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HUMAN CENTRIC SYSTEMS ENGINEERING

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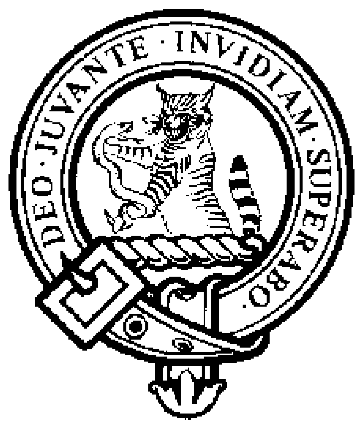

[1]

[1] The Thoms family crest, as worn at the Battle of Culloden, 1746.

ABSTRACT

This thesis is a study into an engineering technology that enables us to investigate the cognitive aspects of systems. Where previous techniques have focused on individual human roles undertaking defined tasks, this work develops engineering technologies to understand the cognitive contribution of the human team participating in the system and how the deployment of machine decision making technologies can influence and change the possible human contribution in that system.

This work first develops a framework for understanding an individual's cognitive focus and then an engineering process that enables us to model the individual human cognitive contribution to the system and by combining these models to create a rich system model. This model can then be used to consider the deployment of advanced machine technologies, to identify new human or machine interaction requirements that are focused on maintaining the effectiveness of the human contribution.

It then operationalises and verifies these engineering techniques by applying them to two systems. The first study chosen took an existing system whose effectiveness had been changed by the deployment of machine automation which has known problems; the use of the framework enabled the prediction of these problems and the identification of potential solutions. The second study investigated an existing human system and the potential deployment of machine technology. This study used the framework to create models of the human cognitive focus and joined them together to form a rich system model, into which the deployment of the machine technology was considered. This resulted in the ability to identify the impact of the machine technology across the entire human team, enabling the identification of additional requirements to support the human cognition and to maintain human knowledge.

Finally this thesis revisits the framework and process presenting them in a format used in industry to enable timely exploitation.

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I must also express my thanks to my mother Andy Thoms who was brave enough to review this thesis as someone who had no understanding of either the system or engineering challenges but as a layperson, providing a valuable insight to my often unique use of the English language and technical terms that may have otherwise obscured the simplicity of the developed technology.

1 INTRODUCTION

This is a study into an engineering technique that enables us to investigate the cognitive aspects of systems. The ideas behind cognitive systems are being matured across a number of different disciplines, as evidenced by the associated literature. To date the literature shows that the engineering focus has been to support the engineer by focusing on tools to understand individual humans doing predefined roles; such a view does not address systems which involve more than one human or enable the understanding of the consequences of any engineering design decisions on those other team members. Engineering needs tools to enable them to understand not only the individual but the emergent system cognition that results from the interaction of the human team with the machine technologies. To this end this thesis develops an engineering framework and process that enables the systems engineer, in undertaking systems engineering, to take into account the human cognitive contribution in delivering the system purpose.

We start with an empirical investigation into the cognitive contribution of humans in a system for which we have chosen that of military planning. In doing this we find that it is appropriate to consider the human cognitive contribution in terms of three attributes; awareness, understanding and deliberation. We then develop these three attributes as a framework to be used by an engineer, and an engineering process with which to use it. To understand the potential benefits of the use of, and to verify, both the framework and process associated with this human centric system engineering approach, this thesis then presents two applications to military systems. These applications were used both to mature the process and to develop guidelines for the use of both the framework and the process.

This thesis first provides a new view on systems engineering that is intended to begin to move engineering away from designing systems that are designed to operate against a constrained context, to a view that supports adaptability and flexibility that will enable our designed systems to adapt to an evolving operational context. To do this the framework and process enables the engineers to embrace the human and the human team's cognitive contribution that enables our designed system to operate as a complex adaptive system.

This section presents the background of the research, the problems which this research addresses and why we need engineering to change to seek to solve these problems. It introduces the approach that was adopted, identifies the research results and the contribution that has been made. It then outlines the remaining sections of this thesis.

1.1 Background

Over the centuries we have seen the skills and knowledge of mankind evolve to meet their changing requirements. Much of what we once needed has become obsolete and subsequently been lost, changes, which with the introduction of mechanisation and the computer have been the most marked in history. Today we are seeking to create machine technologies capable of thinking and choosing independently of humans. When we deploy these technologies it is highly probable that we will see an even more rapid change in human knowledge and skills.

In any endeavour it is currently the human that recognises the decisions that are appropriate in a given context in order to achieve a desired outcome and it has been the human that has made those decisions and taken responsibility for their outcome. As engineers enable machines to make decisions for us they will change the human's role in the system, which will in turn change the knowledge and skills the human will need to participate in the system, consequently the deployment of these machine technologies will impact:

- how humans seek to observe their situation
- their ability to understand that situation
- their ability to recognise what decisions are appropriate
- their ability to make those decisions

The retention of human knowledge is especially necessary in military operations where platforms and systems are lost during combat, leaving humans to fall back on their own creativity and ingenuity to achieve their objective or sometimes to survive. Therefore the successful development and deployment of machine technologies in a military context is dependant on evolving systems engineering to deliver an appropriate balance of interactions and decisions relationships between humans and machine technologies within the system. To do this we need to understand the decisions or cognitive aspects of the system that is currently provided by humans.

When we look at system engineering techniques we find those that have considered humans in the context of the system they have focused on the human tasks associated with a system, not on the decisions that the human may need to make due to the evolving context. Tasks are an artefact of a constrained system context, they focus on the "how" to do something, not on the "why": what is trying to be achieved in the light of the system purpose. The resulting systems work well for system problems that operate within a defined constrained context, deployments in which the tasks do not change. Those engineering techniques that have focused on decision making have sought to understand what human decisions could be automated rather than considering the impact that such automation may have on the human's thought processes or cognition. Whilst the deployment of automation for certain types of system challenges may be appropriate, problems such as long term monitoring and repetition, these machine technologies change the human's role and if they remove human knowledge can constrain the system around the automated decision. The resulting system loses some of the agility and flexibility that the humans could have provided.

This research has been undertaken part-time over three years in parallel with the author’s full-time employment with BAE Systems as the theme leader for the Mission Planning and Decision Making Theme of the Systems Engineering for Autonomous Systems Defence Technology Centre (SEAS DTC). The theme leadership role has provided the necessary context to understand the challenges that advanced machine decision making technologies pose to human cognition. Employment with BAE Systems has provided the recognition that to meet tomorrow’s systems challenges we must move systems engineering to focus on designing and delivering complex adaptive systems that deliver adaptability and flexibility.

1.2 Problem statement

Engineering has for many years been developing machine technologies that are capable of making complicated, even complex, decisions faster and arguably more effectively than humans. As part of the systems engineering process it is the responsibility of engineers to seek to forecast and understand the consequences of their design decisions, for systems that look to deploy machine decision technologies this responsibility needs to be expanded to include the consequences of such a deployment on the human cognitive contribution to delivering the system purpose.

To understand this requires systems engineers to understand the human cognitive contribution to delivering the system purpose, both at an individual level and as a team. With such a cognitive system model as a baseline it will be possible for engineers to investigate the possible deployment of machine technology and how that deployment could influence human cognition. For this the engineers will need new tools and guidelines to capture and explore these “cognitive systems”, the development and evaluation of which is the focus of this research. The first stage in achieving this is to be able to analyse the human system and capture it, so our first research question is:

1. How could a systems engineer recognise and capture the human cognitive contribution to a system?

Once we have developed a tool for understanding the human cognitive contribution to the system we can then look to use it to understand the potential implications of deploying machine technologies to support the human cognitive activities, consequently our second research question is:

2. Can we use this technology to understand how changes in one part of the system could impact the potential cognitive contribution of other parts of that system?

The work captured in this thesis is focused on capturing the cognitive aspects of a system and identifying additional machine requirements that may be necessary to support human cognition as a result of the deployment of machine technologies. It does not seek to address how it may be necessary to change how we engineer the physical system elements or to advise upon designing the human computer interaction.

1.3 Research approach

This research has grown out of SEAS DTC requirement to develop methods and techniques that would enable systems engineers to design and develop autonomous systems. Initially it was necessary to find a way to articulate the technical challenges that needed to be met by suitable technologies to enable the development of a machine capable of independent decision making, here referred to as deliberative autonomy. It quickly became apparent that for any system that exhibits deliberative autonomy the choice of an appropriate decision, and even what decisions would be appropriate to make, is contextual, so cannot be predefined [Thoms, 2006a]. For the engineer this deliberative autonomy challenge needed some way of being thought about, which would capture recognition of the context, identification of decision options based on resulting changes in the context, choosing between those decisions and the decision making itself. To understand the technical challenge it was decided to focus on developing engineering techniques that would enable engineers to understand the human cognitive contribution in a system.

To do this we set about investigating a human system, during this work it was found that awareness, understanding and deliberation captured the key attributes of cognition and provided a suitably abstract way of thinking about the human contribution. The result of this work was the development of the three stage engineering framework [Thoms, 2007] that is described in section 4. The framework would later be found [Thoms 2008] to have the potential to be extended across multiple humans to capture larger systems and specifically human teams.

Whilst a framework provides a way of thinking about a problem, engineers will need a technique or process to use the framework to create their understanding which will hopefully lead to them solving the problem. How to develop such a technique? It is possible to hypothesise on how it may be possible to use such a framework, see section 5, but validation would require it to be applied to real system problems.

To validate the framework we chose to undertake two studies that would investigate different aspects of the engineering challenge. For the first study we revisited an existing system in order to assess whether the use of the framework promotes new insights as originally intended. The chosen system was that of ship based anti-submarine tracking, a system which has, over recent decades, seen the introduction of new machine decision technologies which have given rise to changes to the system's operational effectiveness. This system was specifically chosen as the author has knowledge of the existing system implementation and system effectiveness resulting from participation on the UK MoD's ARP RE306: Combat System Integration, Interoperability and Performance System Requirements and Dataload study [Thoms 2004] and has unrestricted access to a subject matter expert of the earlier anti-submarine tracking systems. As the study progressed the engineering process was refined and updated.

The second study investigated the potential deployment of an algorithm being developed by Imperial College into an existing military capability: Force Threat Evaluation and Weapons Assignment (FTEWA). This system is responsible for the allocation and routing of force assets (manned or unmanned aircraft) in order to engage in coming threats. This study required us to capture the existing human system as a single cognitive system model. The use of the framework enabled us to gain an understanding of each human role's cognitive focus and the information they required, as well as the information flows and interactions between the team members required to deliver the system purpose. Following the defined engineering process we then investigated what constituted operational effectiveness for the FTEWA system by using the framework to understand how the machine technology could influence the human contribution in the system.

To generate a potential system design we started by investigating the input and output data flows associated with the algorithm, considering how they related to the information flows in the (human) cognitive system model and how the data flows could influence the human's cognitive focus. This allowed for the detection and understanding of the consequences of mismatches, which would need to be addressed in the system design. This resulted in the identification of additional information requirements that would need to be provided to engage the human in the algorithm's solution and recognition that the deployment of the algorithm had the potential to erode human knowledge, for which a potential solution was identified.

These two studies enabled the refinement of the engineering process and the generation of guidance to support the engineer in following the process.

1.4 Results and contributions made

This thesis introduces a new engineering framework and a process, which have been validated across two studies, that enables an engineer to capture a **rich system model** that includes the **individual human and team's cognitive contribution** towards delivering system functionality.

The two studies used the engineering framework to capture and then create "data flow diagrams"[2] of the human cognitive focus. These diagrams enabled the identification and capture of the individual's information requirements. By combining the individual models we created a team cognitive system model, which is compatible with existing engineering modelling practice. In the second study this model proved suitable to investigate the deployment of the chosen machine technology and enabled the identification of additional human machine interaction requirements, which had not been identified by a parallel human factors study [McLeod 2008] carried out by Ian McLeod of BAE Systems.

[2] Data Flow Diagrams are a basic system modelling technique that is used in both Structured Analysis and Systems Design [DeMarco 1978] and Yourdon [Yourdon 1979].

The two studies have shown that the framework for thinking about the human cognitive contribution in terms of awareness, understanding and deliberation along with the recognition of information flows between these three cognitive elements is a useful tool. It has enabled the recognition of what individuals are trying to achieve rather than how they work and the information they need. The combining of the individual models into a rich system model has provided an insight onto the emergent team cognitive process and allows the engineer to recognise the implications of the deployment of machine technology beyond the individual role that we may choose to deploy it with.

The rich system model provides the engineer with the opportunity to embrace the human cognitive contribution in the system and to make design decisions that seek to exploit the human contribution that provides the agility and flexibility needed to continue to deliver the system purpose in the evolving real world.

1.5 Outline of sections

This thesis is presented in nine sections. Section two introduces the reader to Human Centric Systems Engineering. It starts by considering how the way we think about the nature of systems has evolved over time and how we have grown to recognise their increasingly complex challenges. It then considers the challenges of social systems, systems that contain multiple "agents" that come together to meet a need or purpose. This thesis then shows how cognitive science has helped shape the way we think about purposefulness and what contributes towards it. These three descriptions provide the reader with the basic understanding of system properties and behaviour to be able to consider the system design challenge. It then moves over to consider how we design systems first by looking at classical systems analysis and engineering, then by looking at recent attempts to embrace the human contribution in the designed systems, using what has been termed cognitive systems engineering [Hollnagel 1983], which we prefer to call "*Human Centric Systems Engineering*", to avoid confusion with cognitive science's attempts to understand or engineer cognition. It leaves us with the recognition of the challenges that still need to be addressed, some of which are addressed in this thesis.

The approach used to undertake this research is presented in Section three. It captures the study process that was followed and the intent for each of the activities that are captured in the subsequent sections.

In section 4 we start by considering how it may be appropriate for a systems engineer to think about the cognitive aspects of systems. To do this we consider the challenge of planning first as a basic human skill and then as a complex planning challenge for which the example chosen is military planning. From this study we recognise three key cognitive capabilities that the human are using: the ability to form awareness, to create understanding and then to make a decision from the multitude of possible decisions (deliberation) in order to achieve their purpose. We then use these three attributes as the basis of an engineering framework with which to think about the human's cognitive contribution in a system and how that framework could be applied to understand the team cognitive contribution.

Section 5 starts by presenting to the reader a viewpoint on systems that includes the use of this engineering framework to capture the human cognitive contribution to system functionality within the bounds of the system. To operationalise the framework we introduce an initial process for using it to analyse and design a system. As an initial stage in the process we assert that we need to capture our understanding of the system purpose slightly differently so that we embrace the human contribution. It then discusses capturing the human cognitive focus, their contribution to system effectiveness and creating a human team model. With this understanding of the human contribution the process then focuses us on understanding what constitutes system effectiveness, when we include the human contribution within the system bounds. The final stage of the engineering process uses the human team model to understand the implications of deploying machine technologies into the human team. It concludes by looking at what is hoped to be gained by using the framework and process and their possible short falls.

Section 6 presents the first application of the framework and process to an existing system consisting of humans and machine technologies with known human engagement problems. This study shows that the use of the framework and process would have aided the engineer to identify the emergent problems resulting from the deployment of new machine processing capabilities and makes recommendations to seek to overcome them.

The second application of the framework and process is presented in section 7 . The system challenge this time is again an existing system, but this time considering the deployment of new machine technologies into that system, which would require changes to the concept of operations. This study shows the use of data flow diagrams to capture the human cognitive contribution and their combination to form a rich view of the system. It then shows how this rich system model and the framework can be used to investigate the deployment of a specific machine technology into the system. It also considers the value of an associated human factors study.

Section 8 reviews the framework and provides an updated view of the process developed over the two studies. It provides additional guidance for the engineer to enable them to use this new set of engineering tools and considers the practicalities of deployment into the engineering process.

Finally section 9 concludes the thesis by considering this work in light of similar work and its unique contribution. It presents an overview of this thesis, what has been provided and the potential limitations before looking at the outstanding challenges and future applications of this technology.

2 ON THE PATHWAY TO HUMAN CENTRIC SYSTEMS ENGINEERING

Human Centric Systems Engineering (HCSE) is an emergent discipline which builds upon work from many different specialisations, which have shaped and evolved our way of thinking about the human system challenge, its aim is to embrace the human contribution in the systems engineering process.

We start this review by looking at **how we think about the nature of systems** and the observer's relationship with the system. We start by considering the traditional view of systems is that they are static and obey simple rules, to the modern view that recognises that systems are complex and if they are to survive must evolve to meet the challenge of their context. We will see how we moved from believing that systems could be considered to be independent from its context (i.e. closed systems), to recognition that systems were open, exchanging *energy* with their environment. In this transformation we would move from thinking about systems as linear entities, through non-linearity to recognise that they were truly complex and that the behaviour of such systems is an emergent property of the system in context[3].

In section 2.2 we consider **how we seek to understand the internal organisation of systems** by looking at work into social systems. Our early understanding of the control mechanisms of these social systems comes to us from studying human societies, from the early hierarchical structure of overlords, through the distributed structure characterised by rational-self interest and competition, to our modern view of evolving societies. It is from looking at societies we find that systems emerge from the complex social environment to meet their shared need before dissolving back into the environment. These systems contain human or animals etc. which by their nature are capable of reasoning and choice, so we can describe them as exhibiting cognition.

To understand the challenge of cognition section 2.3 enters the realm of cognitive science looking at man's work trying to understand how the human mind works with the aim of creating thinking machines. In this we recognise some distinct challenge of embodiment and how that influences the nature of knowledge and what can be understood by an individual entity within our system. This will have a significant impact when we seek to understand the nature of human information and machine data.

We then move from thinking about the nature of systems to techniques to engineer them. We start by considering why systems engineers have designed systems based on

[3] For techniques used to analyse specific contexts see Soft Systems Methodology [Checkland 1998, Wilson 2001]. Whilst SSM is considered by some to be part of systems thinking its principle application has been for analysis of non-systemic situations, where it may be difficult to define the system problem, rather than analysing the system itself which is the focus of this thesis.

predefined tasks designed to solve constrained system problems and why the human factors team have focused their attention on the human interaction with the system. More recently it considers how human factors have begun to recognise the need to consider the human's awareness needs in order to identify the data items to provide to the human operator of the system and that recently there has been some recognition that this influences the human's decision processes.

In section 2.5 we look at how a new discipline, *cognitive systems engineering*, has been growing in parallel to classical human factors, taking a more systems viewpoint on the human system. We see that they have recognised that human cognition contributes to delivering the system purpose and that they have begun to seek to provide tools to address the engineering of the cognitive functionality. We will see that whilst they have been working with the best intentions their background of human factors continues to be difficult to shake off. Because of this we find that there are still key challenges that have still to be addressed that provides the basis of the research questions captured in section 2.6 .

2.1 Systems thinking

To begin our journey we need to consider how we as humans have learnt to think about systems, this understanding can be traced back to the fourth century BC to the Greeks, to Plato and Aristotle. Plato taught us that a system can be understood by deduction from priori principles, in contrast Aristotle required that observations were made of the system of interest and from that observation the knowledge of the essences of the system could be determined. Both of these views we can consider to be *traditional forms of systems analysis*, in that they seek to understand the system by breaking it into constituent parts, techniques that are still employed today to understand systems.

We now recognise that this breaking down of the system denies the observer the ability to consider the system's dynamic properties, but we must recognise that for many years such analysis was beyond what scientific knowledge, numerical representation and mathematics could support. It was not until the 17^{th} Century that Sir Isaac Newton [Newton 1686] would provide us with the long awaited mathematical tools with which to seek to understand dynamics of a system. However it would be another two centuries before Henri Poincaré would take Newton's work and give it our modern form around 1880, in order to seek to solve the n-body problem[4]. In his work Poincaré provided many

[4] Known originally as the three body problem, it was only later renamed the n-body problem. The challenge was made famous when King Oscar II established a prize for anyone who could find a solution to the problem. Whilst the prize was awarded to Poincaré, he did not solve the problem. But his work was recognised as being of such importance that its publication will bring on a new era in the history of celestial mechanics. The n=3 problem would finally be solved by Karl Sundman [Sundman 1912] and subsequently the n>3 by Qiudong Wang [Qiudong Wang 1990].

important ideas that helped us understand the dynamic properties of systems, that would later lead us to chaos theory, an important part of systems thinking.

As we entered the twentieth century our view of systems was challenged by Ludwig von Bertalanffy, who in the 1930s, recognised that the traditional view of systems, which viewed systems as "closed", did not comply with second law of thermo dynamics[5] [Sadi Carnot 1824]. Von Bertalanffy's theory of open systems [von Bertalanffy 1950], developed within the discipline of biology, recognised that systems internalised energy and matter from the environment in order to maintain the system's structure or to change their structural complexity. These systems were equally likely to be developing towards states of higher complexity as towards lower states of complexity. He recognised that his theory was not only applicable to biology but could also be applied to wider fields of systems thinking. The key foundations of this new general systems thinking would be the emphasis of holism over reductionism, organisation over mechanism, his work changed the systems thinking landscape.

Further advances were to be made within systems thinking when in 1940 Norbert Wiener and Julian Bigelow's work on automatic rangefinders for anti-aircraft guns recognised the effects of the negative feedback[6] loop: the closed "information" loop required to correct any action. This work was later to be published by Wiener [Wiener 1946] in "*Cybernetics, or Control and Communication in the Animal and the Machine*".

During the early 1940's the recognition of the challenges of systems was rapidly expanding and in 1946 a series of interdisciplinary meetings, known as the Macy Conferences, were held that would result in breakthroughs in systems theory and lead to the foundation of what was later to be known as cybernetics. Whilst the attendees of the Macy Conferences today reads like a who's who of systems thinking it is through their subsequent papers that we can trace the evolution of system's thinking.

One of the attendees at the 9th Macy Conferences was W Ross Ashby, who presented his homeostat [Ashby 1948]. The homeostatic machine enabled Ashby to investigate the behaviour of an ultrastable system and consequently gave us many important insights into systems: the law of requisite variety, the principle of self-organisation and the principal of regulatory models, captured in his 1956 book "Introduction to Cybernetics" [Ashby

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5 The universal law of increasing entropy; *"the entropy of an isolated system which is not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium"*

6 Negative feedback applied to mechanical systems had been known about for many centuries: for example in 1787 James Watt [Watt 1787] patented the use of negative feedback in the form of his Watt Governor to control the speed of his steam engines. But his "invention" had been taken from an earlier governor, thought to date from the 16th century, that he had observed controlling the speed of a water wheel. This recognition that system properties repeat themselves across the scientific disciplines is something that we are increasingly using to understand system properties.

1956]. Which contained many ideas that would later re-emerge when system thinkers started to try to understand complex adaptive systems.

Most systems that were being studied could be understood using linear theory but increasingly it was being found that the observed behaviour of some systems could not be explained in this way. Some of these systems could be characterised by sudden shifts in behaviour due to relatively minor changes in their input parameters, these system exhibited what is termed catastrophic behaviour. Work by Rene Thom in the 1960's and by Christopher Zeeman in the 1970's provided us with the mathematical tools with which to recognise system properties that would result in these catastrophic behaviours [Zeeman 1977].

But in some systems it was found that the behaviour of the system did not seem to reflect the input conditions as defined. It would be the work associated with chaos theory that would recognise that our measurement imprecision and environmental noise was having a large effect on these systems. A notable pioneer of the theory was Edward Lorenz who during 1961 was working on weather prediction, who discovered that small changes in initial conditions produced large changes in the long-term outcome. This sensitivity is often referred to as the butterfly effect due to Lorenz's paper [Lorenz 1972] given in 1972 to the American Association for the advancement of science.

Chaos theory is also responsible for giving us the concept of "attractors" a phase state in the system behaviour into which the system can settle, giving rise to the observer's potential view that the observed system is stable. The problem being that an external influence can tip the system away from it current attractor towards another, changing the observed system behavioural stability. These attractors can provide a different approach to influencing the behaviour of systems from the classical feedback techniques and are also applicable to controlling systems that contain complex feedback paths.

