0.83	0.83	0.85	0.73	0.60	0.55	0.55
System deployment time (minutes)	State #1	State #2	0.07	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	30	120	0.10	0.33	0.67	0.67	0.86	0.33	0.33	0.22	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability at any time required by the ground commander	State #1	State #2	0.10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	6	9	0.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.12	0.40	0.40	0.40	0.40	0.40	0.40	1.00	1.00	0.80	0.80	0.80	0.80	0.80
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.64	0.67	0.67	0.69	0.63	0.64	0.69	0.67	0.86	0.85	0.83	0.83	0.82
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

A.5 Stakeholder #2's attribute weights

Table A-15 to Table A-16 showed Stakeholder#2's attributes weights in the various epochs.

Table A-15: House of Quality of Stakeholder #2 in Epoch #1, 3, 5 & 7

Mission Purpose - Surveillance function (Epoch #1, 3, 5 & 7)

Normalised Weights	Weights by Users	VOC\ Technical Attributes	ECO / NUD	Coverage Range (in km) (+)	Flexibility to mount different cameras payload such as EO or IR cameras (+)	System Weight (-)	Time to deploy (-)	Endurance (minutes) (+)	Resource Availability any time any where (+)	Technology Readiness (+)	Ability to survey an object (+)
0.13	4	Able to perform surveillance over an area or object	NUD	9	9	0	0	3	3	9	9
0.06	2	Able to use in full spectrum of operations	NUD	9	3	3	3	3	1	3	9
0.06	2	Prefer to be Manportable	NUD	0	0	9	1	1	9	0	0
0.16	5	Easy to deploy within half an hour	NUD	0	0	3	9	0	3	0	0
0.13	4	Sufficient operating time within a mission profile	NUD	3	0	1	0	9	0	1	0
0.16	5	Prefer On Demand, Real Time Intelligence Information	NUD	0	1	1	3	0	9	3	0
0.09	3	Prefer to be fielded as soon as possible	NUD	0	0	0	0	0	0	9	0
0.09	3	Obtain clear videos and pictures on object of surveillance	ECO	0	9	0	0	0	0	1	3
0.06	2	Able to operate in day and night conditions	ECO	0	9	0	0	0	0	9	3
0.06	2	Provide Safety Cover for soldiers in operation	ECO	3	0	0	0	0	0	0	3
		Relative Weights		2.25	2.88	1.50	2.13	1.75	2.88	3.41	2.34
		Normalised Weights		0.12	0.15	0.08	0.11	0.09	0.15	0.18	0.12

Table A-16: House of Quality of Stakeholder #1 in Epoch #2, 4, 6 & 8

Mission Pupose - Dual function such as augmenting EOD operation, HAZMAT detection or striking the target using munitions (Epoch #2, 4, 6 & 8)

Normalised Weights	Weights by Users	VOC\ Technical Attributes	ECO / NUD	Coverage Range (in km) (+)	Flexibility to upgrade and mount other payloads such as sensors or weapons (+)	System Weight (-)	Time to deploy (-)	Endurance (minutes) (+)	Resource Availability any time any where (+)	Technology Readiness (+)	Ability to survey an object (+)
0.13	4	Able to perform surveillance over an area or object	NUD	9	9	0	0	3	3	9	9
0.06	2	Able to use in full spectrum of operations	NUD	9	9	3	3	3	0	3	9
0.06	2	Prefer to be Manportable	NUD	0	0	9	1	3	9	0	0
0.16	5	Easy to deploy within half an hour	NUD	0	0	9	9	0	0	0	0
0.13	4	Sufficient operating time within a mission profile	NUD	1	0	3	0	9	0	1	0
0.16	5	Prefer On Demand, Real Time Intelligence Information	NUD	0	1	1	3	0	9	3	0
0.09	3	Prefer to be fielded as soon as possible	NUD	0	0	0	0	0	0	9	0
0.09	3	Obtain clear videos and pictures on object of surveillance	ECO	0	9	0	0	0	0	1	0
0.06	2	Able to operate in day and night conditions	ECO	0	9	0	0	0	0	9	0
0.06	2	Provide Safety Cover for soldiers in operation	ECO	1	0	0	0	0	0	0	3
		Relative Weights		1.88	3.25	2.69	2.13	1.88	2.34	3.41	1.88
		Normalised Weights		0.10	0.17	0.14	0.11	0.10	0.12	0.18	0.10