Understanding these complex systems requires us to move us beyond Von Bertalanffy's recognition of the importance of organisation over mechanisms, to consider how the relationships of the system parts and their relationship with the external environment gives rise to "emergent" system behaviour. There is a fundamental difference between chaotic systems and complex systems, with chaotic systems a perfect knowledge[7] of the initial conditions and the environmental context enables you to predict system behaviour, with complex systems this is not true [Holland 1998]. Knowledge of the initial conditions for a system that contains complex relations between its elements is not the issue, rather it is the temporal dynamics of the relationships between the elements and their changes during "run-time" that delivers the emergent system behaviour [Gell-Mann 1994].

Some complex systems have the ability to adapt [Ashby 1960], they have the ability to change and this adaptation could be interpreted as the ability to learn from experience. John Holland [Holland 1992] defines a Complex Adaptive System (CAS) as "a dynamic network of many agents, acting in parallel, constantly acting and reacting to what other

[7] Which we should note cannot be achieved.

agents are doing". Holland's definition, to be complete, needs to be extended to include the agent's responses to changes in the environmental context and we can look to Stuart Kauffman's work [Kauffman 1993] on self-organisation and selection in evolution to provide us with the insight into the potential impact that the system environment can have on these systems. Consequently in this type of system what we think of as "learning" may not exist as tangible knowledge but rather manifests itself as restructuring of the interactions between the agents in the system, we have a system that exhibits intentionality as an emergent property although the agents in that system would not be aware of it [Thoms 2007].

If we consider our systems engineer as an observer of a system that contains humans, systems thinking informs the engineer that:

- Whilst systems could be broken down into their constituent parts to do so denies the observer an understanding of their dynamic properties.

- The dynamic behaviour of the humans in the system is characterised by the responses of the individual in the system to information feedback.

- Catastrophe theory warns the engineer to be aware that even minor changes to the input parameters may lead to substantial changes in system behaviour.

- Chaos theory shows us that whilst a system will settle into a basin of attraction that appears to the observer as stable system behaviour, relatively small changes to the input parameters could tip the system into a different basin and the observable behaviour for the same input parameters is likely to be noticeably different. As a result small changes can give rise to situations where subsequent observable behaviour is noticeably different for the same input pattern.

- The organisation and the temporal dynamics of the relationship of the system parts (humans) and their relationship to the external environment will give rise to *emergent* behaviour, which cannot be predicted.

Systems thinking provides the engineer with an understanding of the potential properties and behaviour of systems, which will influence what they consider to be relevant and chose to capture as part of the system modelling activity. In this thesis we are interested in understanding and engineering systems that contain humans. These are systems that are open, highly dynamic and adaptive, as such they are systems that we would classify as CAS but they are more than this because they are systems that contain system elements or entities that are capable of higher orders of cognition and hence intentional behaviour. It is this intentionality that provides for the system adaptability, flexibility and self-organisation. To understand how an engineer can seek to understand the organisation of such systems we need to consider the relevant work into social systems.

2.2 Social systems thinking

The term social system is used in general to refer to entities in definite relation to each other, which have enduring patterns of behaviour in that relationship. Our thinking on these systems has evolved from studies into human society:

For our first major work on human society we need to look to Thomas Hobbes [Hobbes 1651] who in 1651 published his book *Leviathan.* Hobbes recognised the need of social contract to establish a civil society, without which the population would be in a constant state of war of all against all (*bellum omnium contra omnes*) condemning them to lives that are solitary, poor, nasty brutish and short. His underlying model of the social system is hierarchical requiring some sort of sovereign authority to which all members cede their natural rights for the sake of protection.

In contrast to Hobbes work, a hundred years later Adam Smith [Smith 1776] in his book *Wealth of Nations* suggested how rational self-interest and competition in a society can lead to economic prosperity and well-being; without the need for the sovereign role. He also recognised that the division of labour could improve productivity by instead of having a few specialists who could make products (and hence the availability of products pushed up the price) but by breaking the manufacturing process into a number of steps done by less skilled individuals, productivity would be greatly increased. In this society the entities were engaged in an economic model which required its participants to have diverse skill sets and to work together to achieve the common good. The social system model that Smith provided for us was the opposite of Hobbes; it is a flat distributed model in which the network and information flows become as important as the societal needs that bind them together.

Over the centuries there would be a great deal of work looking at specific aspects of human society but this is not directly relevant to the way we need to think about systems. The first major attempt to bring together systems thinking and social systems was by Ludwig von Bertalanffy’s [von Bertalanffy 1950] who tried to apply his general systems theory to social systems only to find a number of difficulties due to the complexity of the interactions between the natural sciences and the human social systems. It would be another twenty years before the first major joining of systems work and social sciences was undertaken by Talcott Parsons [Parsons 1951]. Parsons postulated that the systems being looked at by social and behavioural science were open systems, systems that were embedded in an environment consisting of other systems. The social system, he observed, is constantly responding to changes in its environment, so it is appropriate to say that it is evolving.

Where Parsons used his analogy of systems on society as an analytical tool to understand the societal processes, Niklas Luhmann, who studied under him, took the idea much further. Some of Luhmann’s earlier work with Berger [Berger & Luhmann 1966] looked at how society shapes our individual knowledge. When people interact, they do so with the understanding that their relative respective perceptions of reality are related and as they act upon this common understanding their common knowledge of reality becomes reinforced. The implication is that humans in a social system will share a concept of their environment, which will be distinct and that they are likely to have little understanding of how other social systems perceive their environment. This viewpoint has implications for the observer of these social systems, in that the observer will not share the same perception as members of the social system against which to interpret their observations.

Later, Luhmann [Luhmann 1982] would see social systems as being systems of communication, in which the "bound system" functioned by selecting a limited amount of all the information available in the environment. These systems emerge from the complex environment to meet a need (or purpose) and when that need is no longer meaningful, dissolves back into the environment in a process he termed *autopoiesis*. These systems work strictly according to their own code, so we could take his work further and say that these systems have their own distinct internal culture. To understand these systems Luhmann would start using network theory. If we stand back and look at the type of system being described by Luhmann in light of this thesis's previous section on systems thinking, we can recognise that he too has recognised that social systems possess all the properties of complex adaptive systems, from which we can deduce that what we will be able to understand from the use of network theory will be of limited value.

For our systems engineer observing these social systems they may well seek to understand the internal control mechanisms of a system in terms of some sort of hierarchy or market. But as Parsons recognised that the control mechanisms and organisation will be constantly responding to changes in the environment, so the results of any observation can only be true for that system at the instance of time the observation was made. Subsequent observations are likely to result in different interpretations of the control mechanisms and organisations in place.

Social systems, Luhmann has shown us, are subject to autopoiesis. For the observer this means that there will be a finite time during which they will perceive a system, before it dissolves back into the environment. This type of system only exists in the eyes of the observer, when there are system properties that they can separate from the environment.

From social science we can recognise that, for systems that contain humans, the internal structure and binding mechanism employed in these systems will be an emergent property of the system in its environmental context. How the system elements choose to "setup"[8] this system organisation is a result of their purposeful behaviour or cognition. To understand our current understanding of cognition we need to look towards cognitive science:

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[8] Luhmann's work shows us that *"setup"* is not really an appropriate term: It is rather an emergent internal culture, that only exists within the system and an observer who is not part of the system cannot understand it. They are as such third order cybernetic systems.

2.3 Cognitive science thinking

Cognitive science is a broad set of disciplines that are seeking to understand the mind and its' behaviour. If we look back in history this idea of a "mind" was invented by Descartes [Descartes 1637], he saw it as something that could be studied separately from the physical body[9]. The question for cognitive science would be how did this "mind" work? And later could we make a machine that could think?

During the seventieth century the mind was seen to use logic for the "art of thinking" and even up to the nineteenth century Boole's [Boole 1854] entitled his book "An Investigation into the Laws of Thought", although the book actually focused on the foundations of mathematics rather than the working of mind. It would be Gottlob Frege [Frege 1884] who would recognise that humans do not always think logically and would start cognitive science looking at the problem differently.

As part of Gödel's incompleteness theorem [Gödel 1931] Gödel proved that for any consistent logical system rich enough to contain elementary arithmetic, there is at least one meaningful sentence that cannot be proven by mathematics, but which humans could see to be true. How the mind did this would become a canonical point of reference in debates over human cognition as symbolic processing and human versus machine intelligence. But Gödel's theorem's did not stop Turing [Turing 1936] claiming that anything that was computable could be computed by a Turing machine.

By the end of the 1940's Turing [Turing 1947] would define a different type of machine for thinking; a connectionist system, one which today we would recognise as a neural network. Turing was not the only person who had been thinking of intelligence in terms of networks; Sigmand Freud [Freud 1901] had introduced the ideas of networks and associative or inferential principles in his work on cognition. Once they started thinking about intelligence resulting from a connected network cognitive science started questioning the nature of the structure of the mind and "nodes" in that structure and for that matter the nature of the result of that thinking.

It would be Craik [Craik 1943] who suggested that the brain is a system which constructs "models" representing the world and possible conceptual worlds. He considered that the mind's perceptions and memories are models of the things which can be run to see if they can solve the problem at hand. Craik's work may have led to the modern concept that when we interact with machines we form a mental model of the states of that machine, something that is fundamentally flawed when we consider the natural complexity of cognitive systems. Craik himself was under no such elusion as he recognised the complexity of the problem and would not have encouraged such naive system models.

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[9] For many years Descartes work was misinterpreted that mind and body were physically separate entities. Recent re-interpretation recognised that Descartes work also embraced the modern view that mind is an emergent property of the body.

Craik also considered man not as an external element of a system but as an integral part of that system [Craik 1947], for which he declared that as an element in a control system a man may be regarded as a chain consisting of the following items:

> 1. Sensory devices, which transform a misalinement between sight and target into suitable physiological counterparts, such as patterns of nerve impulses, just as a radar receiver transforms misalignment into an error-voltage.
>
> 2. A computing system which responds by giving a neural response calculated to be the appropriate response to reduce the misalignment
>
> 3. An amplifying system-the motor-nerve endings and the muscles-in which a minute amount of energy (the impulses in the motor nerves) controls the liberation of much greater energy in the muscles.
>
> 4. Mechanical linkages (the pivot and lever systems of the limbs) whereby the muscular work produces externally observable effects, such as laying a gun.

An interesting viewpoint that would be later echoed by Parasuraman et al's human information processing model [Parasuraman et al. 2001].

Even Minsky [Minsky 1965] argued that any creature that could answer a hypothetical question about itself must possess knowledge in the form of symbolic models of the world and that it would need to construct a model of itself to be able to answer these questions. This implies that knowledge representation for both man and machine would determine what each of them could think about.

But if these symbolic models did exist what would they look like? Von Uexkull [Von Uexkull 1934] had earlier recognised that different species have different perceptual and motor abilities, so the animal's environment (world) or world model, is that subset to which the creature can respond and which it can affect, something that he called Umwelten. Critically Von Uexkull recognised that to the members of different species, the umwelt of other species are invisible and thus unliveable. The implication is that the "mind"[10] of one species could not be understood by another, something that we need to remember when we come to considering the nature of the cognitive elements in our system: a human's umwelt and that of a machine will always be different. This can be further extended to recognise that it will also influence their concepts of time and distance [Troupe et al. 2007].

Whilst under cognitive science many people would study how humans created knowledge and how they solved new problems using that knowledge, others continued to consider the challenges of how machines could do similar. For Gregory [Gregory 1977] this meant that we would need to allow machines to learn about the structure of the world, so that they can develop internal representations adequate for finding solutions within themselves. As engineers, seeking to create cognitive systems, the challenges of internal

[10] Mind here refers to Descartes definition as being the emergent property of the body.

knowledge representation is of less importance than the cognitive function that they can provide for us. What Gregory showed us was that if machines were not able to create new knowledge structures then they would only be able to solve defined problems. In effect they would provide automation of problems that humans would have to define for them.

Where cognitive science sees cognition as an emergent property of the physical body, systems engineers need to recognise that, in some systems, cognition is an emergent system property. Whilst cognitive science may be seeking to recreate the abilities of a human's mind as a machine, the systems engineer only requires a means of thinking about the cognitive contribution of the individual components. Craik provided us with an initial means to consider a human but we need to move beyond his linear chain to a simple model that embraces the complex challenge of cognition. Cognitive science has also shown us some of the underlying differences that will exist if we seek to compare human cognition and that of a machine, which will have implications for the exchange of data and information between humans and machines.

If we can find some way for a systems engineer to abstractly think about the human cognition and knowledge requirements then they should be able to embrace the human cognitive contribution in the system design.

Whilst the focus of this thesis is not about how we think about systems, we assert that the development and application of any engineering technique requires that the practitioner has a suitable grounding in the potential properties and structure of systems, which we have discussed in these last three subsections. With this baseline systems understanding we can next look at how engineering has sought to include an understanding of humans in the system engineering process.

2.4 Systems analysis and engineering

To understand how engineering has taken account of humans in the system analysis and design stages we need to go back and start with a common understanding of what we mean by a system, from its original Latin or Greek definition it means:

> *to combine, to set up, to place together.*

This early definition embraces the act of construction that we would today associate with engineering, later definitions such as from the Websters International Dictionary provides us with a view that a system describes a holistic entity:

> *A system is that body considered as a functioning unit, which is formed of many often diverse parts subject to a common plan serving a common cause or purpose.*

From this definition we recognise that a system consists of a multitude of different lower level elements that together seek to deliver the overall purpose (goal). When we look at systems engineering what we find is not one discipline but a multitude who together design the system from cradle to grave: Bahill [Bahill & Dean 1996] describes it as "systems engineering is an interdisciplinary process". Whilst it is supposed to be an interdisciplinary process we have to recognise that in reality it is a number of different disciplines, who each have their own languages and specialisations, who together design the system under the auspices of a chief engineer. The engineering team is itself a system, whose purpose is to create a system, which exhibits all the classic challenges[11] that we associated with third order cybernetic systems.

The way in which systems engineering has sought to design systems has used techniques such as Yourdon [Yourdon & Constantine 1979], Structured Analysis and System Design [DeMarco 1978] and more recently component or object based techniques such as UML [OMG 1996]. Whilst the system engineer has considered the human cognition as part of the design process and actually focuses the system design on supporting the human decision process[12], these techniques do not provide a formal way of supporting the human contribution to delivering the system purpose.

In amongst the team of engineering disciplines we find “human factors” a team who up until recently participated in the implementation phase of the system rather than the development of the system concept. If we look to the advice of the various standards for instance the DoD Human Engineering program [DoD 1999] they define the requirement for the need to apply human engineering to system engineering to achieve required operator performance, maintenance personnel, to minimise personnel skills and training requirements. But they do not require systems engineering to consider the impact of system design decisions on human effectiveness; we could consider that this reflects the unwritten assumption that the human is not considered to be part of the system. Consequently the focus of the human factors work is on the interaction of the human with the system and various methods were developed to help them tackle this, a few that would seem to relate to our challenge are captured here:

One of the well known models for analysing human interaction with computers is GOMS: Goals, Operators, Methods and Selection of rules, which was based on early work by the cognitive scientists Newell and Simon [Newell & Simon 1972] and later developed as a modelling framework by Card, Morgan and Newell [Card et al. 1983]. GOMS starts off with good intentions claiming to make use of a model of human behaviour referred to as a model human processor (MHP) of which one of the three interacting subsystems is the cognitive system. This cognitive structure is assumed to contrast four components: a set of goals, a set of acts or operators, a set of methods for achieving goals and selection rules for choosing between the methods. The development of a GOMS model involves a detailed analysis of the user’s tasks in order to represent “how to do it”. As such it is not a system analysis tool but addresses the procedural aspects of the human interaction at the human interface design stage, using

[11] We consider the chief engineer being the observer on the specialist engineering groups, which we could consider as subsystems, who each have their own culture language viewpoint on their purpose etc.

[12] The specific decisions required to be made we assert are contextual. Because of the nature of system requirements there is an implied defined constrained context against which the system is being designed.

predetermined task structures; consequently it is addressing constrained context problems.

Before leaving GOMS we should also mention the work into Cognitive Complexity Theory (CCT) [Kieras & Polson 1986]. This theory attempts to predict the amount and structure of the knowledge required to use a device. It focuses the designer in towards a designed (or being designed) product rather than supporting the analysis of the wider system challenges or any aspect of cognition.

A tool that takes a more systems viewpoint is Finite State Machine (FSM) Models [McCulloch & Pitts 1943] which provide a way of describing a system with finite, well defined, possible configurations. They have been used to represent the observable states of a machine and to represent human tasks and procedures in the context of a device. However it is applied, the model has only a finite set of inputs and outputs that it can respond to and a finite set of behaviours that it can produce [Turing 1936]. FSMs have been used to model human interaction with a computer terminal from as early as 1969 [Parnas 1969] used them to understand human errors; inconsistent ways to reach a state and data entry problems. Over the years there have many further applications [Jacob 1983, Bosser & Melchoir 1990] of FSM to describe the behavioural aspects of the human interaction problem. But we must remember that behaviour is contextual, where as this type of engineering tool, as recognised by Turing, restricts itself to a definable set of stimuli and produces a specific set of behaviours: designing our system using it denies the human the ability to respond to context.

The Operator Function Model (OFM) is another control engineering technique that has been applied to understanding operator activities in light of a given machine. It has enabled the engineer to capture a hierarchical model of the functions the user must conduct in order to operate the machine for the purpose of achieving their goal. It uses a framework of nodes (states) and arcs (transition) to capture how a user may decompose a control function into simpler functions and coordinate those functions in order to supervise a complex system [Jones et al. 1995]. OFM moves the human-machine engineering activity earlier in the lifecycle than GOMS, CCT or FSM, enabling the definition of human tasks and the distribution of tasks across a team. But it is still a design tool addressing “how” to do something for a specific defined context, not “what” is required to be achieved, which is context independent.

This recognition that engineering needs to design systems that respond to changes in context is not new, as early as 1939 Simon Wright [Kauffman 1995] recognised that good designs are only applicable for a specific environment. But chaos theory has shown us very small unpredictable things can change the environment in ways we cannot predict and cannot adequately specify, so the goodliness of engineering designs based on constrained context can only hold true (if ever) for a brief moment in history.

To seek to overcome this systems engineering has recently adopted the use of Architectural Frameworks [DOD 2003, Uk MoD 2005] to capture aspects of the context of systems. These frameworks have recently [MoD 2008b] seen attempts to capture the human contribution to the system and whilst they allude to the use of methods such as cognitive work analysis, they generally show a traditionalist view on the application of HF to systems. A more human decision orientated approach to the use of MoDAF had been earlier captured in 2004 [Thoms 2004].

That is not to say that human factors have not been considering the human needs in decision making, one of the key areas that we have seen a lot of work is that of Endsley's consideration of situation awareness [Endsley 1995]. Endsley's model tries to capture a human oriented specific instance of awareness in order to support a definable set of decisions. Her model defines a three stage hierarchical model consisting of: Perception, comprehension and projection, which implies human knowledge requirements without making them explicit and heavily relies on the human's ability to ground the set of decisions in the evolving situation.

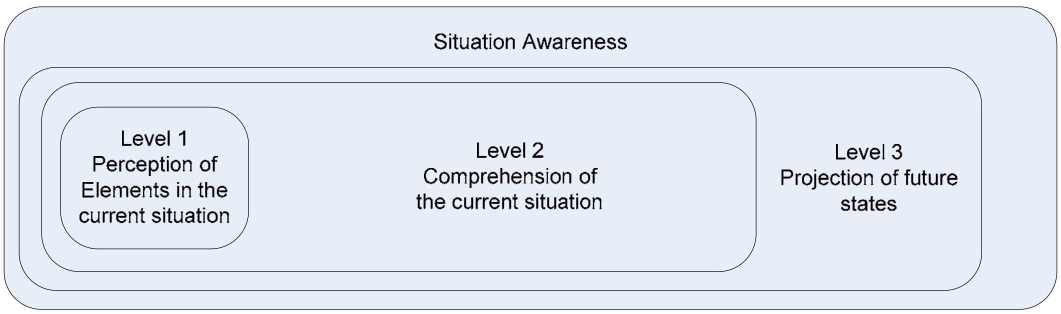

Figure 1 Endsley's model of Situation Awareness.

Once we recognise this need to understand aspects of the external situation, which thanks to chaos theory we know is dynamic and undeterminable, it becomes apparent that to try to capture human awareness as such a model is going to result in something of limited value or use to the systems engineer. To be of greater use it needs to embrace the dynamic aspects of the external situation that is needed to ground the decisions.

Her later work [Endsley 2000] considered the idea of creating a mental model of the individual's system conceptual awareness, capturing a human's knowledge and understanding of the present state of a system (as distinct from the context). A model that suffers from it being situated in the first order of cybernetics, rather than the second, which would recognise that the human is also part of that system and that any such model will be unique to each individual. A further concern is that this model is that of a closed system where as actually it should be considered to be an open system, which will be influenced by the external situation.

On a more practical side (rather than research) as part of the human factors work associated with systems we have seen the development of human-in-the-loop simulation testing that seeks to examine human performance issues including measurement of operator situation awareness and workload [McGuinness & Dawson 2004] which is been seen by many as useful. In Missy Cummings paper [Cummings 2005] looking at the lessons learnt from these types of experiments, she demonstrates the narrow viewpoint of the Human factors situation awareness questions, can lead to the desire to implement system functionality that fails to provide the human with the wider awareness needed in real operations. **She specifically raises the need to investigate ways in which to understand the impact of the machines intelligence on the operator's knowledge states and decision processes**.

Techniques to address the impact of the machine's intelligence or decisions on the human are the focus of an emerging discipline that of cognitive systems engineering:

2.5 Cognitive system engineering (Human centric systems engineering)

The term cognitive systems engineering is a recent term used to refer to the effort to support the cognitive requirements of human work, through system design. It is a term that is often confused with studies into the human brain or people see it as being a discipline seeking to engineer a brain, for this reason we prefer to use the term Human Centric Systems Engineering (HCSE).

This engineering focus can be traced back to the three mile accident in 1979 which Jens Rasmussen investigated [Rasmussen 1986]. Rasmussen identified that mechanically provided "information" sometimes interfered with the control room staff's attempts to understand what was happening in the nuclear plant and their ability to adapt to the circumstances. Somehow engineering needed to be refocused to address the human needs, both as individuals and as members of a team.

It would be Hutchins [Hutchins 1995] who introduced us to the need to locate human cognition in context, where context is not a fixed set of surrounding conditions but a wider dynamical process of which the cognition of the individual is only a part, hence the title of his book *"Cognition in the wild"*. He opened our minds to the challenge that human cognition is not something that can be defined but that it adapts to its surroundings and that the results of cognition are cultural. In discussing the organisation of team performances he refocused us on the higher level challenge of the human team and showed that cognitive processes can be distributed across a group. To support this distributed cognition he recognised that communication within the human team was key and that the nature of what was communicated affected the cognitive performance of the team. What he did not tell us was how to tackle this type of problem or the requirements for it.

The actual term Cognitive Systems Engineering was coined by Erik Hollnagel and David Woods back in 1983 [Hollnagel & Woods 1983]. They recognised that due to the increase in automation the human's task had shifted from an emphasis on perceptual-motor skills to an emphasis on cognitive activities, i.e. problem solving and decision making. They recognised that such systems had to be conceived, designed, analysed and evaluated in terms of a *cognitive system*. This cognitive system produces "intelligent action", it is adaptive and able to view a problem in more than one way. Using their definition they recognised that not only was man a cognitive system but also that machines may in the future be considered as such. But quickly they focused back on the human-machine interface concerning themselves with supporting the operator's model of the system through the interface rather than the human's cognitive contribution to delivering the system purpose.

To move forward we needed someone to define requirements for us and during the early 1990's the focus was getting machines to automate human decisions. In a majority of situations automation was improving the precision and economy of systems, but increasingly a number of unanticipated problems and failures were being observed particularly in the area of automation of the aircraft cockpit [Dornheim 1995]. Billings [Billings 1996] advocated the need to take a human-centred approach to seek to attempt to avoid these pitfalls.

Billing's human-centred approach required that we shift the system boundaries and consider that both the human and the machine are together part of the system. In the original paper the use of *human* explicitly included the human-team, something that would sadly be forgotten for a number of years, as engineering focused on the one human to one machine problem. This human-centred focus would also provide a means to recognise that machine technology changed people's roles. In his later collaborative work with Sarter [Sarter & Billing 1997] they recognised the gap between the human-centred intentions and the human-centred development practices, which showed that engineers had a misunderstanding of the concept of human centeredness or that they had an inability to translate its underlying ideas into actual designs. Maybe they were missing the tools by which to achieve it?

Parasuraman, Sheridan and Wickens [Parasuraman et al. 2000] would rise to the challenge and provide us with a framework to enable engineers to consider what functions should be automated and what should be left with the human. They proposed extending Sheridan's 10 point scale of automation [Sheridan & Verplank 1978] to capture the levels of automation of machine decision and action selection that could be applied to their simple four stage view of human information processing which has a remarkable resemblance to Boyd's OODA loop [Boyd 1976]:

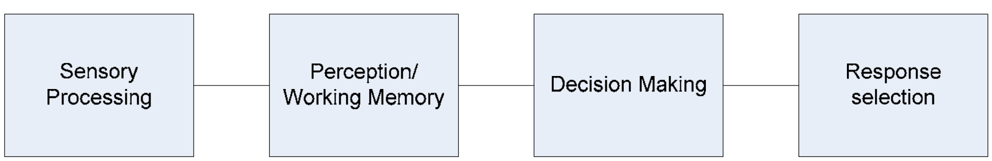

Figure 2 Parasuraman et al's Four stage model of Human information processing

They admit that this model is a gross simplification of the many components of human information processing and suggest that each stage is equivalent to system functions that could be automated. To aid us in using their framework they provide us with a engineering process in which to consider automation:

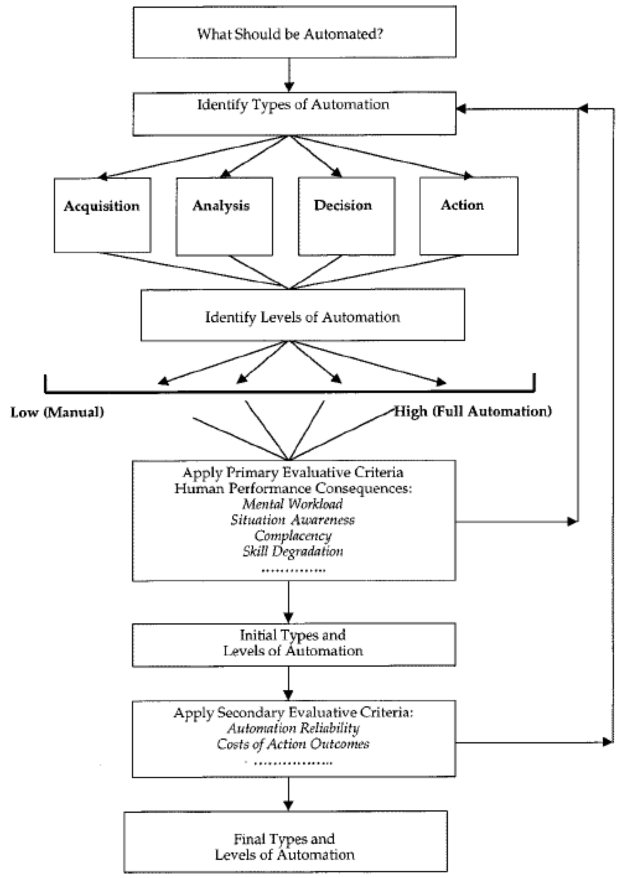

Figure 3 Parasuraman et al's flow chart of the application of their model

One of the key aspects of this framework is that they recognise that particular types and levels of automation need to be considered in light of their associated human performance consequences. Two of these relate to cognition; the ability to form situation awareness and the potential impact on the human's decision making ability when not aided by the machine, but they do not provide the reader with guidance on how to tackle these issues. If we consider their model in light of Billings and of Hutchin's earlier work we recognise that this model is of a single human and nowhere in this paper do they recognise the need to embrace the team view.

During the 1990's task analysis was beginning to embrace the human cognitive challenge with a new technique named cognitive task analysis [Redding 1992]. The aim of this work was to yield information about the human knowledge, thought processes and goal structures that underlie the observable task performances, so that humans could be taught how to do a task. Over the next decade many slightly different approaches to cognitive task analysis would be considered [NATO RTO-TR-24 2000], but fundamentally all of these fell into the trap of assuming a defined task and a single individual. Even recent papers into Cognitive Task Analysis (CTA) by Zachary et al. [Zachary et al. forthcoming] which used cognitive task analysis to investigate Anti-Air Warfare (AAW) chose to only consider a single human role even after they had identified that AAW was a team task!

A slightly different approach was taken by those advocating cognitive work analysis (CWA) [Vicente 1999]. Vicente's process for CWA is made up of five phases:

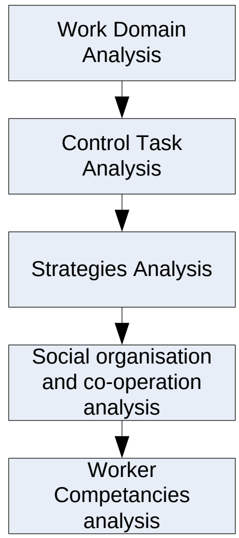

Figure 4 Vicente's five phases of CWA

This method provides a top down analysis of how work can be done in a constrained work context, i.e. one in which the cognitive tasks can be explicitly defined and it does include consideration of the team view of the work. As such it models what is done without the need to understand why it is being done. The knowledge of why these things are being done is necessary if the resulting model is to be evolved to support changes in the system context.

To produce a cognitive model that supports system evolution we need to focus on the "why": the goals both of the individual and of the team. In 2003 Bryant [Bryant 2003] as part of his work for the DRDC, introduced a new model: Critique, Explore, Compare, and Adapt (CECA) to aid the understanding of command's and the entire command and control (C2) cognitive processes:

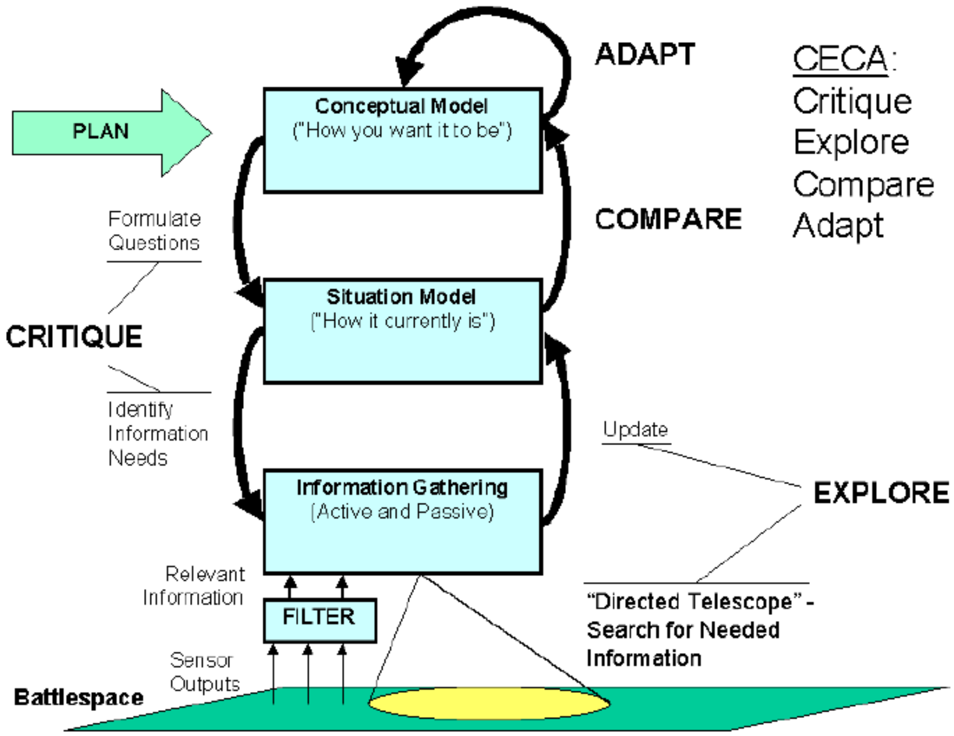

Figure 5 The CECA Loop.

The CECA model is based on the premise that humans use goal-oriented mental models to represent and to make sense of the world. It begins with a conceptual model of what is trying to be achieved (the goal), it then compares this with a situational model of the state of the Battlespace (context) at any point in time. At the bottom of the model is the information gathering which is used to populate the situation model. This framework is intended to aid the designer to ask questions related to human cognition that is being used to update or maintain the situation and conceptual model in order to consider practical ways by which to improve the human performance. The focusing of the information gathering on the needs of the situation model is hoped to improve the delivery of needed information, rather than available data. Not made explicit but hidden within the model is the need to consider the commander's decisions that are needed to transform the current situation into the conceptual model. Bryant does not provide guidance on how to use this framework either for the individual or for team cognition.

Cognitive systems engineering set out with good intentions recognising cognition not only of the individual but of the importance of the team cognition. The work to date has not delivered against their vision.

2.6 The challenges to be addressed

In our journey looking at the progress towards Human Centric Systems Engineering we have looked at how the way we think about systems has changed over time. We have seen how we have moved from the view that systems are closed and independent from their environment, to realise that systems are not only open but that they are complex and are evolving in response to change in the environment In looking at social systems we have seen that different types of internal organisation can exist within a system and that those which contain elements capable of cognition can autopoiesis, to spontaneously emerge from the environment to meet a purpose and to dissolve when that need is no longer meaningful. We have seen that the internal structure and binding mechanism employed in these systems will be an emergent property of the system in its environmental context as such the emergent properties of such systems will always be uncertain during the engineering process. To understand what is meant by cognition in these systems we have delved into the world of cognitive science selecting from it a few key nuggets that we need to keep in mind as we began to think about engineering cognitive systems, systems that contain not only humans but machine elements capable of decision making.

When we looked at both systems engineering and cognitive systems engineering we did not find any techniques that enabled the engineer to capture the human cognitive contribution to delivering system functionality, either as an individual or as a team. So our research questions are:

1. How could a systems engineer recognise and capture the human cognitive contribution to a system?

2. Can we use this technology to understand how changes in one part of the system could impact the potential cognitive contribution of other parts of that system?

This second question is focused on using the technique to support engineering design decisions, by understanding the consequences of the redistribution of decision making both on the emergent team contribution and its information flows, but also on their underlying knowledge requirements.

The new technology needed to analyse and understand the cognitive aspects of a system is the subject of this Thesis.

3 THE STUDY PROCESS

In the previous section we found that the engineering activities have focused on delivering systems designed against a defined context where as in reality the context is continually evolving. To deliver systems that are agile and flexible it was proposed that engineering needs to embrace the human's ability to use their knowledge to adapt the way in which they work to continue to deliver the system's purpose in spite of the evolving context. We explored the engineering tools and techniques to find that they only supported consideration ofindividual humans doing defined tasks. The tools did not support the consideration of the human cognitive contribution which was being used to respond to context changes or the wider team cognitive contribution to delivering the system purpose. We concluded by recognising that engineering needed some means of recognising and capturing the human cognitive contribution, which could then be used to support engineering design decisions.

In this section we introduce the research process that was used in conducting this work and how it meets our research questions. The process used in this work is split into two distinct phases:

> Phase 1: The theoretical work which initially focuses on investigating a human planning system and then using that understanding to develop a framework to be used as a tool to capture the human cognitive contribution and a process with which to apply it in engineering.
>
> Phase 2: The validation exercises apply the framework and the process to real world systems in order to verify their applicability and where possible to evolve them to better meet the engineer's needs.

3.1 Theoretical work.

We need to start by exploring the system challenge represented by cognition; our challenge is to develop cognitive systems thinking, not to seek system solutions. To seek understanding in the previous section we investigated cognitive systems engineering to see if it can help us focus and understand those aspects that need to be captured in a model of cognition. We found that it provided very little, so we start this work by investigating the challenges that a cognitive system would need to meet, to do this we have chosen to use the example of a planning system.

In doing this we will seek to identify the fundamental challenges that an adaptive cognitive system needs to be capable of solving and investigate them. This work is presented in section 5 as a framework that captures the cognitive capabilities and the potential information flows between them. This will enable us to answer our first question:

1. How could a systems engineer recognise and capture the human cognitive contribution to a system?

To enable an engineer to be able to use the framework we introduce the possible utility of this model for understanding the cognitive contribution of the individual and it's potential for understanding the human team's cognitive contribution. This thesis then steps through an initial process for using this framework from the initial capture of the system capability statement through to looking to deploy machine technology. As part of this work we consider the potential attributes required to assess the level or type of cognitive capability needed and to enable us to recognise potential emergence from such a model. This will enable us to answer our second question.

2. Can we use this technology to understand how changes in one part of the system could impact the potential cognitive contribution of other parts of that system?

The artefacts of the initial process are:

- Potential modelling technique (framework) to capture a system cognitive process

- Identified attributes that will enable the capture of key systems aspects that deals with the intentional "emergent" cognitive capabilities.

- An engineering process for using the framework to capture the cognitive aspects of a system.

- Recognition of the emergent system or team cognitive behaviours.

It is then necessary to take the theoretical work and to apply it to specific studies in order to validate the theoretical work and to further mature it. The study process is shown in Figure 6.

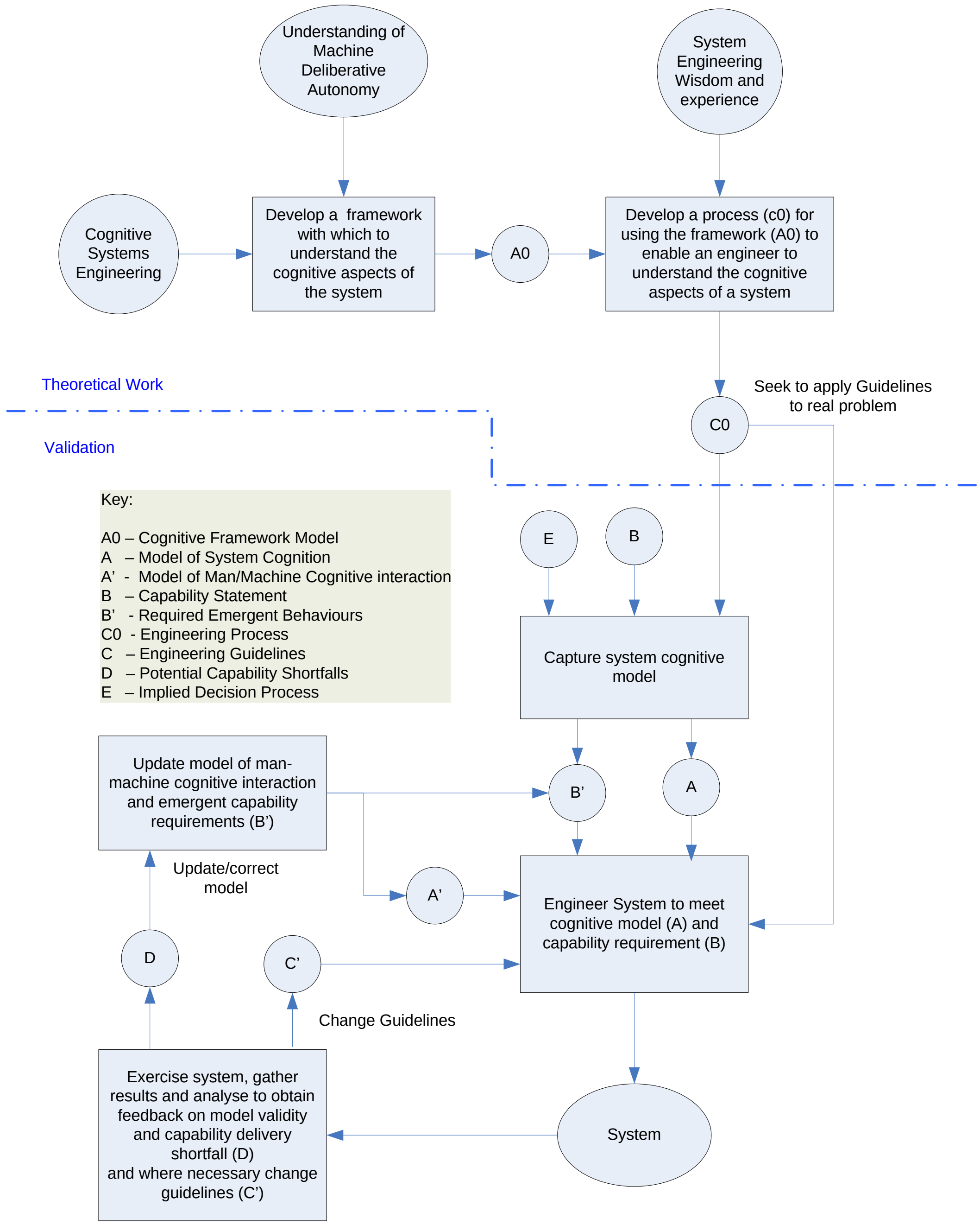

Figure 6 Study Process

3.2 Validation exercises

Armed with the theoretical work we verify the framework and process by applying them to two military systems. The first study will look at reverse engineering an existing system with known problems to investigate if the use of the framework and process could have anticipated the problems that the system exhibits. The second takes an existing system and seeks to investigate the deployment of new machine technology that will enable the evolution of the system capability.

3.3 Legacy system analysis

Our first study undertakes an analysis of the cognitive aspects of an anti-submarine tracking system. To do this it follows the initial engineering process using the cognitive framework to understand the cognitive aspects of the system problem. The aim in doing this is to develop the use of the framework and process in order to

- Support the analysis and assessment of the cognitive aspects of the system,

The intent is to develop the use of the framework to enable systems engineers to:

- Predict the potential impact of the deployment of the low level machine technology (ies) on system (**Human** + Machine(s)) level effectiveness.
- Seek to use the framework to identify mechanisms to overcome the impact or shortfalls.

A key aim is that this framework should provide an engineer with a way of thinking about the cognitive aspects of a system, without pre-empting the implementation.

3.4 Investigation of the deployment of machine technology into a human system

In the second study we apply the framework to an existing military capability that is currently delivered by a human team working seamlessly together in what we will term a "*cognitive system*". Into this human *cognitive system* we will use the framework to investigate the potential introduction of advanced machine decision technology.

Our aim in applying this framework to this military problem is to understand how systems engineers can use the framework to capture the cognitive aspects of a system as a model and at a lower level to capture the cognitive focus of individual humans within that cognitive system. Then to use these models to investigate the potential deployment of machine technology by focusing on how that deployment relates to a human's ability to form awareness, create understanding and to deliberate.

We will see that our framework:

- Supports the analysis and assessment of cognitive systems.
- Provides a basis for considering and assessing alternative design or redesign solutions.

The aim is to enable engineers to:

- Enable the engineer to understand the cognitive functionality contribution provided by the individual humans in the system and by the human team.
- Recognise the human cognitive contribution to delivering system effectiveness.

- Be able to understand the potential impact of the deployment of the low level machine technology(ies) on system (**Human Team** + Machine(s)) level effectiveness.

3.5 Assessment of HCSE as an engineering tool.

Stepping back from the two studies in section 8.1 we return to the framework and engineering process to capture them as engineering tools. For the framework this requires us to remove the theoretical "*baggage*" needed to describe each of the cognitive attributes and to express them as short description that the engineer will be able to internalise without the need for constant reference material. For the process this requires that we capture each activity as simply as possible and we have chosen to use the outline process defined in the BAE Systems Lifecycle Management Guide [BAES 2006], as it represents a good example of engineering process definition used in industry. We therefore need to capture:

- Purpose: Describes the purpose of the stage in the process and what the engineer will get out of doing it

- Inputs: Identifies the information required to undertake this activity.

- Outputs: Identifies the key deliverables from the activity.

- Verification: Potential means to verify the outputs of the stage

- Guidance and notes

We will then consider the key achievements of this work and if the use of the framework and the process has delivered what was anticipated. We will also consider the cost[13] of the exercise and the practicalities of deployment.

3.6 Limitations of the chosen process

We have used two case studies to develop and validate the engineering framework. The choice as to what case studies to use was one of possibly balancing the use of many small simple problems, which ran the risk of not being complex enough to illustrate the value of these engineering tools, against the use of much more complex and sophisticated problems that had the potential to stretch the use of the cognitive framework and process.

It was chosen to conduct two complementary complex cases; the first applied the engineering tools to a legacy system, to understand if they would help identify the source

[13] An additional advantage of the studies being undertaken within an industrial setting is that all man hours are recorded.

of problems in existing systems and the second to apply them to a possible future system to understand if their use aided the design process.

We recognise that the validation studies reported on in this thesis were carried out directly by the author. Whilst this early work focused on understanding the conceptual space that needs to be analysed for the development of the engineering tools, later work will need to refine the application of these tools and at that point it will be appropriate to have a third party undertake the evaluation. We have compared the conceptual HCSE approach to the relevant conventional human factors approaches and found that this technique is complementary to it.

We also recognise that because this work was not conducted as part of a customer funded research package access to subject matter experts (SME) was severely limited. For the second study availability of the SME was a matter of a couple of days over the period of a year.

3.7 Conclusion

The defined study process starts by providing us the necessary theoretical basis to enable the development of systems thinking focused on the cognitive aspects of system. By using a planning system as the focus of the initial work, it enables us to explore the human cognitive contribution. From this work we will recognise three key attributes that we will use as the basis for the development of a cognitive framework and will develop a process with which to apply it.

The study process then provides a means of validating the theory through the application of the framework and process to two real world systems. Each of these validation exercises will investigate different aspects of the framework and the process, which will enable their maturation and, as we shall see, enable the identification of emergent engineering opportunities to aid our understanding of the cognitive aspects of systems.

The conduct of these studies will provide for us, new information and knowledge from them we will create new understanding and identify new challenges that need to be embraced by the engineering technology, the act of doing the studies will itself investigate the practicality of their application. With this in mind this study will return to the engineering framework and process and seek to present them in a form that is more directly exploitable for a system engineer.

We can consider the work captured in this thesis as a journey with the purpose of seeking answers to our research questions, the first stage on our journey is to seek to find ways with which to understand the challenges of cognitive contribution of humans in our system.

4 UNDERSTANDING THE SYSTEM COGNITION CHALLENGE

In this first theoretical section of our study process we look to understand how, as systems engineers, it may be appropriate to think about the cognitive aspects of systems. As part of this journey we will address the first of our research questions:

1. How could a systems engineer recognise and capture the human cognitive contribution to a system?

We approach this question by investigating the challenge of planning, initially as a basic human skill and then as a complex system for which we have chosen military planning, a system that consists of a planning officer and a commander working together to deliver the intended system purpose. In doing this we are introduced to the fact that planning is more than an initial exercise undertaken before commencement of the activity but rather a dynamic engagement with the context, the planning officer constantly changing their plan as the situation evolves and the commander takes that plan, grounds it in the actual situation they find themselves in, executes the corrected plan and provides feedback to the planning officer as to the outcome.

By investigating the military planning system we will find that in seeking to describe the human contribution in the system we use three attributes: awareness, understanding and deliberation. We will then develop our understanding of what these three attributes provide, their complex relationship and how we can use them as an engineering framework to understand not only the individual human contribution in delivering the system purpose but also as a means for understanding team cognitive contribution.

In undertaking the work captured in this section we have engaged Battlespace and systems engineers, military subject matter experts, Dstl and members of TTCP JSA AG14 (Complex Adaptive Systems for Defence) to provide expert advice and guidance, in certain areas.

4.1 Understanding the planning challenge

In this first section we use planning[14] as a system challenge through which to explore system cognition and the human's contribution towards it. We start by investigate planning as a basic human skill recognising how human development and how we perceive the world, plays an important part in our ability to plan. With this basic understanding of the planning challenge we will then consider military planning, a challenge whose complexity has resulted in the need for a human team. For our purposes we have identified this team as consisting of a planning officer and the commander. We

[14] If the reader wishes to know more about the the challenges of planning refer to Lucy Suchman work [Suchman 1987], or the work by Arnoud DeMeyer [DeMeyer 2006].

will see how this separation of the planning challenge introduces new challenges which must be coped with by the cognitive attributes of those involved.