A.6 Utility of Attribute "Technology Readiness Level" and "Ability to survey an object"

Although there were differences in preferences in the control range, the system weight, endurance, Technology Readiness Level (TRL) and ability to survey an object between Stakeholder #1 and #2, the method of eliciting their utility plots is similar. With regards to the control range, system weight and endurance, a linear interpolation is performed between the desired attribute values of utility 0 and 1. For Technology Readiness Level" and "Ability to survey an object", the values are shown in Table A-17 and A-18 respectively. Stakeholder #2 preferred a system with a higher TRL of 8 and 9 as compared to Stakeholder #1, who can accept system of TRL 7 and above. Stakeholder #2 will obtain a higher utility level if the ISR system is stationary during the survey of an object, as compared to a hovering ISR platform during the survey.

Table A-17: Utility levels of Attribute "Technology Readiness Level"

	Attribute: Technology Readiness Level (TRL)		
	Applicable in all epochs		
	State #1	State #2	State #3
Description	TRL = 7	TRL = 8	TRL = 9
Utility Level	0	0.5	1

Table A-18: Utility levels of Attribute "Ability to survey an object"

	Attribute: Ability to survey an object			
	Applicable in all epochs			
	State #1	State #2	State #3	State #4
Description	Unable to survey object	Survey an object from a flying platform (i.e. need to circle the object)	Survey an object from a hovering platform	Survey an object from a stationary ground platform
Utility Level	0	0.4	0.8	1

A.7 Stakeholder #2’s Utilities and Cost of ISR systems in all Epochs

Table A-19 to Table A-28 shows Stakeholder#2’s utilities in using the different ISR systems in each epoch.

Table A-19: Stakeholder #2’s utility-cost data in Epoch #1

	Stakeholder #2 : Ground Infantry Troop Battalion Commander																
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	10	20	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	[1,2,3]	2	2	2	2	2	2	2	2	3	3	3	3	3
System weight (kg)	20	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	60	180	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	7	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	3	3	4	4	4	4	4

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	Aladin	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	10	20	0.12	0.00	0.00	0.50	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	0.15	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00
System weight (kg)	20	0	0.08	0.40	0.25	0.10	0.45	0.15	0.25	0.15	0.15	0.25	0.00	0.00	0.00	0.00
System deployment time (minutes)	State #1	State #2	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	60	180	0.09	0.00	0.25	0.25	0.39	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.50
Resource availability at any time required by the ground commander	State #1	State #2	0.15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	7	9	0.18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.12	0.40	0.40	0.40	0.40	0.40	0.40	0.80	0.80	1.00	1.00	1.00	1.00	1.00
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.60	0.61	0.65	0.63	0.63	0.58	0.62	0.62	0.82	0.80	0.80	0.80	0.76
			Estimated Cost (US$)	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-20: Stakeholder #2's utility-cost data in Epoch #2

	Stakeholder #2 : Ground Infantry Troop Battalion Commander															
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	10	20	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	[1,2,3]	1	1	1	1	1	1	1	1	2	2	2	2	2
System weight (kg)	100	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	60	180	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	7	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	3	3	4	4	4	4	4

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	Aladin	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	10	20	0.10	0.00	0.00	0.50	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50	0.50
System weight (kg)	100	0	0.14	0.88	0.85	0.82	0.89	0.83	0.85	0.83	0.83	0.85	0.73	0.60	0.55	0.55
System deployment time (minutes)	State #1	State #2	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	60	180	0.10	0.00	0.25	0.25	0.39	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.50
Resource availability	State #1	State #2	0.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	7	9	0.18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.10	0.40	0.40	0.40	0.40	0.40	0.40	0.80	0.80	1.00	1.00	1.00	1.00	1.00
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.57	0.59	0.63	0.60	0.61	0.56	0.60	0.60	0.80	0.78	0.76	0.76	0.71
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-21: Stakeholder #2's utility-cost data in Epoch #3

	Stakeholder #2: Ground Infantry Troop Battalion Commander															
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	2	10	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	[1,2,3]	2	2	2	2	2	2	2	2	3	3	3	3	3
System weight (kg)	20	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	60	180	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	7	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	3	3	4	4	4	4	4