4.1.1 Planning as a basic human skill

As small children we learn to achieve something, in a given situation, by a means of trial and error, or by being shown how to do it. As we get older these skills and behaviours form part of our tacit knowledge that we can call upon without deliberative thought and we become able to apply that knowledge to solve problems in new situations which we may have not encountered before [Quortrup 2003]. But it takes many more years before we can plan a sequence of behaviours to achieve something more difficult and it is not until our teenage years that we recognise that our choices change our future options [Erikson 1990].

We learn that we do not live in a three or four dimensional universe where we can predict the future from our observation of the current situation but that we live in at least a five dimensional universe; the extra dimensions exist because there are alternative futures that we can, through our actions, influence the likelihood of occurring. Such an option space quickly becomes huge and unmanageable, so one of the key human skills is to be able to apply their knowledge to know when and how to constrain the option space they consider. We also learn that not only does the world change due to what we choose to do but it also changes through the actions of third parties meaning that our initial plans may need to be changed to meet the evolving situation if we are going to succeed in our aim.

4.1.2 Military planning

Military planning has added complications due to its scale, dynamics, uncertainty etc. It also has to cope with environmental elements that act autonomously and to make matters worse there is often an adversary who is actively trying to foil what they are trying to achieve with their plan. The result is that in the field, the activity of military planning is separated from that of command, enabling the planers to cope with the complexities of bringing together the right information for their planning activities, whilst command is busy coping with the dynamics of the military operation [Patel 2006]. Consequently military planning is a continuous process: the planning and execution of the plan is sequential. The planning directs the execution, which in turn informs subsequent planning, see Figure 7.

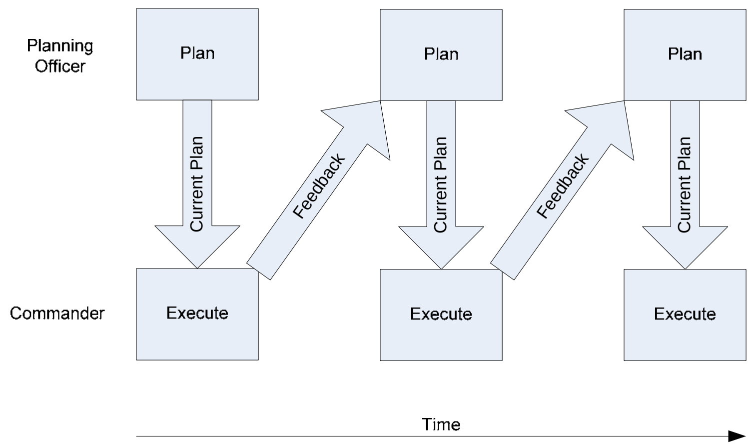

Figure 7 Sequential planning

But military planning is based on a preconceived concept of the world and in the time used to create a plan, the real world changes. Consequently when command receives the plan they must adapt it to meet the current situation and then feedback what actually happened to the planner as a reference for future planning, see Figure 8.

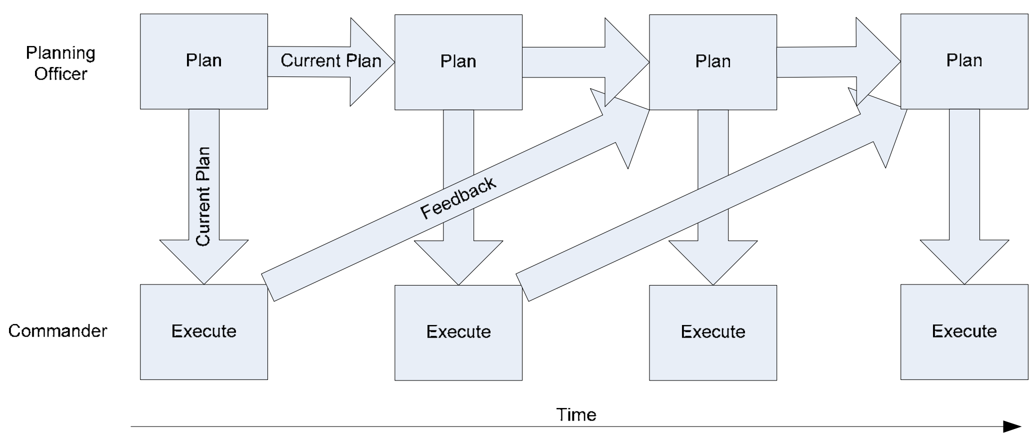

Figure 8 Concurrent planning

But even this view is not strictly true, as we achieve continuous execution by planning and executing concurrently. Consequently whist the initial planning directs subsequent execution any feedback informs future planning and so on, see Figure 9. The result is that the plan will always lag the real situation and that the commander will always have to adapt the plan.

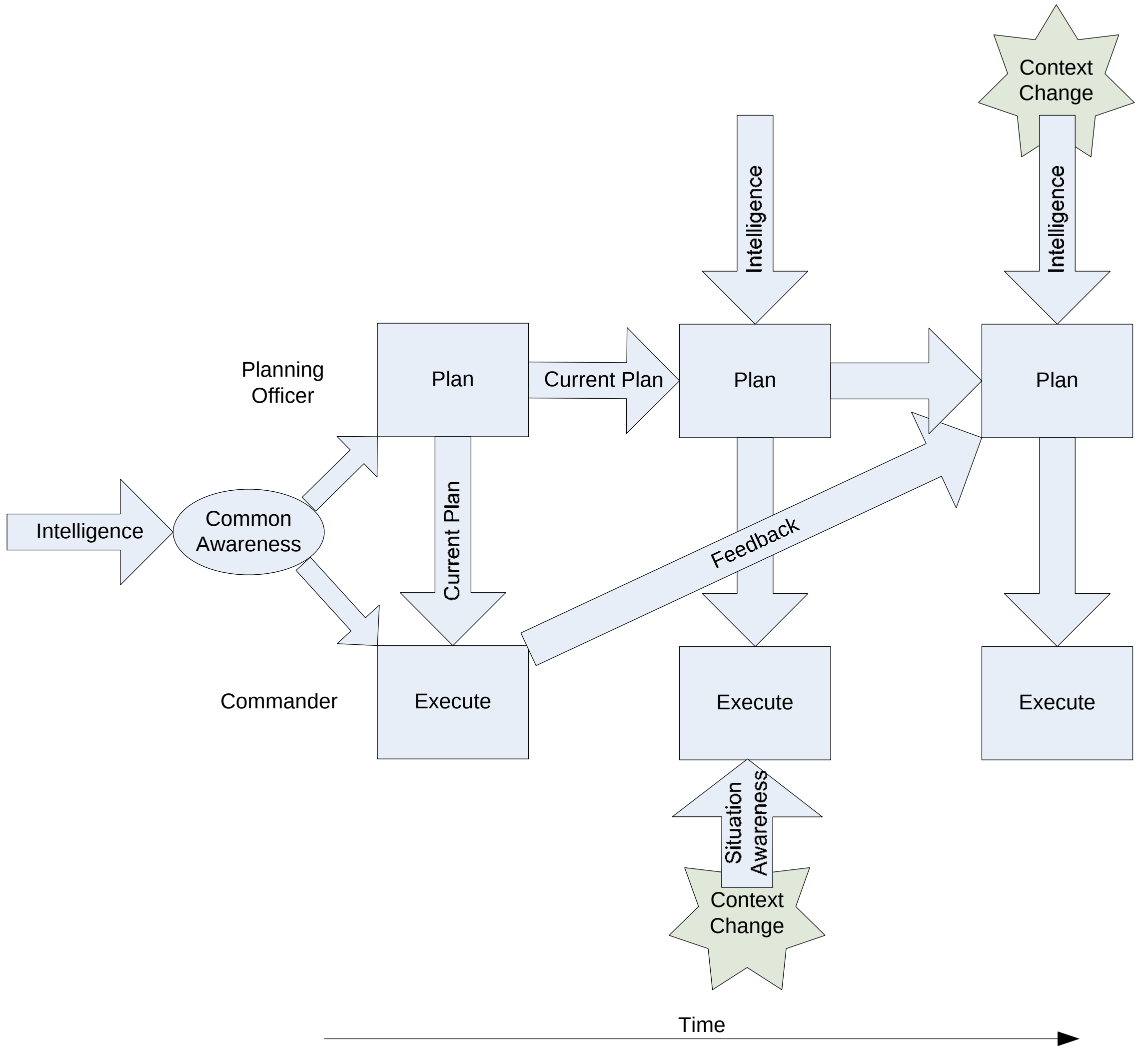

Figure 9 Real world planning

By breaking the planning task from the commanding task we create new challenges, for as the operation unfolds their initial common awareness will diverge, the planning officer is forming his awareness based on intelligence reports and is focusing on the longer timeframe to understand the possible evolution of the context; the commander whilst interested in the long term will focus their awareness and their choice of goals more on the immediate situation. It is thus necessary for the planning officer to maintain three conceptual views of the situation for planning, see Figure 10:

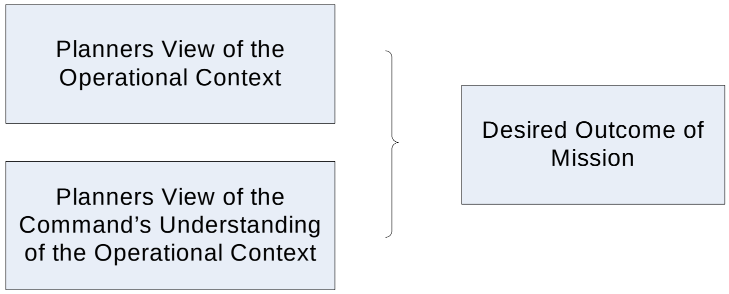

Figure 10: The planning officer's conceptual views of the situation

Both the planning officer and commander need to have a common understanding of the desired outcome of the operation, this gives them a common basis that, whatever else happens, can be used to re-synchronise the operation. They will have their own awareness of the current situation built up from their knowledge, the multitude of data and intelligence that they have available, a view that by its nature will be delayed from the reality that the commander is operating to but which considers the opposition's possible intents and values. In addition the planning officer needs to have a perception of command's awareness of the operational context to enable him to present the plan in a form that the commander will be able to quickly understand and use.

When the planning officer presents an updated plan to the commander they need to provide with the plan their understanding of the current situation and the expected outcome of undertaking the plan. The commander then needs to reconcile the planning officer's view of the situation, with their own situation understanding[15] and to understand based on their own view, if the provided plan will produce the desired outcome. We can continue to build up these views by adding views such as the commander's view of what the opponent thinks the situation is.

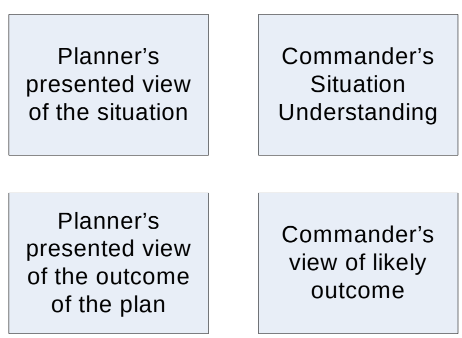

Figure 11 Commander's conceptual views of the situation

The result is that the commander has several different concurrent views of the situation, which are being used to create a "common understanding" see Figure 11. We need to

[15] Situation understanding is referring to the various possible ways in which the current situation may evolve.

recognise that both the planner's and commander's views are likely to be incomplete and there will be uncertainties in the data available. In the real world we have to plan against an artificial concept of the future reality and when that reality does not match what actually comes to pass we must alter our plan to meet the evolving context something that represents a major challenge for maintaining the synchronicity of the awareness of the planning officers and the commander. At the beginning this is not a problem as prior to deployment we minimise the problems by briefing the participants. This provides them with a common understanding[16] of the operational context, the mission and its desired outcome and the actual plan itself. So they should start with the same operational awareness. But as soon as the operation begins the awareness diverges caused by their individual experiences and the source of their information, see Figure 9:

In a dynamic context there are likely to be changes that cause us to need to alter our plans, changing a plan itself causes new challenges: During an operation we do not have the time or luxury of briefing our service people as to the change, they must absorb it often whilst continue to conduct the existing plan. Often what happens when we re-task our people is that they suffer with a short period of disorientation before they can regain their orientation and undertake the new plan. This slows the operational tempo, which is undesirable; consequently sometimes it may be better to complete a now irrelevant task to maintain the overall operational understanding of our people. In doing these both the planning officer and the commander are taking a human centric viewpoint, they are recognising how the change of goal will impact the cognitive focus of the individuals.

4.1.3 Analysis of the Cognitive Challenges of Planning

The description of planning as a basic human skill has suggested that we first learn to be aware of our situation and to use that observation to make behavioural decisions to achieve our desire; this could be represented as shown in Figure 12

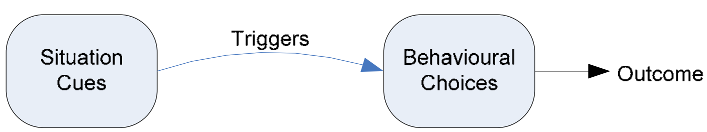

Figure 12 Conceptual view of simple cognition

As we get older we develop new knowledge and are able to apply it to go beyond identifying situation cues to form an awareness of the situation. This awareness is focused on our intent and servicing the decisions to achieve it, see Figure 13.

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[16] This common understanding goes beyond what was defined as *common understanding* by Luhmann and Berger [Berger 1966] and more recently by Herbert Clark as *common ground* [Clark 1996] to recognise the temporal dimensions of possible future options and how the multitude of decisions that could be made will change that future option space.

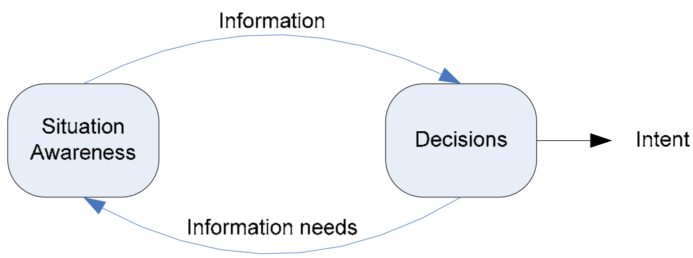

Figure 13 Conceptual purposeful cognition

To achieve more difficult tasks we learn to use a number of behaviours or sequence of actions that from the current situation would promote our desired outcome, we could say that we seek and form understanding. Because we now have multiple ways in which to achieve our desire we have to choose or deliberate between them. We also change our perception of the world and we create an expanded awareness through the application of our knowledge, we in effect are creating a conceptual model of the world that goes beyond what can be observed. This expands our model of the deliberative cognitive process to contain three attributes of cognition as shown in Figure 14.

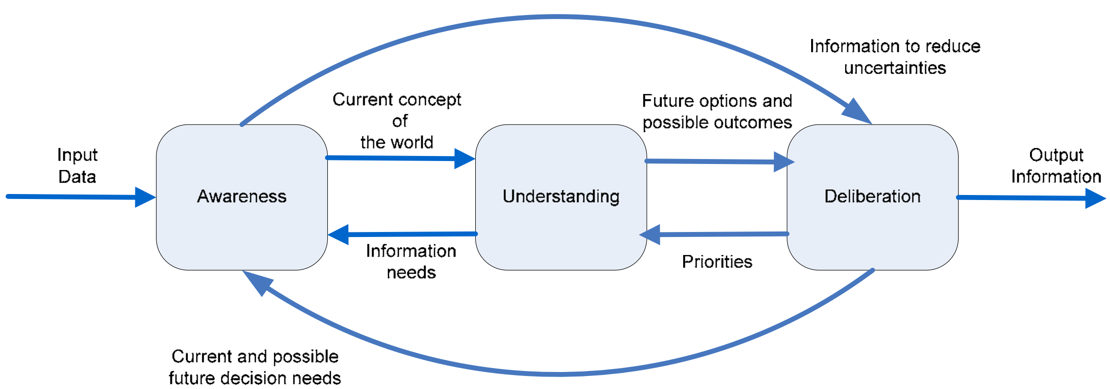

Figure 14 Conceptual model of deliberative cognition.

We can express the relationship between these three attributes of cognition as:

- Awareness informs understanding, which is the basis for deliberation, enabling the individual to identify what they believe is the appropriate decision to be made.
- The individual’s existing knowledge, which is used to form understanding, will shape the way in which they seek to perceive the world, thus understanding influences awareness.
- We also recognise that in order to reduce uncertainties in decision making it is necessary for the decision making to focus the awareness on forming

specific information and providing it in a timely manner to support relevant decisions.

The military planning system is even more complex; to understand cognition in the military system we could use a single system level model of Awareness, Understanding and Deliberation to capture the top level system. An alternative view would be to use separate models for each of the roles in the system and join them together showing the exchange of information between roles to form a rich view of the system that captures their cognitive focus.

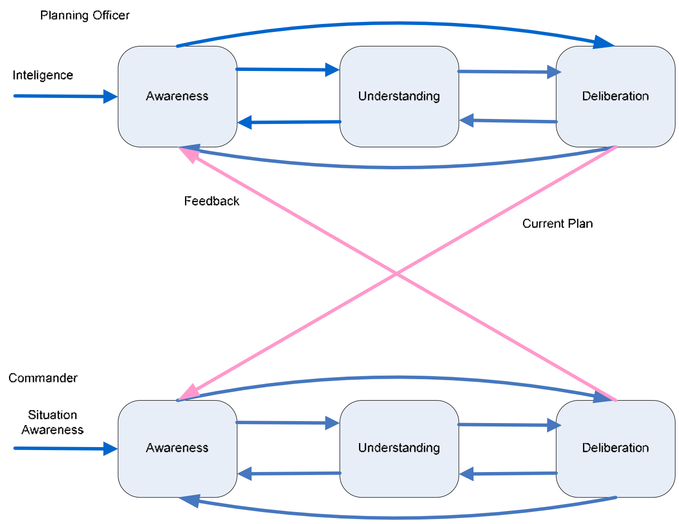

Figure 15 A conceptual model of the relationships of the individual roles cognitive attributes in the military planning system.

In the descriptions of the military planning process provided in 4.1.2 we recognised that the information flows between these two individuals will be subject to temporal delays, uncertainty etc. To understand better the cognitive contribution of both the planning officer and the commander we need to look in more detail at each of the stages of military planning.

4.2 Investigating military planning from first principles

"The skills to plan do not come naturally to most military officers and must be developed. Despite the fact that military planning, much like ordinary non-military planning, is based on common sense, the sheer number of military problems associated with the defence of a nation makes planning a major endeavour. Learning the art of planning begins before commissioning with our first lesson in military history, and like any other skill, it is perishable and requires training and relearning. Planning, both formal and informal, is the link which binds the members and activities of an organization together. The more effectively we plan, the more efficiently we can react to changing circumstances."

DoD CCRP

In this section we explore the process of military planning from the pre-planning stage which forms the initial baseline at the point of receiving the mission, the stages of planning before the commencement of the mission and the dynamic mission management or planning stage, we can represent this challenge as a simple model see Figure 16.

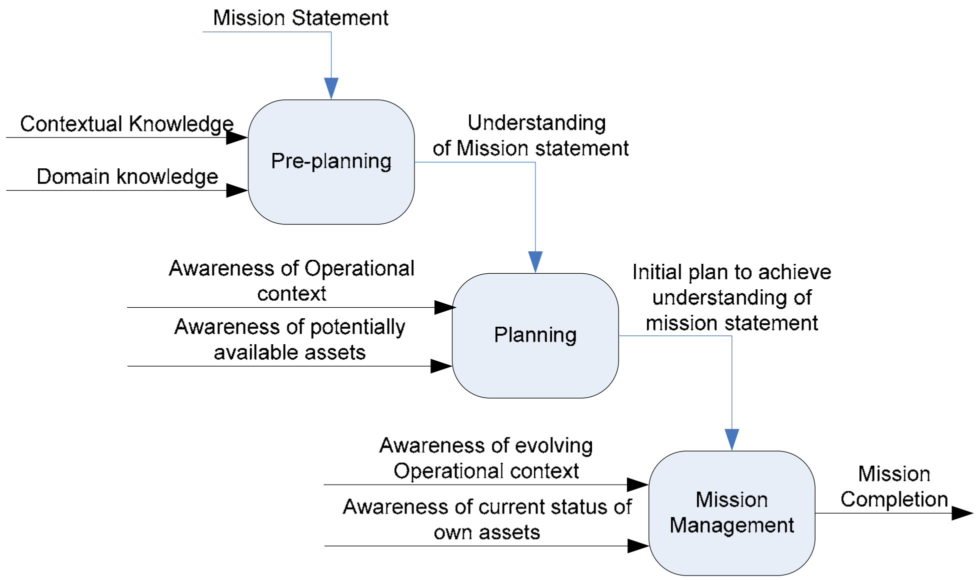

Figure 16 The three stages in the process of human planning

Whilst we can relate to both the planning stage and the dynamic mission management stages, the first stage in this process is normally tacit, it pre-planning exists but we are not aware of it. If we are going to understand the cognitive aspects of systems we need to explore all three.

4.2.1 Pre-planning: The Stages before planning

Whilst it is easy to believe that we only start planning upon receiving our order or mission statement, we have to recognise that this is not true. If we were to consider ourselves as the "planning system" we are not an empty vessel without structure or form but are complex cognitive systems that have developed over many years. The reception of the mission statement and our understanding of it will be based on this prior condition and it is this that will enable us to determine the needed data and the ability to assemble or collect the data in order to define strategies to define a solution. We must therefore the consider the stage of the planning process that existed prior to the act of planning that enabled us to receive, and seek understanding of the mission we have been given within the operational context, this could be:

Recognition of the Precondition

Reception of the order or mission statement.

Data gathering and expansion of understanding.

This final stage will not only reduce the uncertainty relating to the meaning of the mission but provide access to the challenges that may need to be met and the assets that can be brought into play during the planning stage.

4.2.1.1 Recognition of the precondition.

Before a mission statement is received both the planning officer and the commander will have a precondition against which they will seek to understand the mission statement. This precondition is formed by their knowledge and current situational understanding.

Practically we must accept that each individual human is unique and as such there is little value in trying to capture that individualism, it is therefore necessary to generalise our understanding of these aspects. For the military domain the nature of military training shapes an individual's attributes bringing them much closer together than that found within the civilian domain and as such it would be possible to define our expectation of the precondition at a generic level. They will have been provided with:

Domain Knowledge:

- Strategic: How it may be possible to achieve something.
- Procedural: How to do things.
- Declarative: What things are able to do.

Contextual Knowledge:

- Organisational Structure and implied bounds of authority.
- Their understanding of Political, Religious, Military and Civilian situation.
- Their Institutional and personal background: Culture, Values, education, skills and abilities.
- Their understanding of recent and historical events in the locality.

The individual's domain knowledge provides them with the knowledge of how to deliver an outcome. This knowledge is shaped and formed as part of the military training program, which provides them with the ability to recognise the class of engagement that they may be asked to deliver and a set of preferred templates with which to achieve it. This knowledge is available both to the planning officer and commander and to a lesser extent the individual service people who are going to deliver the mission. This common knowledge forms a critical element that will be used during the deployment to enable situation prediction and to enable individuals to behave as expected by command.

Contextual knowledge provides the baseline against which the mission statement is interpreted. There are two sides to this contextual knowledge: one focuses on our own forces, the second on the locality or more specifically on the people who are likely to be encountered in the area of the mission. We provide our service people with this contextual knowledge prior to deployment in the form of a briefing, from which they will build their own situation awareness and make decisions during the operation.

4.2.1.2 Understanding the mission statement or intent.

The mission statement or intent is provided by higher command, but what is a mission statement or intent? The DoD defines command intent as “a concise expression of the purpose of the operation and the desired end state that serves as the initial impetus for the planning process”, the definition of which is a function of command.

Whilst a mission statement or command intent is meant to be a concise statement, in reality this is never the case. To get it expressed adequately, would place further pressure on the higher commander and even then the statement is likely to be able to be understood in a number of ways. The human interpretation of a mission statement is a direct result of many influences and can be considered to be an “aggregation or de-aggregation phenomenon based on an individual’s knowledge and situation understanding. In reality the individual’s knowledge of their commander will fill the gaps.

From this initial interpretation of meaning there will be a number of possible interpretations, to identify a single distinct meaning it is necessary to reflexively limit the possible interpretations (values) that can be assigned to the statement, recognising that there may be more than one distinct element in the signal and where there are multiple elements it will be necessary to understand and reconcile individually their priority or temporality etc. To do this it is necessary to make observations or to seek to gain data relating to the operational context. Only once both the planning officer and command have a single common agreed definition of the mission can they seek to commence planning.

4.2.1.3 Creating the baseline for planning: an awareness of the operational context

Armed with a distinct meaning to the mission statement the planning officer develops two concepts (models) of the world:

> A model of the current situation
>
> A model of the outcome of the mission.

The model of the **current situation** can be ascertained by an extended data gathering using passive data gathering or active data gathering.

> Passive gathering requires the planning officer to wait for data to be made available to it to populate their awareness. The emphasis here is that the planning officer will only act upon what they are told or given and can only recognise gaps or errors in understanding upon the receipt of further data. The planning officer has no control over data reception and thus is unable to predict when sufficient

data will be made available to reach a level of certainty or understanding that is needed to start planning. They also have no way of recognising when further data is likely to become available which could substantially change the planning perspective or probabilities relating to the plan. It also has a tendency to lead the planning officer towards the classical problems of decision making as illustrated in [Thoms 2006a]:

- Anchoring and adjustment – Decisions can be unduly influenced by the available initial data as it will shape the way in which subsequent data is converted into information (contextualised). The order of delivery of data shapes the view of subsequent data.
- Repetition bias - A willingness to believe what we have been told most often and by the greatest number of different sources.
- Recency –Placing more attention on more recent information and disregarding older information.

Alternatively the planning officer can adopt active gathering which requires the planner to seek out the data they need. The major advantage being that they can recognise what data may be available more quickly and make the decision as to when to baseline their contextual understanding and start the planning process. With active gathering the planning officer is likely to fall into two distinct pitfalls:

- Premature termination of search for supporting information- We tend to accept the first solution that looks like it might work, rather than attempting to undertake an exhaustive search.
- Selective search for evidence and selective perception – seeking to gather facts to support existing awareness, whilst disregarding or even screening out other facts that support a different situation or conclusions.

If the planning officer seeks to use the active gathering mode they will require the authority to gain access to all of the available data: **Information that is not made available will be excluded from their planning process**.

The planning officer combines the data to create a cognitive model of the current situation, which must be reconciled with the commander's understanding of the current situation, using suitable media such as a bird table etc. The aim is to create a shared situation understanding which can be used to understand what the completion or outcome of the mission may look like. Planning can begin when sufficient understanding has been achieved to mutually recognise potential responses to achieve the desired outcome.

4.2.2 Analysis of the precondition.

During this stage the planning officer and the commander are working together to form a common understanding of the "Mission" or system purpose. We can use the conceptual model identified in section 4.1.3, to capture a model of the relationships of the planning officer's cognitive focus and that of the commander as described in this section, see Figure 17.

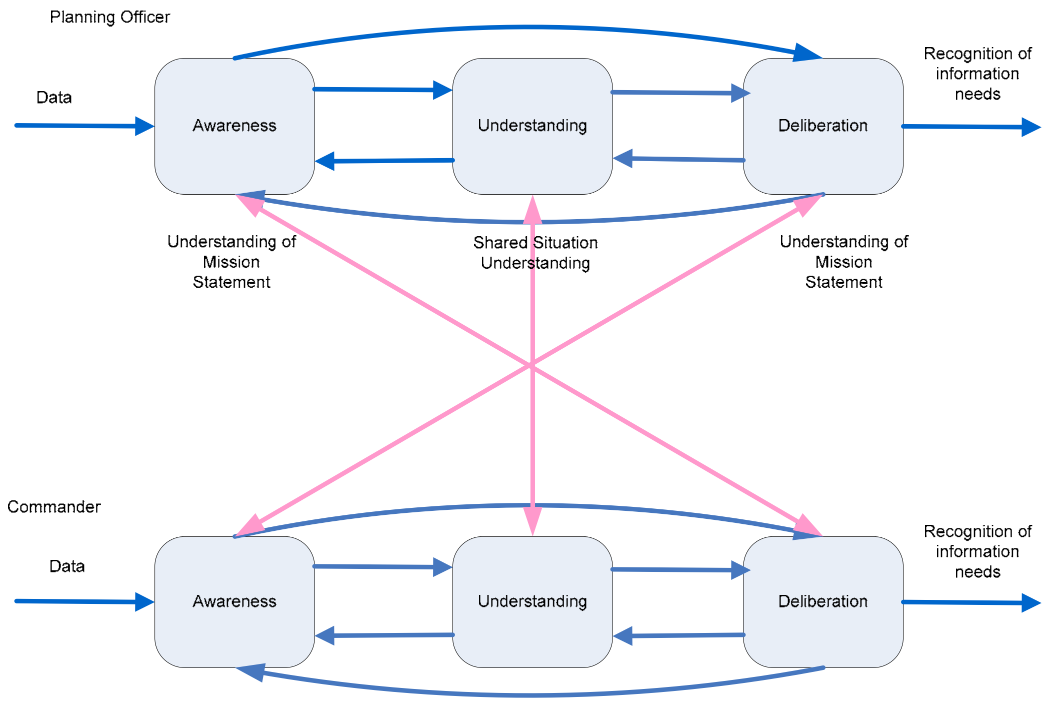

Figure 17 Conceptual model of the information exchanged during the planning precondition.

The population of this conceptual model allows us to capture the information exchanges between the two roles and enables us to see that they are focused on achieving the shared situation understanding and the common understanding of the mission statement. Both individuals will be seeking information to help form their situation understanding, which will be received in the form of data[17].

[17] At this stage we need to define the difference between data and information: Information is data in context that is relevant to the current decision requirements. Any data received by an individual needs to be grounded in the relevant context for them to be able to apply it to decision making. Their request for information will, for them, be grounded in the context of interest, but for the individual receiving that information request it will once again be data and need contextual reference.

It is only once a common situation understanding is built up within a team that the "flow" around the human team will be information, from which other team members will be able to identify information needs and provide it when available. External feeds will still be data as the human team will need to ground it in their common situation understanding to be able to make use of it.

Both the commander and the planning officer are using their awareness to ground any data they receive into their current understanding of the mission statement. How they seek to structure that data item into their existing awareness will be shaped by their knowledge, the uncertainties that they perceive in their understanding of the world and their current interpretation of what they have been asked to achieve. They will be still deciding from a number of alternatives what the mission may mean and this will include recognition of what the desired mission outcomes may be and equally what outcomes may be undesirable.

4.2.3 Planning

Military planning builds heavily on military training, we teach our commanders and planning officers to be able from a mission statement to recognise what class of engagement is required and with knowledge of force structures or templates by which to achieve that which we require of them. The key planning skill is to be able to apply their experience to be able to recognise the contextual considerations for the operational domain, applying them to a generic template, to identify a practical plan and the military system by which to deliver that plan, see Figure 18:

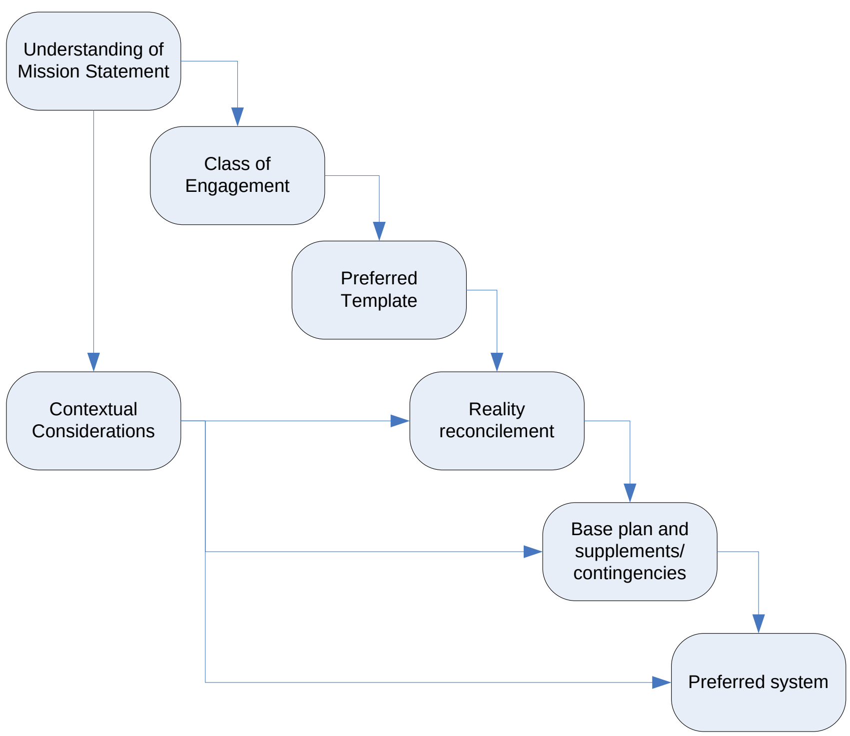

Figure 18 Military Planning

4.2.3.1 Planning system capability

Our planning officer and commander will, from a mission statement, have knowledge of the class of operation or engagement that is implied and from their training have a preferred template of a military system to use for achieving it. The first need is to ground this template in the operational situation, to identify the basic system capability needs and supplementary one that will enable it to cope. This system capability is not static, at any instance in time what the system, or part of the system, is capable of will result from:

- The individual system elements. Each system element that we may seek to deploy can offer us new military capabilities based on their individual knowledge or skills. Provided that we can provide the tools and information with which to understand it.

- The organisation of those elements. For which the elements may provide information, be available to participate in a specific task or hold the authority to make decisions.

- Current activities of the elements. Clearly if the elements are already doing something then they are not available to do something else. But there is also the consideration of the challenge of re-orientation from their current task onto a new task.

Consequently we should not think of military capability as being a single definable capability it is instead a dynamic function resulting from the complex interaction of the individual system elements, their organisation and their current local behaviour in context, see Figure 19.

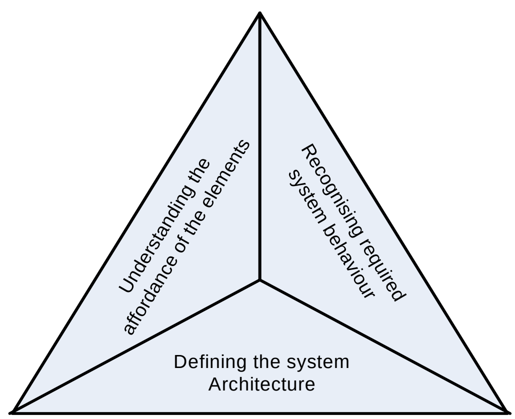

Figure 19 System Capability Planning

It would be inappropriate to consider this system capability as emergent as it is being intentionally designed and planned for. Emergence is due to unanticipated properties, which is why the planning officer and commander are also seeking to understand and plan the challenges of getting the system elements to work together.

4.2.3.2 From mission to goals and actions

Knowing what capabilities are potentially available enables the planning officer and commander to consider what goals could be achieved and to define alternative sets of goals that can result in the desired mission outcome. In the same way we could consider breaking down a mission statement into a number of phases which contain goals, this structure could be considered to represent the mission plan, see Figure 20.

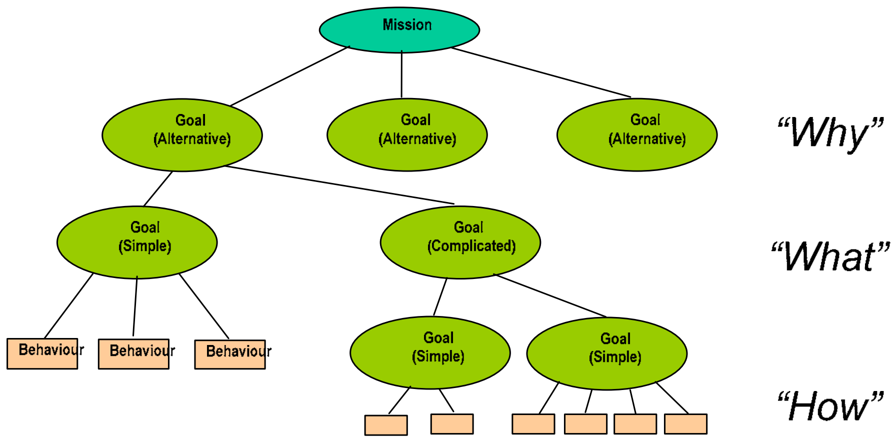

Figure 20 Mission, goals and behaviour hierarchy

This type of hierarchy is known as an end means abstraction, with the current level specifying *what*, the level below the *how* and the level above the *why*. This view of planning is too simple, as goals do not normally exist in perfect isolation they have relationships with other goals, relationships that could be enabling, dependant or even prevent the execution of another goal. Critically each choice of goal in seeking to create a plan will change the future options for achieving the mission from the point of enacting that goal: What you may be able to do now, you may not be able to do in the future, and what you chose to do now will change what you can choose to do in the future.

Generally we can say that the relationships between goals are a result of the evolving mission context consequently they cannot be fully determined prior to mission execution. The commander and planning officer can identify general types of relationships that will exist to do with: Temporality, Assets and Information needs. Temporality recognises that some goals have an implied order in which they need to be conducted, and in planning the use of assets needs to recognise that if they are planned to participate in the conduct of one goal they will not be available concurrently to participate in a second goal, but the challenges of the information and decision domains are much less obvious.

All goals and system behaviours have associated with them decisions of one form or another, which imply agent knowledge and information needs. This information is not raw sensor data; it exists at the symbolic level in a form appropriate to the agent's type of knowledge being employed in the decision. The ability to form and deliver this information to meet the decision needs is a key planning challenge.

4.2.3.3 Understanding the complexities of planning

The operational context in which we conduct military operations is a highly dynamic environment as such the act of planning does not seek to define a single optimal solution; rather it seeks to create alternative strategies that can be used to achieve the desired outcome in the operational context. The dynamic nature of the context means that whilst the commander and planning officer will have achieved a level of awareness of the operational context there will always be residual uncertainties in it.

This uncertainty in the initial (boundary) situation, even in an apparently stable context rapidly can lead to divergence in the potential outcome of any action. As a result of these uncertainties, our ability to predict how the future context may evolve rapidly reaches what we term the planning horizon. This is without considering the possible impact of other actors (enemy, civilians etc) on the evolving context.

Consequently whilst the act of planning can identify a detailed set of actions by which to achieve a specific goal in the short term where the residual uncertainties in the contextual understanding are acceptable, beyond that timescale the team must seek to identify potential strategies (goal sets) and the system capabilities that could be deployed during mission execution.

The real challenge for the team is to recognise the strategies and to deliver potential capabilities that can be put into use during the mission execution to achieve certain goals; it is mission management that is responsible for delivering the real-time detailed planning and management of the system. It is only when command has approved the plan, that the forces that are to be employed to deliver the mission are briefed as to their involvement.

4.2.4 Analysis of the planning stage

The act of pre-mission planning will be done with both the commander and the planning officer co-located. This means that they are more likely to hold the same agreed situation understanding and will use it to identify alternative ways to transform the current situation to deliver the desired outcome.

They will both be seeking information about the assets that could be available, their potential status and location over time. This provides the necessary input for them to apply their knowledge to create an **awareness** of the potential capabilities that could be deployed. The act of planning system capability, identified in 4.2.3.1, is all about using this awareness to create an **understanding** of the option space available to undertake alternative goals. Each of these alternative ways of addressing the mission will deliver slightly different changes in the operational context, it is then necessary for both the commander and the planning officer to understand the consequences of possible options and to prioritise between them. This choosing between alterative options is more than decision making; it is **deliberation** as it is taking into account the potential temporal and spatial decision space resulting from the alternative choices. As a conceptual model we would recognise that the commander and the planning officer are both forming a common understanding of the options and future situations that may result from those options, see Figure 21.

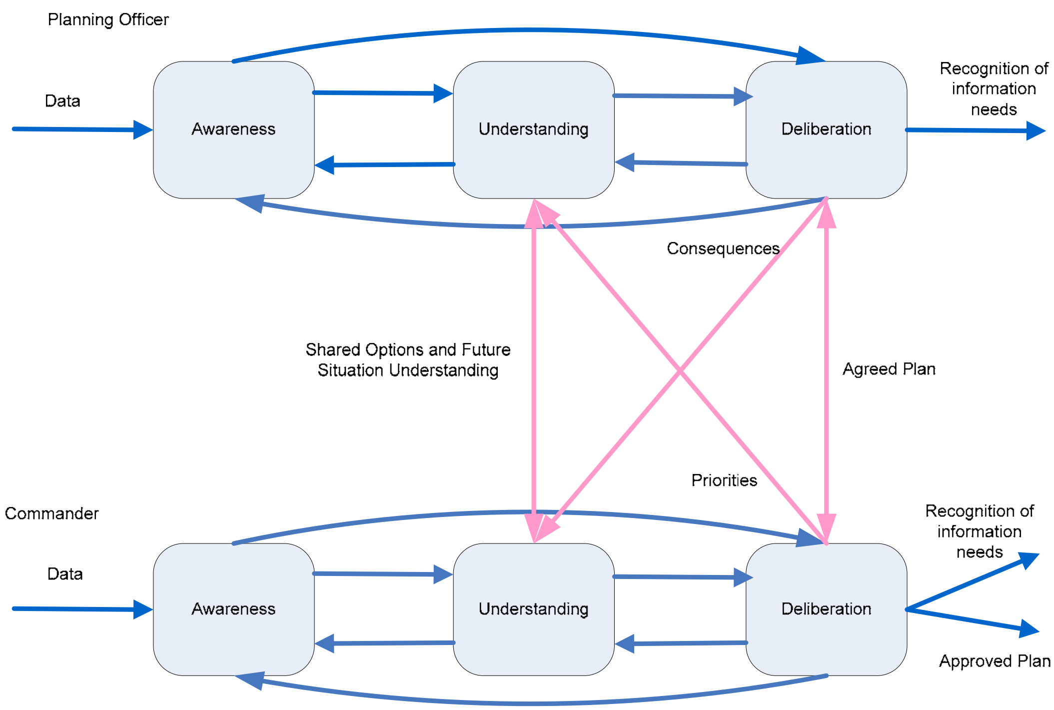

Figure 21 Conceptual model of the Information exchanged during pre-mission planning

The final stage of the pre-mission process is the briefing of the system participants; we consider this to be outside the scope of the purpose of this analysis, which is investigating the relationship between the commander and the planning officer.

4.2.5 Mission management

Whilst the act of planning defines the actions by which it should be possible for the mission to be achieved, it is mission management that delivers the mission by dynamically adapting the plan, the military system and its current goals as the context evolves. This is a massive problem hence it is split into two parts: command provides the real-time dynamic management of the military system, whilst the planners provide the longer term planning view.

4.2.5.1 Maintaining awareness of the military system

To manage the military system it is necessary for command to have a view of the current status of the overall military system in relation to achieving the desired outcome as well as a view into that system. Efficient management requires that the system is observed by differentiation, the artificial grouping of elements into distinct functional subsystems: groupings of elements with a common goal within the main system, this provides command with a means of conceptualising the current deployment and understanding the relationship of groupings (subsystems) within the overall military system. As such the commander is using a highly complex form of awareness viewing the overall deployment at a conceptual level.

The planning officer's awareness needs are similar to commander's awareness in that they are viewing the system at a conceptual level but as seen in Figure 9, the planning officer's awareness will be slightly delayed from reality. Whereas command focuses on the second by second evolution of the situation towards the desired outcome, which we can consider to be "narrow but deep", the planning officer needs to take a longer view which we can consider to be "broad but shallow". They seek to expand their awareness in order to focus on predicting the evolution of the situation through the application of military intelligence: information from third parties. This information will be presented to command if they believe that it will be beneficial to shaping the commander's awareness and ability to predict the evolving mission.

4.2.5.2 Managing system capability

If we look at the real time management problem and relate it to the original complex challenge of planning we find a subtle difference, the commander is now working with what is available to deliver the current goal with a focus on immediate options to deliver the main plan time line. Whereas the planning officers are seeking to understand the probability that the situation will evolve as expected, as they are looking to select future mission goals and to identify when to employ contingency plans.

As part of this planning process the planning officer has time to consider the challenge of evolving the military capability by changing the architecture of the deployed forces, the elements in each of the groupings and if changes to local authority, RoE etc is needed to comply with the over arching mission constraints, see Figure 22.

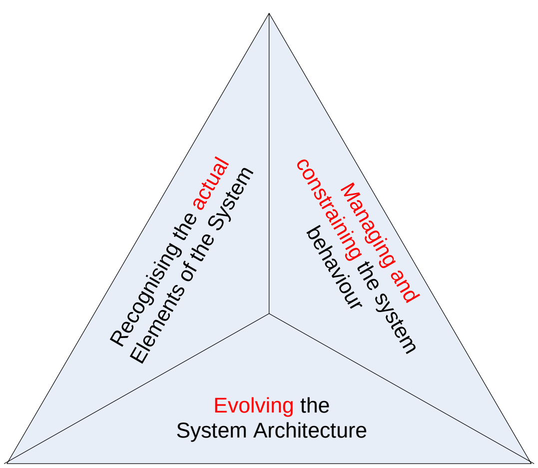

Figure 22 System planning during the mission

The planning officers will consider not only the goals that specifically seek to deliver certain outcomes but also how it may be possible to influence future changes in the operational context that may increase the probability of future success or to minimise any negative implications of the goals that may need to be chosen. This requires that the planning officer continues to identify multiple ways to succeed and to make provisions to be able to move between them as the evolving situation changes.

4.2.5.3 Understanding the complexities of mission management at the goal level.

If we drop down to the local commander's level we can examine the practicalities of delivering optimal capabilities to deliver goals. Whilst we can seek to evolve our capability to meet the capability we predict we will need, our prediction of the future will always be imperfect. The result is that our intended capability and what is actually needed is likely to differ, see Figure 23.

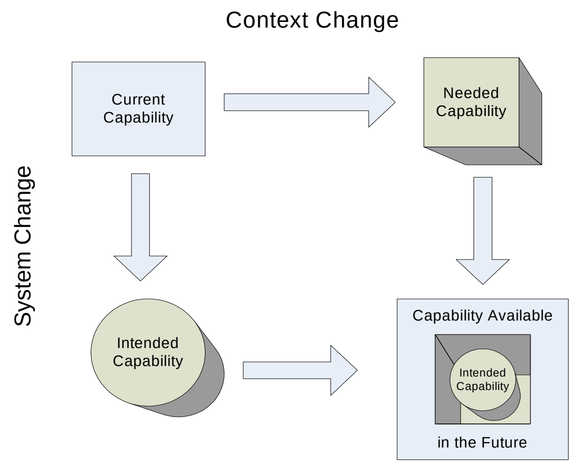

Figure 23 Planning System Capability

Consequently our planning officer needs to seek to deploy capability that has the flexibility not only to deliver the intended goal but that also still achieves it when the context changes. The policy for planning is not to identify or deliver the optimal capability to achieve the goal but to deliver something that can suffice to deliver the goal in the changing situation and is subject to the individual's predictions and expectations.

This in turn requires the local commander to create their own action or task plans for their people to achieve the goals allocated, guided by the current RoE that will provide the basis for arbitration and constrain their options from which to chose. This flexibility to allow the local commander to dynamically change the goal implementation requires a goal oriented reporting mechanism to the planning officer that strips away the contextual irrelevances.

4.2.5.4 Analysis of the mission management stage

During the conduct of the mission the commander and the planning officer may or may not be co-located, but their cognitive focus during the operation will be distinctly different, the commander is focused on the actual capability of the available assets against that which was planned and seeking to achieve a best fit for now and their next set of goals, whilst the planning officer will be focused on future capability and how changes to current capability is altering the future options space.