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	2	10	0.12	1.00	1.00	1.00	0.38	1.00	0.75	0.38	0.75	0.00	0.00	0.00	0.00	0.00
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	0.15	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00
System weight (kg)	20	0	0.08	0.40	0.25	0.10	0.45	0.15	0.25	0.15	0.15	0.25	0.00	0.00	0.00	0.00
System deployment time (minutes)	State #1	State #2	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	60	180	0.09	0.00	0.25	0.25	0.39	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.50
Resource availability at any time required by the ground commander	State #1	State #2	0.15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	7	9	0.18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.12	0.40	0.40	0.40	0.40	0.40	0.40	0.80	0.80	1.00	1.00	1.00	1.00	1.00
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.71	0.72	0.71	0.68	0.69	0.67	0.67	0.71	0.82	0.80	0.80	0.80	0.76
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-22: Stakeholder #2's utility-cost data in Epoch #4

Attributes of ISR System	Stakeholder #2 : Ground Infantry Troop Battalion Commander Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	2	10	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	[1,2,3]	1	1	1	1	1	1	1	1	2	2	2	2	2
System weight (kg)	50	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	60	180	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	6	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	3	3	4	4	4	4	4

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	2	10	0.10	1.00	1.00	1.00	0.38	1.00	0.75	0.38	0.75	0.00	0.00	0.00	0.00	0.00
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3 =	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50	0.50
System weight (kg)	50	0	0.14	0.76	0.70	0.64	0.78	0.66	0.70	0.66	0.66	0.70	0.46	0.20	0.10	0.10
System deployment time (minutes)	State #1	State #2	0.11	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Endurance (minutes)	60	180	0.10	0.00	0.25	0.25	0.39	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.50
Resource availability at any time required by the ground commander	State #1	State #2	0.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	7	9	0.18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.10	0.40	0.40	0.40	0.40	0.40	0.40	0.80	0.80	1.00	1.00	1.00	1.00	1.00
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.59	0.61	0.60	0.57	0.58	0.56	0.56	0.59	0.72	0.69	0.65	0.64	0.59
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-23: Stakeholder #2's utility-cost data in Epoch #5

	Stakeholder #2 : Ground Infantry Troop Battalion Commander																
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	1	10	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	[1,2,3]	2	2	2	2	2	2	2	2	3	3	3	3	3
System weight (kg)	20	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	30	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	7	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	3	3	4	4	4	4	4

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	1	10	0.12	1.00	1.00	1.00	0.44	1.00	0.78	0.44	0.78	0.00	0.00	0.00	0.00	0.00
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	0.15	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00
System weight (kg)	20	0	0.08	0.40	0.25	0.10	0.45	0.15	0.25	0.15	0.15	0.25	0.00	0.00	0.00	0.00
System deployment time (minutes)	State #1	State #2	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	30	120	0.09	0.33	0.67	0.67	0.86	0.33	0.33	0.22	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability at any time required by the ground commander	State #1	State #2	0.15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	7	9	0.18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.12	0.40	0.40	0.40	0.40	0.40	0.40	0.80	0.80	1.00	1.00	1.00	1.00	1.00
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.74	0.76	0.75	0.73	0.72	0.71	0.70	0.72	0.82	0.80	0.80	0.80	0.80
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-24: Stakeholder #2's utility-cost data in Epoch #6

	Stakeholder #2: Ground Infantry Troop Battalion Commander															
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	1	10	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	[1,2,3]	1	1	1	1	1	1	1	1	2	2	2	2	2
System weight (kg)	50	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	120	240	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	7	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	3	3	4	4	4	4	4

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	Aladin	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	1	10	0.10	1.00	1.00	1.00	0.44	1.00	0.78	0.44	0.78	0.00	0.00	0.00	0.00	0.00
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50	0.50
System weight (kg)	50	0	0.14	0.76	0.70	0.64	0.78	0.66	0.70	0.66	0.66	0.70	0.46	0.20	0.10	0.10
System deployment time (minutes)	State #1	State #2	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	120	240	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.50	0.00
Resource availability at any time required by the ground commander	State #1	State #2	0.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	7	9	0.18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.10	0.40	0.40	0.40	0.40	0.40	0.40	0.80	0.80	1.00	1.00	1.00	1.00	1.00
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.65	0.64	0.63	0.59	0.63	0.62	0.62	0.65	0.78	0.75	0.71	0.65	0.60
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-25: Stakeholder #2's utility-cost data in Epoch #7