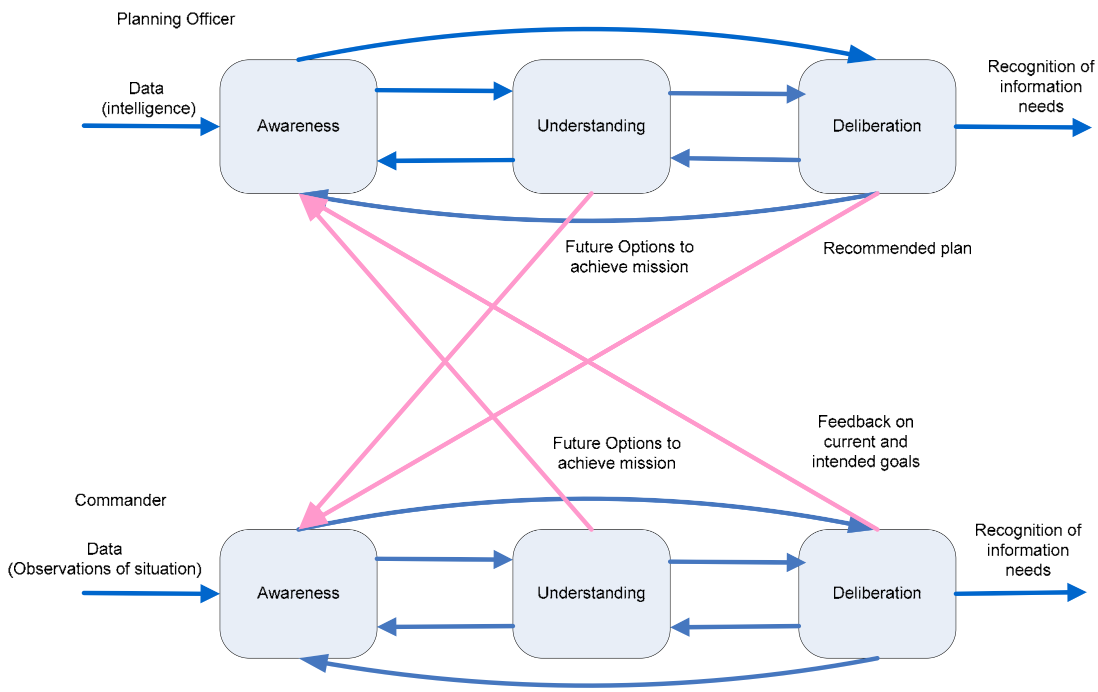

Figure 24 Conceptual model of the mission management planning stage

From this conceptual model we can see how the two team members are now making independent decisions which are having direct consequences on each other's decision space.

4.2.6 Mission completion

At the end of the mission the commander and the planning officer will review the operation identifying the successes and failures. This valuable knowledge is captured and fed back to the training establishments to adapt the training to deliver different knowledge that will better meet their future planning needs, see Figure 25.

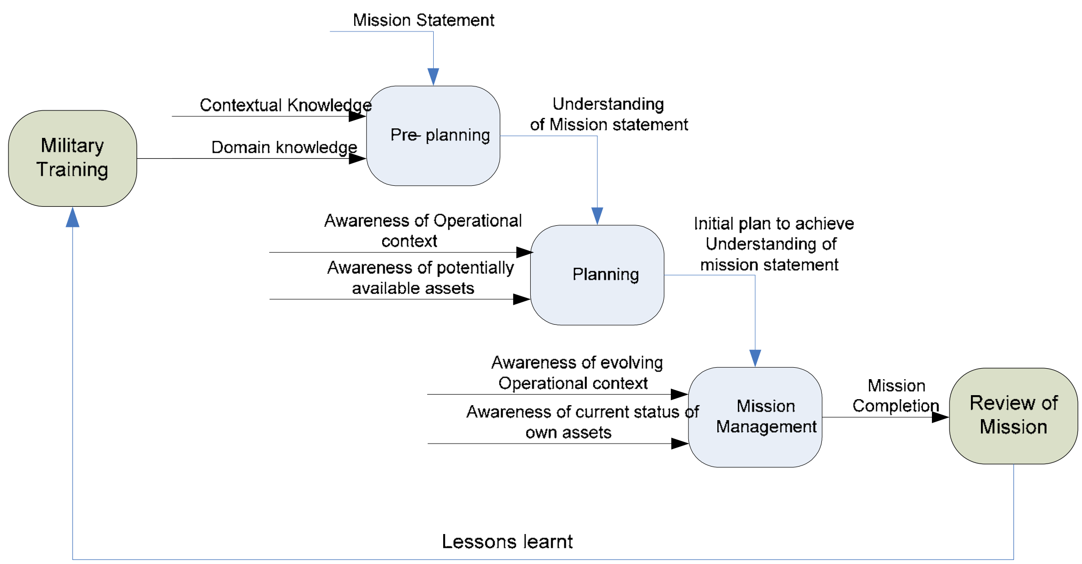

Figure 25 Learning from our experience

This feedback results in a closed loop system that the military adapts to changes in the operational context.

4.2.6.1 Conclusion

We have investigated military planning in order to understand the cognitive challenges faced by humans in a system. What we have found is that human planning is complex and is dependent on the domain knowledge and experience of the individuals.

We have recognised three distinct stages to planning that each represent unique challenges. In each stage in our investigation we have talked about the need for awareness, the act of understanding and making decisions, which has given us three attributes by which to understand the human cognitive contribution: awareness, understanding and deliberation. Underlying these three capabilities are models of the world: the world that is believed to be, the desired future world, future predictions of potential changes in the world and models of how others see these world(s).

In the final stage of planning we have recognised that the military seeks to learn from its deployments and adapt its training program accordingly. As such we should consider military planning to be a complex adaptive system.

4.3 Three attributes to capture the human cognitive contribution

In this section we provide a more detailed investigation of the three attributes of cognition that we have used to model the human cognitive contribution in the military planning system.

4.3.1 Awareness

The first of the attributes we have identified is awareness. In young children that are not yet capable of constructing awareness, their decision making is based directly on events in the current situation, older children apply their knowledge to focus their observation and interpretation of their situation towards achieving their intent. For mature humans decision making is based on their current awareness: for them awareness is a cognitive reaction resulting from the application of their knowledge to interpret their perception of a condition or an event. Whilst this type of awareness is driven by their desire to achieve their intent or purpose it is also driven by their recognition that there are alternative possible means to achieve it. The choice between these alternatives will require them to use their knowledge to form different information from their observations to meet their understanding and decision needs.

We need to understand how this awareness triggers knowledge in order to enable understanding of what is being observed. If we look to the field of human learning Qvortrup [Qvortrup 2003] provides us with a useful set of levels of human knowledge that we can use to recognise how a human does this: At the simplest level, which Qvortrup calls the first order of knowledge, knowledge consists of statements (facts or rules) that an individual believes to be true and can justify. Above this simple type of knowledge, Qvortrup suggests, that humans apply three further types of knowledge:

- Reflexive knowledge: how to use the knowledge (2^{nd} Order)
- Knowledge of the preconditions for (i.e. When to use) the reflexive knowledge (3^{rd} Order)
- Recognition of the bounds of the knowledge (4^{th} Order), including that which we know we do not know and that which we cannot know.

Qvortup's work asserts that teaching provides a student (or learner) with access to the first order of this knowledge. To move to the second order the student themselves are required to question this knowledge, by placing themselves in an observation point outside the basic facts and asking what they can be used for. Enabling a student to access 3rd order knowledge requires that they are taught theories and paradigms enabling the individual to not only observe their primary factual knowledge from a pragmatic point of view by asking what it can be used for, but to question the way in which observations are made. The final level of knowledge requires the student to understand that there are limits for understanding, that certain horizons condition our knowledge of the world.

We can map this view point of the acquisition of knowledge onto Ensley's Situation Awareness model to provide us with a model of how each level of knowledge supports the cognitive process and enables us to understand the current situation see Figure 26:

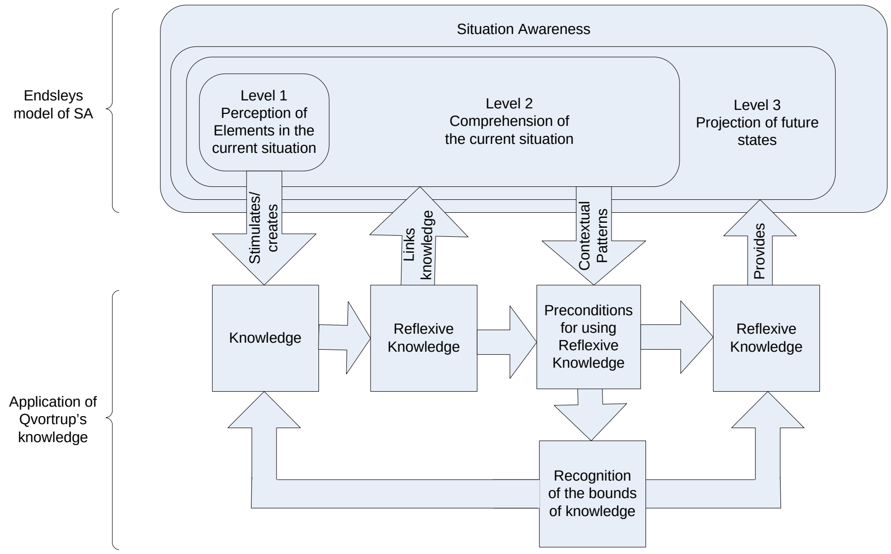

Figure 26 Mapping of Qvortrup's orders of knowledge to Endsley's SA model

From our work in section 4.2 we see that awareness has non-linear properties. The interpretation of any observation or reception of data will be against the individual's existing awareness and knowledge at that instant in time. Awareness is likely to suffer from biases:

- Anchoring and Adjustment: The observation or data will be interpreted against the individual's current awareness, using the knowledge available. This will alter the way in which the individual seeks to translate data into information and the decisions against which they may seek to apply it.
- Ascription of causality: There is a tendency to ascribe causation to something when in fact there is insufficient information available to make this association.
- Conservatism and inertia - Unwillingness to change the existing patterns of awareness in the face of new observations or data.
- Credibility of the Source: Third party data may be considered to be more reliable than data from another source based on the reliability of the provider rather than the data item and the way in which it has been collected.
- Rejection of the unfamiliar: We are likely to ignore those aspects of the data or our observation, that are less familiar to us.
- Selective perception: There is a tendency for the individual to make associations with existing "facts" that they believe to be true, even when the link may be almost non existent.
- Uncertainty: The individual is more likely to seek to make associations with existing knowledge that results in situations that their experience leads them to expect to be more likely to exist, rather than to make connections that result in less likely situations.

This tells us that, when we consider the awareness of an individual any form of detailed analysis will be of limited value, so it would be preferable to undertake the analysis of someone's awareness at a high level based around the role rather than a detailed study of any specific individual in a specific context.

Awareness is considered to be the link between what is perceived or conceived to be the current situation and the ability of an individual to form an understanding of the multitude possible future evolutions of that situation, what may cause it and the appropriate decisions that will attempt to evolve the current situation into the desired outcome.

4.3.2 Understanding

The second attribute we are using to model cognitive contribution is that of understanding: Understanding is the ability to recognise relationships in the current awareness and through the application of knowledge, is used to achieve a number of things:

- It provides a baseline of the current situation and how it may evolve, against which we can plan to achieve our goals. It includes the ability to access knowledge to infer intent the of those entities that are known about in the current situation.
- It enables the recognition of changes in the context, both resulting from an individual's own actions or that of any third party or natural phenomenon, and the evaluation of the desirability of the logical outcome from that change in the context.
- Affordance[18]: It provides access to the potential options for action and the resulting likely changes to the context, based on current awareness and the known available objects or entities.
- Future affordance: It enables us to understand "What could I potentially do in the future". This enables the identification of potential future actions and the changes to the context, based on a hypothetical future context and what objects or entities could be available at that point.
- Significance: "How could something (an occurrence or an observation) influence or change what I am trying to do?" This provides access to what

[18] Note: the definition of affordance above is distinct from Gibson's [Gibson 1977] original use of the term. Gibson used the term to refer to "all the action possibilities latent in the environment, objectively measured and independent of the individual's ability to recognise them, it is always in relation to the actor and is therefore dependent on their capabilities." Where as we contend that affordance is only useful if the individual them self can recognise their potential behaviours and thus be able to choose to utilise them to achieve their end.

could happen (due to third party actions or natural occurrences) in a current situation to alter the potential future situations that may be brought about.

- Future significance: “How could something influence or change what I could do in the future?” This enables the identification of how something or someone may influence a future context to alter the potential evolution of the planned situation.
- The ability to create conceptual models of potential future worlds resulting from possible changes to the context. This enables the recognition of changes that could be made in the context that would change the way in which it may evolve.

It would seem logical that this definition of understanding would also include the recognition of relevance, but we assert that relevance is not driven by awareness but by purpose. We will see later as we investigate the relationships of the key attributes that the ability to identify relevance results from deliberation, which feeds not only into understanding but also into awareness.

Within understanding we assert that we have four concurrent processes: the ability to form or maintain a current understanding of the world, recognition of what could be done and the significance of what is happening in the current situation, so as to project the current understanding of the world into the future. The nature and quality of understanding achieved is a direct consequence of an individual’s knowledge, which has been formed by experience and training, the ease of access to which requires “regular” usage.

As we form our understanding the key need is to be able to identify the decisions within this potential future. We need to be able to identify:

- The decision points within a set of goals or actions that would enable us to follow alternative paths through the future, and thus enable us to improve our chances of success.

- The criteria to monitor, to *know*, when a current projected evolution of the potential future path may no longer be valid and an alternative path would need to be chosen. For example: this could be the recognition that the required initial conditions to achieve a certain goal would not be met at the point that we would seek to choose that alternative path.

- Those cues in the future that may bring about different potential paths that may currently be unobtainable. For example: Having identified that having transport would enable the current mission to be achieved quicker, faster etc, would led to a desire to identify vehicles that may be able to be used.

- What data or perception may cause us to identify a change in the nature of the context and thus the likelihood of the outcome that we are seeking to achieve. This may refer directly to the outcome itself or to the acceptability of the consequences of that outcome. For example: Knowing that a surface to air missile battery was located on top of a hospital could mean that we would seek to identify alternative choices that would, if possible, safeguard that hospital, when we looked to remove the missile battery.

Understanding is all about recognising alternatives, their causes and the potential consequences in the situation; it embraces the multiple dimensions of possibilities which implies that it leads to an exponential explosion problem. It is here that the human traits come into account and we naturally constrain the potential solution space that we consider.

The nature of understanding, like awareness and as we will see deliberation are all non-linear the solution they return will be based as much on their initial conditions as on the contextual stimuli to which they are responding. When we seek to analyse the type of understanding that a role is seeking to form we are looking to be able to understand the criteria or characteristics of the option space they need to solve and not solving the option space itself. The solving of the choices within the complex option space are achieved through deliberation.

4.3.3 Deliberation: Decision making in a complex space

Our third cognitive attribute is deliberation. Where understanding provides access to what could possibly be done or that may occur; deliberation is the ability to choose and make decisions that will deliver the direction, or we could say route, through the evolving situation as we believe it is likely to evolve.

Deliberation itself consists of multiple concurrent choices, which individually we would recognise as decisions and a major part of the deliberation problem is to decide on which decisions should be made. But, as we have said, deliberation is a non-linear problem that must:

- Take into account the possible current choices that could change the current situation and how the result of those choices could be evolved over time[19] using actions that should be possible at the time at which they will need to be conducted to achieve the desired goals. The choice of do nothing[20] is an important choice that must also be considered.

- For the current choices, to be able to recognise what the potential decisions that may need to be made are and if applicable, the order in which they need to be made.

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[19] Note: this considers not only the intended change to the situation but also the consequential side effects.

[20] The choice to do nothing allows the context to evolve without our direct intervention. The context change will be identified by the awareness and applied to the current future options.

- To constrain the number and complex relationships of the concurrent decisions so that it is possible to make timely decisions that enable progress towards the end goal. But this should be balanced with the ability to retain options that should ultimately lead to achieving the desired outcome.

- To recognise if the information needed to support the individual decisions could be gained from the context. Thus removing those decisions that could not be made or reforming the decisions such that they require different information or that the uncertainty associated with the missing information could be considered acceptable.

- To identify support decisions that could refine awareness of the context so as to gain the information needed in a timely manner to service the preferred decisions.

- It needs to be able to recognise the point in time and space when making a specific goal or choice of decision that had been identified becomes no longer valid.

From this it can be seen that there are three major threads to the challenge of deliberation which both require the application of knowledge and information:

1. To be able to put together and manage the decision space

2. To be able to make the current decisions.

3. To manage the availability of information to support the current and future decisions.

But what makes a good choice or decision? The context will be a major contributor as will the individual's current goal. On top of this, there will be social factors or constraints[21], the individual's personal and cultural values, both with respect to the immediate outcome and for the projected possible future outcome or side effects in the future that will influence both the decision space they choose for themselves and the decisions they make.

4.4 Understanding the complex relationships of the cognitive attributes

So far we have explored the three cognitive attributes of awareness, understanding and deliberation as independent elements. But as we saw in section 4.1.3 they are not independent, they exist in a complex relationship with each other, see Figure 27

[21]For the military this will include the rules of engagement.

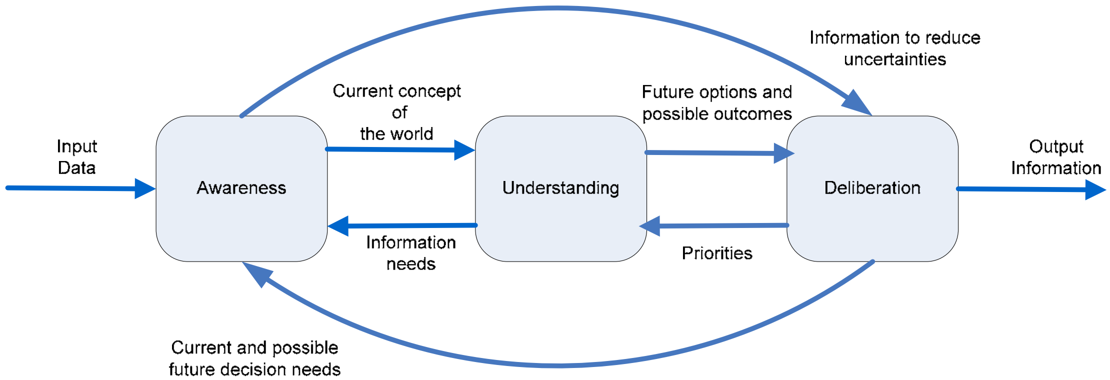

Figure 27 The complex relationship of the attributes of cognition

In this figure the awareness is providing the understanding attribute with the conceptual model of the world against which it can operate. This concept of the world is **contextual** based on the individual's perception of the system purpose and their role within it. The interpretation of the system purpose is provided to the awareness in the form of the current and future decision needs, consequently as the situation changes and the chosen decisions change the awareness and cause it to form different information to be included in the conceptual model of the world and to support the deliberation needs.

Understanding provides access to future options and outcomes from possible decisions which the deliberation process will select between, in light of the evolving situation, in order to achieve the system purpose or the individual's current goal based on their role within the system. To minimise the option space it is necessary for deliberation to identify priorities. These priorities will be chosen based on the individual's knowledge, including their cultural and social values. Deliberation may also require changes or updates to the option space when information received through awareness identifies that changes in the current context effects the validity of aspects of the current decision space.

Deliberation requires that awareness forms the appropriate symbolic information with known uncertainty, in a timely manner to support the current decisions. This information is unlikely to go through the rigour of understanding but will use an existing option set, selected from information formed through awareness. For awareness to support this it needs to be focused by the current and possible future decision needs.

We have two more information flows that have been added to our model, the input data and the output information. The input data represents those items that awareness requires to produce the internal information set used by understanding and deliberation. This requires awareness to apply a contextual reference with which to interpret the data, to transform it into information. The output information is the result of a decision, and whilst it is information for this individual and the team, for any other one who does not hold the same common understanding it will be data that requires to be referenced to their own contextual understanding for use.

The model of an individual's cognitive attributes enable us to understand and capture their key cognitive focus, information needs and what they can provide for other parts of the system. If we were to create models of each of the members in the team and the join up these information sources and sinks in a single model, as we did in section 4.2 , we would have a model of the team cognitive contribution.

In addition to identifying explicit information flows, combining models of the individual roles in a system enables us to recognise potential influences between individual roles and amongst in the wider team. These flows may not be a key information flow but in complex system such as this, they are likely to influence outcome of cognition and we need to be aware that they may exist. If we return to our model we can identify the possible influences of each of the attributes between individuals in the system:

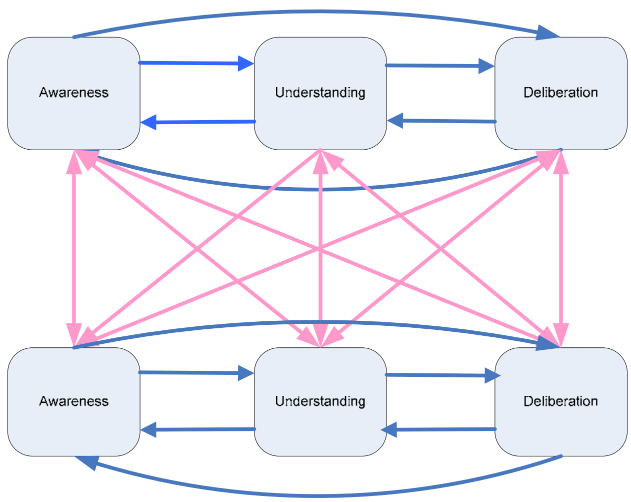

Figure 28 Potential Influences between cognitive models

This simple two element model illustrates that there are potentially 9 separate information or influence paths between only two elements, a system that contained greater numbers of elements would have even more potential paths.

Within this extended model each individual will be creating their own concept of the world based on their view of the system purpose and their role within it. It is likely that they will also be aware of the roles of others within the system and like identifying information needs for their own deliberation process, due to the team's common understanding may well recognise something that would be relevant to other team members and pass that information to them. This could influence one, two or all three of the other's cognitive attributes.

The recognition of the role and responsibilities of the other team members may in turn influence the individual's choices within their own deliberation space and the information that they provide into the wider system. When one individual seeks to understand the situation they may well identify options that may not directly relate to them but that may change the potential options and decisions for another team member.

The model of the cognitive attributes and our new insight into their complex relationship can be considered to be a generic engineering framework which can be used to understand the human cognitive contribution in a system. By extending the framework to include multiple human roles and their complex relationships we are now able to extend the use of the engineering framework to understand the cognitive contribution of the human team in our system.

4.5 Conclusion

This section has used a planning system as an example system by which to examine the system engineering challenge of understanding the cognitive contribution provided by humans in a system. We started by considering the basic human planning challenge before investigating the military planning process, we found that planning is complex and is heavily dependent on the domain knowledge or experience of individual planner. This investigation identified three distinct stages to planning: that of pre-planning, planning and mission management. In each stage we have talked about the human's need for awareness, the act of understanding the options, recognising decision choices, their potential outcomes and being able to make decisions within the evolving context, which has enabled us to recognise three abstract abilities: Awareness, Understanding and Deliberation.

In section 4.3 we explored these three cognitive attributes, recognising the cognitive contribution they enabled the individual to provide for our system. We then looked at their complex relationship and identified the information flows and the influences between them. We then extended the use of this model or framework and used it to capture the team cognitive model as a richer model of the system than has previously been possible. By doing this we were able to answer the first of our research questions:

1. How could a systems engineer recognise and capture the human cognitive contribution to a system?

In the next section we will investigate how a systems engineer can use this engineering framework within the system engineering process to support their understanding of the human contribution within the system design process and consequently to be able make more informed design decisions that take the human contribution into account.

5 TOWARDS HUMAN CENTRIC SYSTEMS ENGINEERING

In section 4 we used a planning system as an example to investigate the human's cognitive contribution in a system. As a result of this study we developed an engineering framework by which to seek to understand the individual and team cognitive contribution. For a systems engineer to be able to use this framework we must consider its use within the system engineering process. Our starting point is to look at how we have historically considered the relationship between the humans and the systems we seek to engineer. We will then go on to see how by using the engineering framework, developed in the previous section, it is now possible to place the human cognitive contribution within the bounds of the system and include it in the systems analysis.

To use this engineering framework section 5.2 introduces a 5 stage engineering process that is designed to fit alongside the existing INCOSE systems engineering process. The initial stage in the process is to capture the appropriate system viewpoint to suit the purpose of the engineering analysis. We then propose capturing the complex decision aspects of the system at a suitably abstract level to enable us to capture a system level cognitive model.

From this system viewpoint, the third stage of the engineering process is to use the framework to understand and capture the individual human and team cognitive model. This provides us with the rich system model, which we will use in the fourth stage of the engineering process, to aid us in identifying system effectiveness measures that include the human contribution. The fifth and final stage of our process is focused on using the rich system model to make design decisions. For the purpose of this thesis we have chosen to consider the introduction of machine technologies into the human system.

In section 5.3 we consider the potential benefits that could gained through the use of this framework and process. The identification of benefits is necessary with any new engineering process to be able to justify "adding" to the engineering burden to gain buying from other team members. Finally in section 5.4 we recognise possible shortfalls in the using the framework and process.

This process was subsequently refined over the two validation exercises captured in sections 6 and 7 . The final engineering process model at the point of completing this thesis is presented in section 8 .

5.1 Viewpoints: How we perceive a system

Viewpoints are an important aspect of understanding systems; they focus the observer at the appropriate level to be able to observe the nature of the system that are relevant to the purpose for which they are observing the system. System engineering's traditional view of systems has been to consider the human external to the system even when their interaction is necessary to achieve the system purpose.

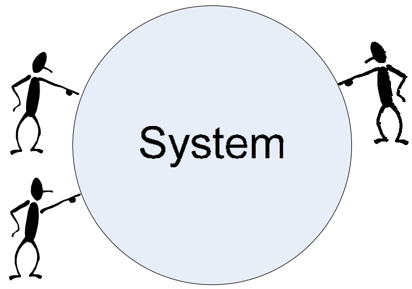

Figure 29 The human is seen as external to the system

Why have we excluded the humans? We can recognise that humans are very complex and even after many years of investigation cognitive science is still struggling to understand them, so it is much easier for systems engineering to exclude them from the system level design process by considering them as an external "*black box*" [Thoms 06b].

However in a large majority of engineered systems it is necessary for a human to interact with the system in order to achieve the system purpose, in recognition of this the idea of *"Use cases"* was introduced originally into software engineering by Jackobson in 1992 [Jackobson 1992] and later embraced by systems engineers and forms one of the key tools of UML [OMG 1996]. Use cases enable the system engineer to describe the system behaviour under various conditions as the system responds to a request from one of the stakeholders [Cockburn 2001]. Each use case is a complete series of events or a task described from the viewpoint of the external "actor" or user. The name of the use case being used to indicate the goal of the actor and the series of events described the interaction sequence that would be acted out to deliver that goal.

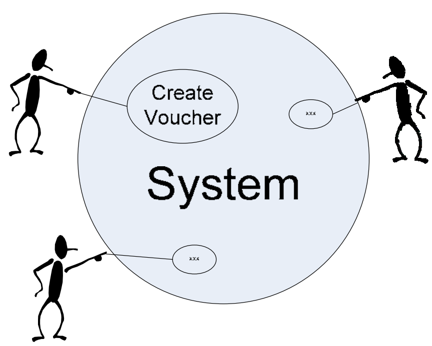

Figure 30 A System with use cases to capture human interaction

We assert that this view is a task oriented view on the human that fails to recognise the cognitive contribution that the human is providing to enable the system to achieve its purpose. We can also assert that if we complied with our initial definition of a system and excluded the human contribution the intended system purpose would be very confusing as it would need to include all the interaction with the human(s) as part of its purpose. Such a complicated definition would capture a system that may well represent an optimal solution, but it would be an optimal solution for the artificial context that we have defined for the purpose of the engineering exercise[22]. In doing this we have also lost sight that if we follow this type of design principle the resulting system would be inflexible and not robust to change. The reason why these systems work is that humans take them and adapt the way in which they are used to make them work in the context they find themselves.

If we consider that the human is actually part of the system not only is the definition of the system purpose easier to define but we can also take into account the system functionality that they are providing to us. We can through our engineering design process seek to support the unique human contributions by not constraining the human's ability to adapt the way in which they operate within the system to meet the evolving system context.

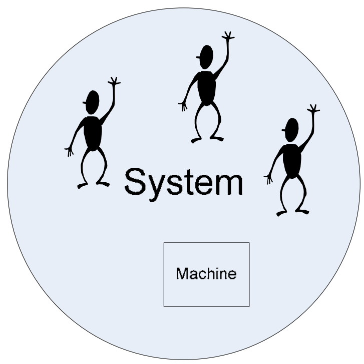

Figure 31 Humans placed inside the system bounds

Placing the humans within the system bounds has been seen traditionally to be very difficult because each human is unique and we can think of all sorts of things that we may need to consider like their skills, knowledge, cultural tendencies etc; which is why system engineering has chosen to leave them outside. But the human's cognitive contribution to delivering the system purpose is important and we could consider it as a type of system functionality. In the previous section we found it convenient to think about the functionality provided by the human cognition in terms of three cognitive attributes. We can use these three cognitive attributes to provide us with a way of looking at and capturing the functionality provided by the humans within our system.

[22] And it would also be in danger of defining implementational aspects of the system that would constrain the system design process.

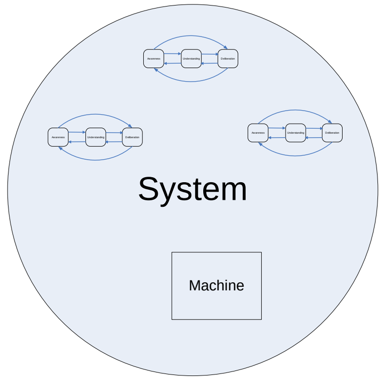

Figure 32 System Model with the humans replaced by their cognitive model

If we think of this model as a classic a data flow diagram we can recognise that we can use the extended cognitive framework to enable us to identify the information flows between the elements in the system and it could also to capture the data exchanged between the humans and any machine technology.

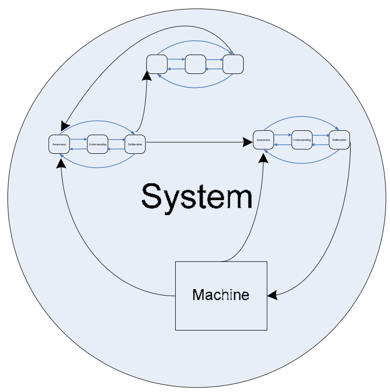

Figure 33 System model including human cognitive model

This rich view of the system offers us opportunities to understand the potential influences and consequences of the deployment of advanced machine technologies into human systems, **something that up to now system engineering has not had the technology to support.**

5.2 A Process

The initial engineering process, shown in Figure 34, for using the framework is based on the INCOSE systems engineering process [INCOSE 2000].

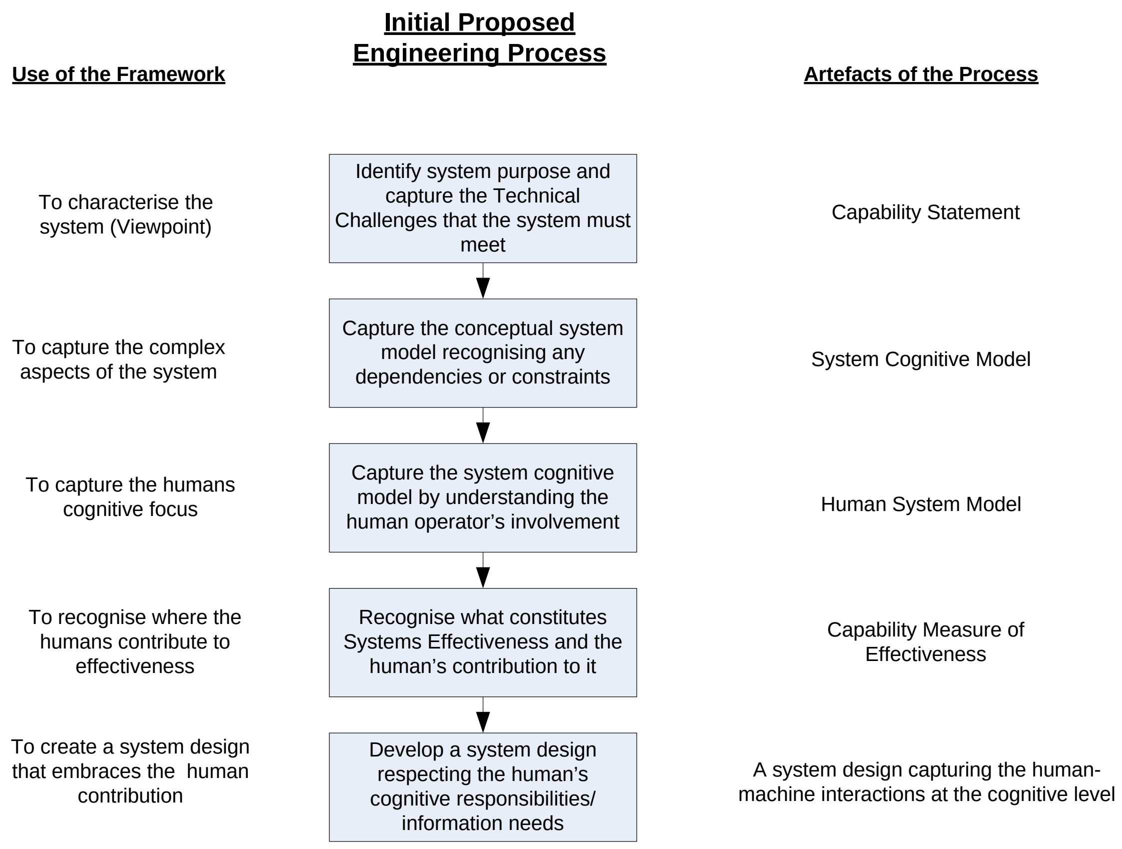

Figure 34 Initial proposed engineering process.

Each of the five stages shown in this process are described in the following sections:

5.2.1 Identification of the purpose of the system.

The first stage in our process is to define the purpose of the system and with it the conceptual challenges that the system must meet. This is a distinctly different problem than that of understanding system requirements. The IEEE-Std '610' defines requirements as:

1. A condition or capacity needed by a user to solve a problem or achieve an objective.

2. A condition or capability that must be met or possessed by a system component to satisfy a contract, standard, specification or other formally imposed documents.

3. A documented representation of a condition or capability as in 1 or 2.

By including the humans within our system bounds we must recognise the higher level technical challenges or purpose above these “requirements” that the system is delivering against. The military have to an extent recognised this problem when they talk about capabilities: *the ability to do something* [MoD 2008a]. So the first stage in our process is seeking to identify “*What does the system achieve*” or what we would recognise as the system purpose.

As we are interested in understanding the human contribution in our system we need to identify the human team, any existing role responsibilities and also the decision authority of those roles. Where there are external constraints that may restrict the freedom of the system design these need to be identified and captured.

The aim of this stage of the systems engineering process is to enable the systems engineer to understand the system capability requirement and the known challenges of the problem space, into which the system will be deployed.

5.2.2 Capture the conceptual system model recognising any dependencies or constraints

The second stage of our system process is to capture a conceptual model[23] of the system.

Initially we seek to capture the system as a simple linear process model and then to add the feedback loops resulting from the dynamic interaction with the environment. This dynamic model of the system is not a model of the internal feedback but rather it is seeking to capture the external or contextual influences that are taken into account by the humans in our system.

From this conceptual model we can then transform it into a top level cognitive framework model by overlaying the conceptual model onto our engineering framework. This involves overlaying the three attributes of awareness, understanding and deliberation onto the dynamic model to identify the complex feedback paths within the system and the information passing along those feedback paths.

[23] It is normal that engineering models such as this are captured as graphical model supported with written descriptions.

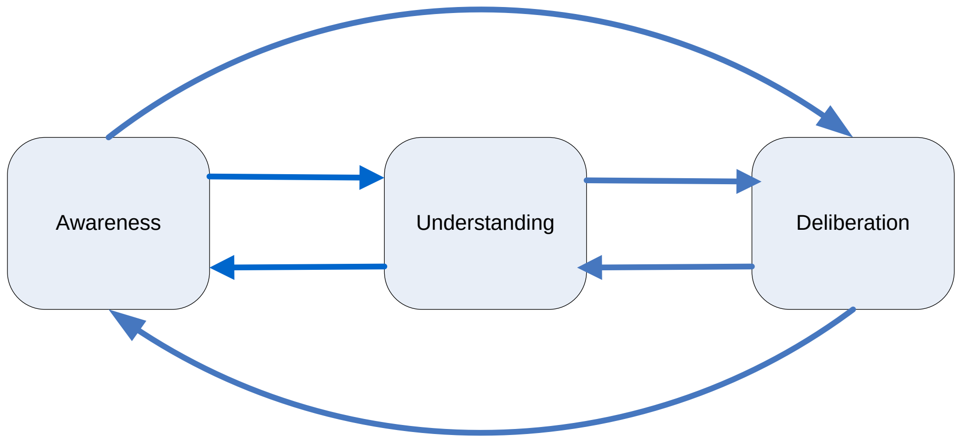

Figure 35 Generic cognitive framework

This can then be captured as a single cognitive framework model consisting of the three attributes of cognition and the information flows between them using the generic cognitive framework, see Figure 35.

5.2.3 Understanding the human cognitive responsibilities and information needs

By using the framework described in the previous section to act as focus for information elicitation, a model of the cognitive focus of each of the human roles can be captured. To understand the human contribution to the system, it is desirable to involve the current operators and to ask them to describe their responsibilities in terms of the three attributes of awareness, understanding and deliberation and of the information they are using to support these.

Once a model of each of the roles has been generated they can be combined together to form the team model. Where information needs that have not been provided for or information flows do not have consumers within the captured individual role models, this identifies possible shortfalls in the captured models or that there is other information sources still to be identified.

A concern in capturing these models is that the model must not be overly detailed; we are not interested in implementation details which would mean that we were focusing on a specific constrained context, only to be able to capture the abstract cognitive responsibilities that will enable humans to adapt the system when it is deployed. If we were to talk about the level of detail in terms of data flow diagrams we are seeking to capture the level 1 diagrams only.

5.2.4 Defining system effectiveness measures that include the human cognitive contribution.

The effectiveness of a system captures how well a system is able to deliver its purpose. In the past we have in the main defined measures that enable us to measure the machine aspect of the systems[24]. But where system effectiveness is a result of the interaction of the humans and the machines within the system, our measurements must embrace both types of system element.

Typically in systems engineering when we seek to identify what constitutes system effectiveness ask ourselves a basic set of questions [Stevens 1998]:

How Much?	(volume)
How Well?	(accuracy, resolution, confidence level)
How Fast?	(time to completion)
For How Long?	(endurance)
How Often?	(ability to repeat at intervals)
How Quickly?	(responsiveness)
When?	(typically a function of the scenario)
Where?	(typically determined by the scenario)
At What Cost?	(level of training needed, level set-up required, levels of stresses and strains, durability of system)

Whilst originally designed to be used to define the criteria for measuring the performance of the physical parts of the system (the equipment), these questions are equally applicable to our application of the framework to each of the three cognitive atributes for any human role and across the wider human system model. It would be difficult to capture this type of system effectiveness as quantitative values, for this reason the use of English that captures the qualitative value would seem more appropriate. As with any definition of performance it is important that this is defined before commencing the system design so that they are focused on delivering system performance in their design activities[25].

5.2.5 Develop a system design respecting the human's cognitive responsibilities and information needs.

The final stage in the engineering process is to make use of the human system model we have developed during our system analysis. There are potentially a number of uses that this model could be used for such as:

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[24] This has enabled us to compare one machine's performance to another.

[25] System performance measures should be defined before commencement of the system design rather than afterwards when there is a tendency to define measures based on what the implementation is capable of. The result of this type of bad practise is system effectiveness measures that are only applicable for constrained system contexts that do not embrace our desire to design systems that are agile and flexible.

2. Seeking to change the human team.

    a. The number of individuals in the team

    b. The roles and the responsibilities in the team

3. Seeking to deploy machine technologies to support the human team.

If we initially consider the opportunity of using the human system model to investigate changes to the human team, we will find that system design activity is seeking to redistribute the implied decision process across the human team. If we were to take a single role we can relate their responsibilities to the top level implied decision process and from the captured descriptions of their role, identify their cognitive contribution and the information needed to support their responsibilities.

Redeployment of those responsibilities implies new requirements to change the individual role's training in order to provide them with necessary new knowledge and experience to be able to deliver their new cognitive responsibilities to delivering the system purpose.

For the purpose of this thesis we have chosen to explore the second suggested use of this framework: to investigate the deployment of machine technologies to support the human team. The opportunity here is to be able to define the machine technology as a component that can be inserted into the human system model, to investigate its deployment into the human team, to understanding the implications to changes in the information flows and potentially the human knowledge requirements. As part of this work it should be possible to investigate the challenge of the transformation of human information into machine data[26] and transforming back into information within the human team.

Other potential uses to the framework are identified in section 9.3

5.3 The Potential Benefits from using The Framework and Process.

One of the major challenges for systems engineering has been how and what to include of the human contribution within the system design. The use of the framework, for capturing the cognitive contribution of the humans in our system, represents a major step forward in trying to embrace humans in our system design. By focusing the system engineer to seek to understand the human role's contribution, in terms of the three cognitive attributes of

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[26] Machines are currently not aware of context. They are able to take human defined measurements of the situation, fuse those measurements to make data and to apply them to human defined decisions as such they only respond to defined aspects of the context. We can anticipate that in time machines will become aware but the progress to date within the SEAS DTC implies that for a machine to be able to exhibit the types of awareness discussed in this thesis is many decades away.

awareness, understanding and deliberation, they should avoid the pitfall of focusing on the physical needs of the human. The fact that they are initially only considering the human team, without any machine elements, should remove the temptation to start working on human computer interaction before they understand the system problem space.

The joining together of the individual role modes into a team model provides a new insight into the information flows in the human team, information which has not previously been considered in the system design process. Knowing what this is will become increasingly important in future systems, where we are seeking to increase the machine cognitive element in the form of autonomous machines and the redistribution of cognition will not only influence the information flows but it has the potential to change the human knowledge requirement. Such changes are likely to alter the human contribution to system effectiveness and have implications for the evolution of human knowledge[27].

The process represented in this section is the initial concept as to how the framework can be used alongside the system engineering process. We have already identified potential uses to support redesigning the human team and to investigate the potential impact of the deployment of machine technologies on that team. The next stage in developing the engineering process is to use the initial process defined in this section and to use the engineering framework to understand real systems.

5.4 Recognition of possible shortfalls

Systems engineers have in the past considered the humans who are going to participate in the system in their system design decisions but they have not actively used any aspect of the human contribution in the system analysis. The responsibility for the humans has been very much seen as the responsibility of the human factors engineers. This change of focus may cause some resentment, especially from the human factors engineers who may see it as an attempt to erode their contribution to the system design process. The systems engineers, who may well have mathematical or physics backgrounds, may find the idea of attributes that cannot be defined using mathematical equations very strange. But if we are honest with ourselves, during the analysis stage, the use of such tools has a tendency to lead towards premature implementation, which is undesirable.

Due to the difficulties of including the human in the system design process over the last few decades a culture of prototype and evaluate has built up. To expect these “creative” individuals to embrace a more structured method of working may challenge their evolved culture.

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[27] In military system changes to information flows and human knowledge can be mission critical with the potential to cost lives.

5.5 Conclusion

In this section we started by considering the challenge of the viewpoint of the systems engineer and saw how their viewpoint has placed the human outside of the system bounds. We introduced the opportunity of using the three cognitive attributes to represent the human contribution to the system, within the system bounds. We also sowed the seeds of the idea that by joining up these individual models we could not only capture a model of the human team but that this model could also be used to investigate the implications of introducing machine technologies into that team, opportunities to understand system issues that we have not previously had the tools to investigate.

We then went on to outline a five stage engineering process that is designed to fit alongside the standard system engineering process. This process initially focuses the engineer on understanding the system purpose, which requires the systems engineer to take a slightly different perspective now that we have to place the humans within the system bounds. The next stage looked at capturing a conceptual model of the system's decision making by initially capturing a linear system process model, then a dynamical model recognising the contextual feedback that the humans are taking into account to produce a top level model of the system that embraces its complex nature. The engineering process then requires that we capture models of each of the contributing human roles' cognitive focus using the engineering framework. The joining up of these models provides us with the team cognitive model or rich view on the system.

The fourth stage of the engineering process requires that we use our new found understanding of the human contribution to define system effectiveness measures that embraces the human contribution so that we have a baseline against which to compare the results of any changes to the system during the final system design stage. The final stage of the process being to use the rich system model for the purpose that the engineer requires, we have suggested it could be used to understand the consequences of changing the human team and to investigate the deployment of machine decision technology into the human team, there are no doubt many other opportunities that it could be applied to.

To be able to understand and verify if this framework and process meets our expectations it is necessary to attempt to apply them to some real system problems.

6 EVALUATING THE APPLICABILITY OF HSCE ON A LEGACY SYSTEM

In the previous section we developed an engineering process to enable us to use the engineering framework to capture the human's cognitive contribution to a system. The study reported in this section applies the engineering tools to an existing system in order to develop their use in order to

- Support the analysis and assessment of the cognitive aspects of the system,
- To provide a basis for considering and assessing alternative design or to choose to redesign the solution.

The intent is to develop the use of the framework to enable systems engineers to:

- Predict the potential impact of the deployment of the low level machine technology(ies) on system (Human + Machine(s)) level effectiveness.
- Seek to use the framework to identify mechanisms to overcome the impact or shortfalls.

The chosen system used for this study is that of ship based anti-submarine tracking, a system which has, over recent decades, seen the introduction of new machine automation which have given rise to changes to the system's operational effectiveness. This system was specifically chosen as the author has knowledge of the existing system implementation and system effectiveness resulting from participation on the ARP RE306. Combat System Integration, Interoperability and Performance System Requirements Dataload study [Thoms 2004] and has unrestricted access to a subject matter expert of the earlier anti-submarine tracking systems[28].

This study undertakes an analysis of the cognitive aspects of an anti-submarine tracking system, to do this it follows the initial engineering process and uses the cognitive framework to seek to understand the cognitive aspects of the system. We start by presenting a description of the technical challenges that the system needs to be able to solve if it to be able to track a submarine. We then identify the two sets of roles who have been responsible for delivering the anti-submarine tracking capability for the chosen legacy system and for the currently deployed system.

In section 6.2 we capture the conceptual system process initially as a linear process, then as a dynamic process before considering it as a complex system.

Section 6.3 we investigate the operator's perspective, in doing this we are capturing the human's cognitive focus. It specifically investigates what has changed from the original tracking problem, aspects of human interaction with the combat system and how the system context has changed.

[28] The author's father, a retired Royal Naval Torpedo and Anti-Submarine Instructor (TASI).

Section 6.4 considers the fourth stage in the engineering process that of understanding operational effectiveness. It applies a set of system capability questions to identify possible effectiveness measures for this system and examines the likely areas where the changes from the legacy system to the current system may have impacted the system effectiveness. Section 6.5 captures the military specialist’s observations of the impact on military effectiveness of the introduction of the machine automation and we find that these reflect our findings from us of the engineering framework. Armed with this understanding of the negative impact of the introduction of the automation section 6.6 , uses the framework to consider system enhancement that can support the human contribution that could overcome the observed negative operational impact(s).

The study concludes by reviewing the use of engineering framework and process correcting any problems in its use and where possible developing the process.

6.1 Introduction

For the purpose of this study we are interested in understanding if we could have anticipated the changes in system capability through the introduction of machine technology to support ship based anti-submarine tracking.