Attributes of ISR System	Stakeholder #2: Ground Infantry Troop Battalion Commander Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	5	15	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	[1,2,3]	2	2	2	2	2	2	2	2	3	3	3	3	3
System weight (kg)	50	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	60	120	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	7	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	3	3	4	4	4	4	4

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	Aladin	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	5	15	0.12	0.50	0.50	1.00	0.00	1.00	0.30	0.00	0.30	0.00	0.00	0.00	0.00	0.00
Flexibility to mount different cameras payload such as EO or IR cameras	State #1	State #3	0.15	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00
System weight (kg)	50	0	0.08	0.76	0.70	0.64	0.78	0.66	0.70	0.66	0.66	0.70	0.46	0.20	0.10	0.10
System deployment time (minutes)	State #1	State #2	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	60	120	0.09	0.00	0.50	0.50	0.78	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00
Resource availability at any time required by the ground commander	State #1	State #2	0.15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	7	9	0.18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.12	0.40	0.40	0.40	0.40	0.40	0.40	0.80	0.80	1.00	1.00	1.00	1.00	1.00
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.68	0.72	0.78	0.70	0.73	0.65	0.66	0.70	0.86	0.84	0.82	0.81	0.81
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

Table A-25: Stakeholder #2's utility-cost data in Epoch #8

Attributes of ISR System	Stakeholder #2: Ground Infantry Troop Battalion Commander															
Attributes of ISR System	Utility = 0	Utility = 1	Additional Notes	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON-ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	1	10	-	10	10	15	5	15	8	5	8	1	1	0.8	1	0.3
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #2	[1,2]	1	1	1	1	1	1	1	1	2	2	2	2	2
System weight (kg)	50	0	-	12	15	18	11	17	15	17	17	15	27	40	45	45
System deployment time (minutes)	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Endurance (minutes)	60	180	-	60	90	90	107	60	60	50	30	360	510	360	180	120
Resource availability at any time required by the ground commander	State #1	State #2	[1,2]	2	2	2	2	2	2	2	2	2	2	2	2	2
Technology Readiness Level (Level 1 to 9)	7	9	[6,7,8,9]	9	9	9	9	9	9	9	9	9	9	9	9	9
Ability to survey an object	State #1	State #4	[1,2,3,4]	2	2	2	2	2	2	3	3	4	4	4	4	4

Analysis

Attributes of ISR System	Utility = 0	Utility = 1	Weights	RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	Skyblade III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
Control range (km)	1	10	0.10	1.00	1.00	1.00	0.44	1.00	0.78	0.44	0.78	0.00	0.00	0.00	0.00	0.00
Flexibility to upgrade and mount other payloads such as sensors or weapons	State #1	State #3	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00
System weight (kg)	50	0	0.14	0.76	0.70	0.64	0.78	0.66	0.70	0.66	0.66	0.70	0.46	0.20	0.10	0.10
System deployment time (minutes)	State #1	State #2	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Endurance (minutes)	60	180	0.10	0.00	0.25	0.25	0.39	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.50
Resource availability at any time required by the ground commander	State #1	State #2	0.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Technology Readiness Level (Level 1 to 9)	7	9	0.18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ability to survey an object	State #1	State #4	0.10	0.40	0.40	0.40	0.40	0.40	0.40	0.80	0.80	1.00	1.00	1.00	1.00	1.00
				RAVEN	SKYLARK LE I	ORBITER	WASP MAV	ALADIN	SKYBLADE III	T-HAWK	FANTAIL	IROBOT SUGV 310	TALON - ENGINEER	MATILDA II	IROBOT PACKBOT	CYCLOPS MROV
			Combined Utility	0.65	0.66	0.65	0.63	0.63	0.62	0.62	0.65	0.86	0.83	0.79	0.78	0.73
			Estimated Cost	100,000	100,000	133,000	150,000	93,000	70,000	360,000	100,000	280,000	200,000	70,000	170,000	250,000
			NPV (US$)	125,359	125,359	166,727	188,038	116,584	87,751	451,292	125,359	351,005	250,718	87,751	213,110	313,397

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