To understand the evolution of this system we need to touch upon its history: the British Anti-submarine Division began developing the technology to detect submarines during the First World War. In these early systems their operators undertook the analysis of the acoustic sonar data to provide information about vessel range, bearing, identification, behaviour and intent using their experience and prior knowledge to provide the tracking of the submarines. Over the years the performance and processing capability of the sonar systems has been increased enabling the machine processing to take on additional aspects of the analysis challenge, in turn changing the nature of the task for the human operator.

Sonar now provides the ability to detect, classify and localise an underwater object. But the challenge of anti-submarine tracking is larger than that: to enable the military to engage a possible target they also require to understand the current behaviour, intent or goal of that target, to enable them to predict the submarine’s future actions.

6.1.1 Understanding the technical challenge

The aim of anti-submarine tracking is to enable the identification and tracking of, and if necessary to decide to engage submarines.

The system provides:

- Object extraction from the sonar returns.
- Assessment of the current situation. This includes creating tracks from vehicles and extraction of underwater features.

- Identification and Evaluation of the behaviour of any identified vehicles.

6.1.2 Object Extraction

The sonar system will provide the tracking system with acoustic measurements of the underwater environment. From an acoustic signal the extraction of the range and bearing for any object must take into account the effects of the natural environment which includes:

- The sound paths available
- shallow water vs. deep water effects
- layer depth (thermoclines)
- seasonal variation in area (wind, temperature, etc.)
- local transient phenomena (rain, afternoon effect, etc.)
- currents in area of operations

Consequently this is a real-time situation dependent processing problem, which may be changed (simplified?) by altering the sonar operation parameters.

Extracting the data relating to a specific object is in itself a complicated task; the signal of interest will be embedded in an acoustic response that includes other subterranean noise such as: own or other ship noise, marine life, sea movement, underwater features etc. Many of the signals extracted will be false returns, relating to underwater features that are not of direct interest. Those that are of interest are recognised by the nature of the response and how it changes over time, for instance a turning submarine can be recognised by a change in the Doppler frequency of the return.

6.1.3 Assessment of current situation

To identify vehicles from the returned objects it is necessary to correlate multiple sensor measurements with each other to form tracks relating to individual vehicles. From these tracks it becomes possible to estimate the trajectory (the position and velocity) of a vehicle, something known as Target Motion Analysis (TMA), a process which needs to take into account the problem that both the target and the sonar on the sensing platform are moving. The result of this process is to create a geo-referenced track.

As the object data is fused into track data much of the underlying acoustic data becomes redundant, however the nature of acoustics means that for each vehicle it is possible to have concurrent multiple track segments relating to the same vehicle. These concurrent segments can be due to:

- Harmonic pairs and multiple sources
- Intermittent signals

- Track seduction and noise.
- Multipath propagation

In addition to these environmental effects, the actions of the target vehicle may be such as to exploit these factors to evade tracking. To overcome this problem it is necessary to examine the particular characteristics of the track segments, where multiple common characteristics (temporal relationships) can reduce the uncertainty such that it is appropriate to associate them.

Where multiple tracks exist, there is a probability that the tracks will at some point merge or cross, in this situation the tracker must seek to maintain each as unique identities. Crossing problems occur when:

- Multiple tracks exist on the same bearing, although at different ranges.
- Touching tracks, this could be a case of a near miss where at least one of the targets undergoes a course change to avoid the collision.
- Merging tracks: Two targets proceed on the same trajectory, matching speed.

The tracking system as well as maintaining the dynamic tracks needs to be able to maintain the location of static objects, e.g. submarines that may be sitting on the bottom.

6.1.4 Identification and evaluation

The final stage in our system needs to recognise what the tracks are and what they may be attempting to do, in order to decide what, if any, action is subsequently required.

The sonar, in identifying an object, will be able to provide a number of parameters associated with it, such as physical and acoustic measurements, which can be associated with the characteristics of known vehicle types. By limiting the possible vehicles types, it is possible to focus down on a specific type by comparing known actions sets for those vehicles, e.g. maximum surface rate, turning rate, depth etc with the observed vehicle behaviour. The observed vehicle behaviour consists of two components:

- The contextual behaviour
- The intentional behaviour

An observed vehicle will behave contextually both to avoid physical objects and to maintain its awareness, the same natural phenomena that will effect our own sensors will impact theirs. The intentional behaviour may also make use of these natural phenomena for instance to enable it to evade tracking, this is valuable information that can be used by the tracking system to maintain correlation of track parts against a single vehicle.

To understand the strategic intent of a vehicle requires observation over time, to enable contextual behaviour to be filtered out. It is only once the strategic intent is known that appropriateness and method of engagement can be chosen.

6.1.5 The human roles associated with anti-submarine tracking

For the purpose of this study we are considering the implementation of a legacy anti-submarine tracking system as fitted to the Type 42 destroyers[29] and the Type 23 Frigates who represent the currently deployed anti-submarine tracking capability.

In the **Type 42** destroyers there are four roles associated with Anti-submarine tracking.

Anti-Submarine Warfare Officer (ASWO)

The ASWO was responsible for:

- Appreciation of Underwater Tactical Situation
- Defence of own ship from submarine attack
- Effective use of Anti-Submarine Warfare (ASW) weapons

Chief Petty Officer (sonar) CPO OPS(s)

The CPO OPS(s) was responsible for:

- Conducting Anti-submarine Planning,
- Appreciation of Underwater Tactical Situation
- Effective use of Anti-Submarine Warfare (ASW) sensors

Sonar Operator (SO)

There were three sonar operators employed, their task being to interpret the acoustic sonar returns and sonar screens, to provide information on the underwater tactical situation.

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[29] Whilst the Type 42 was designated primarily as an Anti-Air Warship its construction during the cold war required that it had anti-submarine tracking capability.

Sonar Controllers (SC)

There were two sonar controllers who were responsible for modifying the sonar parameters to maintain the quality of the sonar measurements.

In the **Type 23** Frigate there are three roles identified who participate in anti-submarine tracking these are the:

Anti Submarine Warfare Director (AWSD)

The AWSD is responsible for:

- The use of the Anti-Submarine Warfare (ASW) weapons and sensors.
- Supervision of the AcPS for the compilation and presentation of the ASW Tactical Picture.

Action Picture Supervisor (AcPS)

The AcPS is responsible for the immediate local subsurface picture.

Sonar Controller (SC)

The single SC is responsible for the effective use of the hull mounted sonar.

It is noticeable that the current anti-submarine tracking system utilises less that half the man power that the legacy system used. This reduction has been brought about by the military's desire to reduce man power through the introduction of greater machine processing. Understanding how this may affect the human cognitive responsibility and system effectiveness is the purpose of this study.

6.2 Understanding the system

In the previous section we introduced some of the challenges of anti-submarine tracking systems and those UK Naval roles who have been and are responsible for anti-submarine tracking. Irrespective of the human roles involved with the system the underlying system challenge is still the same.

If we look to draw the anti-submarine tracking as a simple linear process it would look something like that shown in Figure 36:

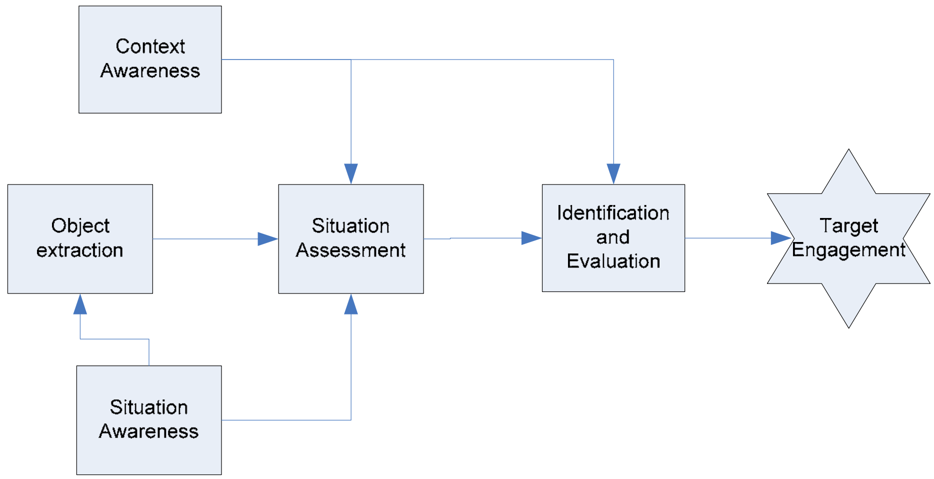

Figure 36 Simple anti-submarine tracking process

In this process the first stage of the process is to extract objects from the sonar measurements taking into account the known current underwater conditions to help interpret the data. Part of this process is to identify returns that may relate to underwater features and those that may relate to other objects, like submarines or whales.

The second stage in the process is to undertake situation assessment, this requires that any potential movement of the object is recognised and a track is formed relating to that object's movement relative to the ship. A knowledge or awareness of the current environmental conditions and underwater landscape provides the ability to maintain track association in situations where returns from the target object may be lost temporarily. The application of wider contextual knowledge provides the ability to constrain the potential targets that may be being tracked and understand the likely dynamics of the tracks.

The third stage in the tracking process is that of identification of the target, what it is and evaluation of its intent[30]. The understanding of possible identifications requires knowledge of the potential submarines in the area and correlation of the likely behaviours or tactics of that class of submarine against the behaviours of the current contact. The extraction of behaviour requires that contextual behaviour, e.g. trying to avoid underwater obstacles, and intentional behaviours, e.g. using the underwater terrain to avoid detection, is filtered out. The aim is to interpret the behaviour of the target submarine to identify its intent, to do this it is necessary to apply military intelligence to recognise the potential target goals and ultimately to decide upon a course of action to respond to that target, if it is perceived to be a threat.

[30] It is not unknown for a shoal of dolphins to follow naval ships giving the impression that it is being followed by an underwater vessel. But the behaviour and proximity of dolphins and that of submarines, to an experienced operative, is very different.

In reality the processing in the simple model of the anti-submarine tracking system is being constantly affected by the context in which the system is operating, see Figure 37.

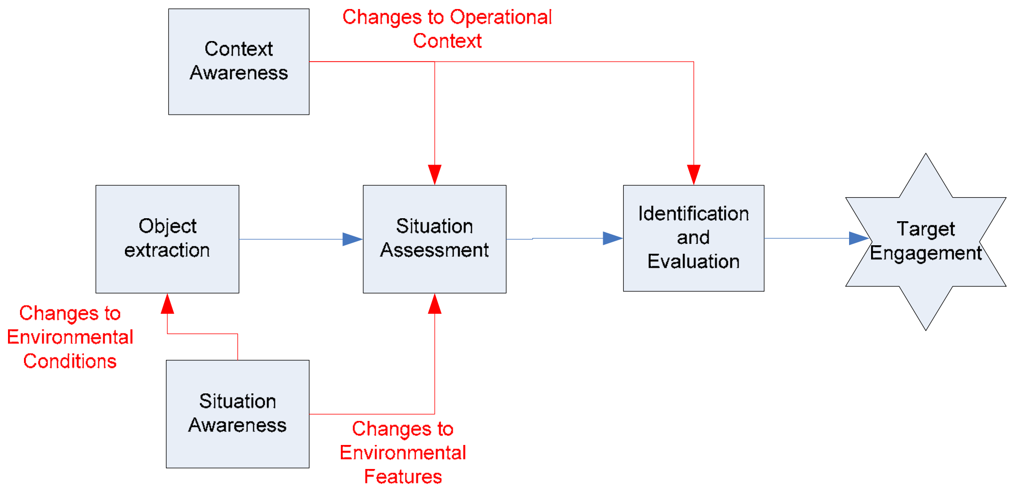

Figure 37 Dynamic anti-submarine tracking process

The dynamic system needs to be aware of changes to the environmental conditions, as this will change the way that it is necessary to seek to setup the sonar and to extract objects from its returned measurements. It must also use its awareness of the current underwater situation to interpret the object's movements but as the ship is moving both the object and the environmental features will seem to be moving relative to the ship's movement, this must be taken into account.

The processing of tracks can also be effected by the reception of contextual intelligence, for instance, they may be informed that there are other possible submarines are in the area. This may introduce new potential platform behaviours that need to be taken into account when seeking to maintain a track. At the highest level we can recognise that changes to the military combat situation may immediately change the interpretation of the intent of the target submarine which may require some form of target engagement, which can be something as simple as making sure the submarine knows that you are tracking them, or the choice to use other engagement effects.

If we overlay the cognitive framework onto the dynamic system model we have a model of the system as shown in Figure 38.

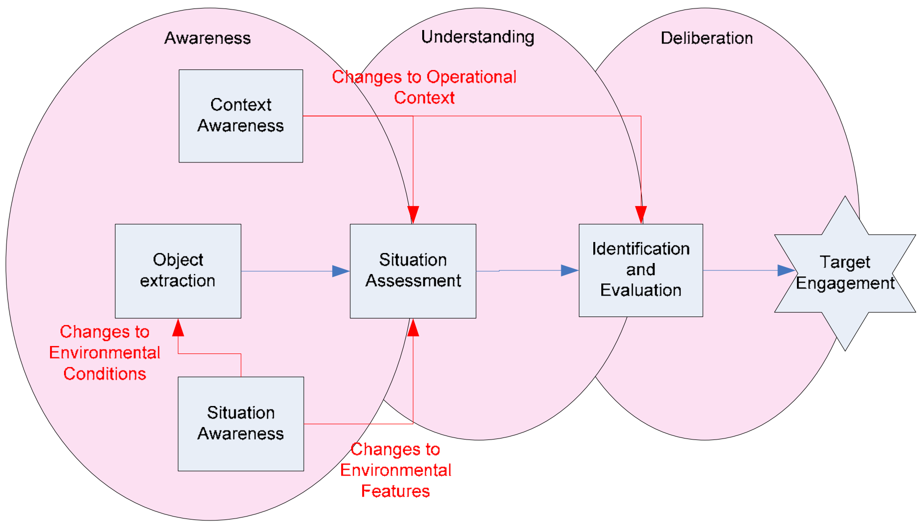

Figure 38 Mapping of the cognitive framework to anti-submarine tracking system

This overlaying of the engineering framework enables us to recognise that the initial stages of the process are focused towards providing the awareness of the underwater situation, the situation assessment and the identification stages to understand what the submarine may be doing, now and may do in the future. From this understanding of its behaviour it is then possible to decide what it may be and what, if anything may be needed to be done in response to its perceived intent.

In reality this dynamic model is a complex system in which the human team are actively applying their knowledge to create an awareness of the situation, to understand the intent of the target submarine and to decide what to do about it, see Figure **39**.

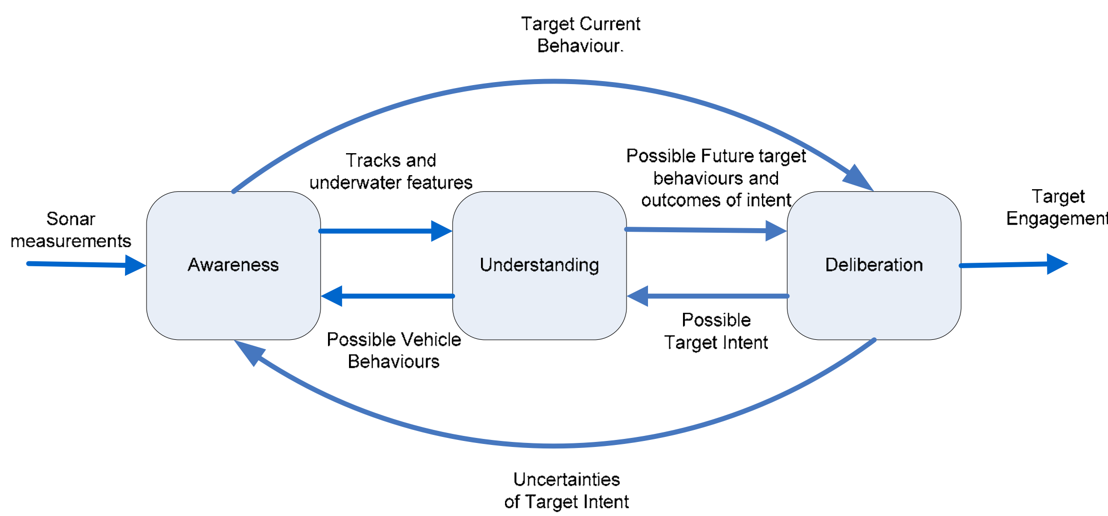

Figure 39 Conceptual information flows in the anti-submarine tracking system

To understand the individual human's contribution in this system we need to look at their individual roles.

6.3 The operator's perspective.

We now use the engineering framework to undertake an analysis of the human roles in our system, and then by joining those roles, we will form a rich system model. Note: This analysis is not intended to be detailed, only sufficient to understand the utility of the engineering framework.

6.3.1 The legacy system

The legacy system consisted of seven individuals: an ASWO, CPO OPS(s), three SOs and two SOs.

Anti-Submarine Warfare Officer (ASWO)

The ASWO was responsible for the defence of own ship from possible attack from submarines, using the available anti-submarine weapons.

To do this required that they were aware of the underwater situation, this was provided to them on a "bird table" on which was manually maintained the current location of any contacts, their recent behaviour and where tracks had been lost a "furthest on circle" indicating the maximum distance the target could have travelled since the last contact was made. Their primary interest was, for any identified submarines, to be able to predict the outcome of their intent and possible future behaviours to enable them to, if necessary, require a target to be engaged.

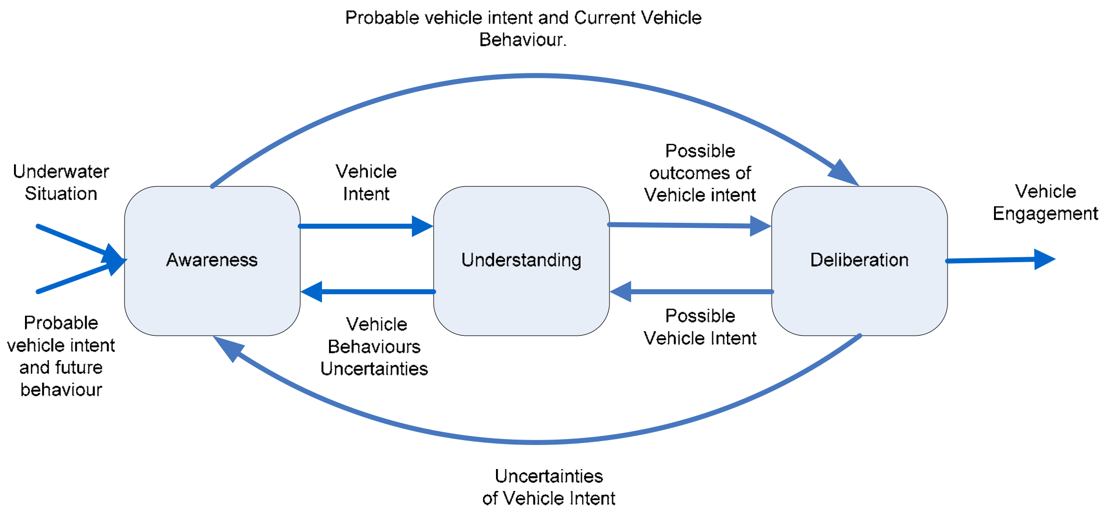

Figure 40 Cognitive focus of ASWO

Chief Petty Officer (sonar) CPO OPS(s)

The CPO OPS(s) was the most experienced anti-submarine war fighter on the ship with extensive knowledge of the ships sonar, underwater combat and submarine tactics. They were responsible for planning the undersea surveillance; this included briefing the sonar operators of the known environmental situation in which they would be operating, providing intelligence as to likely submarine tactics that may be observed, as well as the known targets in the area.

During operations they would oversee the sonar operators and maintain the bird table containing the known underwater situation, e.g. updating furthest on circles for lost contacts.

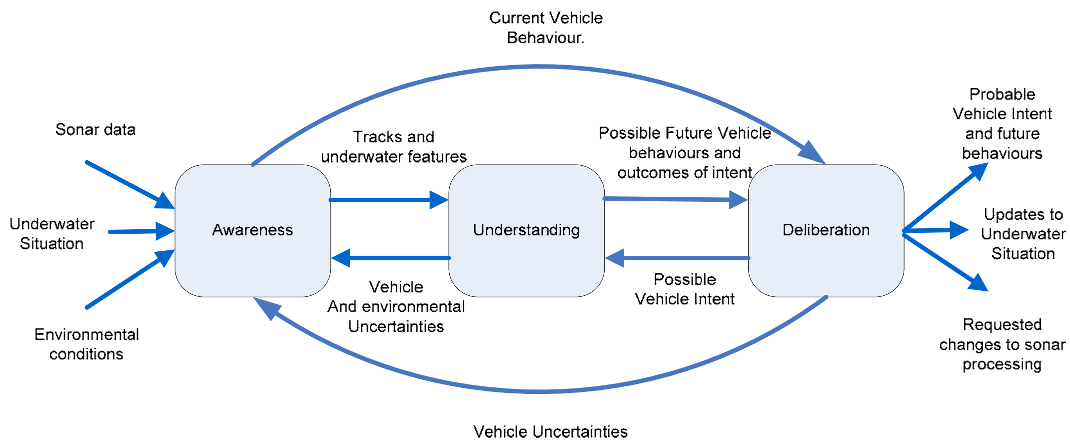

Figure 41 Cognitive focus of CPO OPs(s)

They provided the ASWO with identification of the probable intent of any submarines and an indication of the likely future behaviour of that vehicle, based on their tactical knowledge.

Sonar Operator (SO)

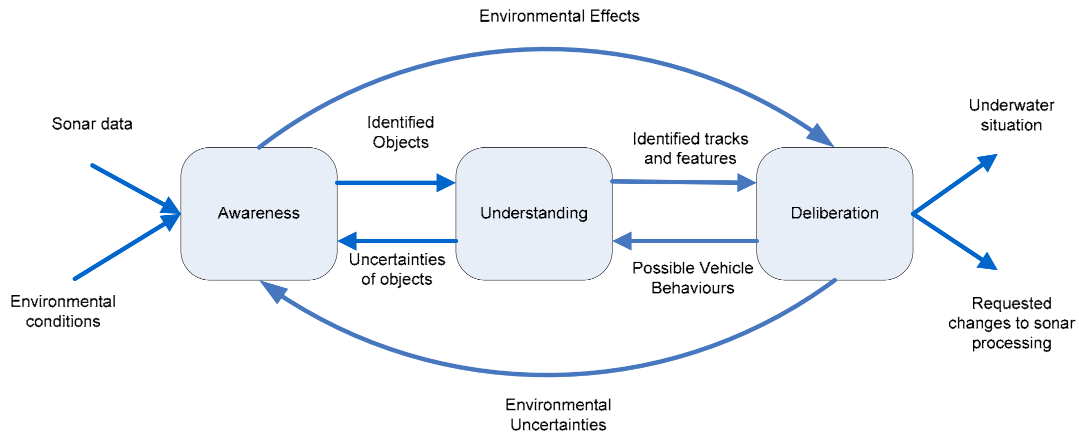

Figure 42 Cognitive focus of SOs

There were three sonar operators employed, their task being to interpret the acoustic sonar returns and sonar screens, to provide information to populate and update the underwater situation on the bird table. In this system the processing of the sonar measurements was being carried out by multiple brains, who were each applying a different viewpoint and experience to the analysis.

In their interpretations and processing of the acoustic signals the sonar operators will be taking into account the information that had been provided by the Chief during their orientation briefing at the commencement of their shift. Information such as:

- Intelligence on potential targets in the area; which provides information on what to look for.

- Latest behavioural patterns of submarines; implying where to expect submarines to be relative to the fleet and the patterns of behaviour to expect to observe.

- Planned operations and movements of own fleet assets; enabling the operators to anticipate acoustic effects due to own assets, such as the appearance of a helo's dipping sonar.

- Known features of the undersea landscape in the area of operations; what to expect to observe and thus how the target may alter their behaviour to make use of the undersea environment.

This information provided the operators with the baseline needed to anticipate the behaviour and movement of submarines in the area. This team was responsible for reporting new contacts to the CPO OPS(s) and ASWO in the operations room and keeping the operations room informed of any targets behaviour.

Sonar Controllers (SC)

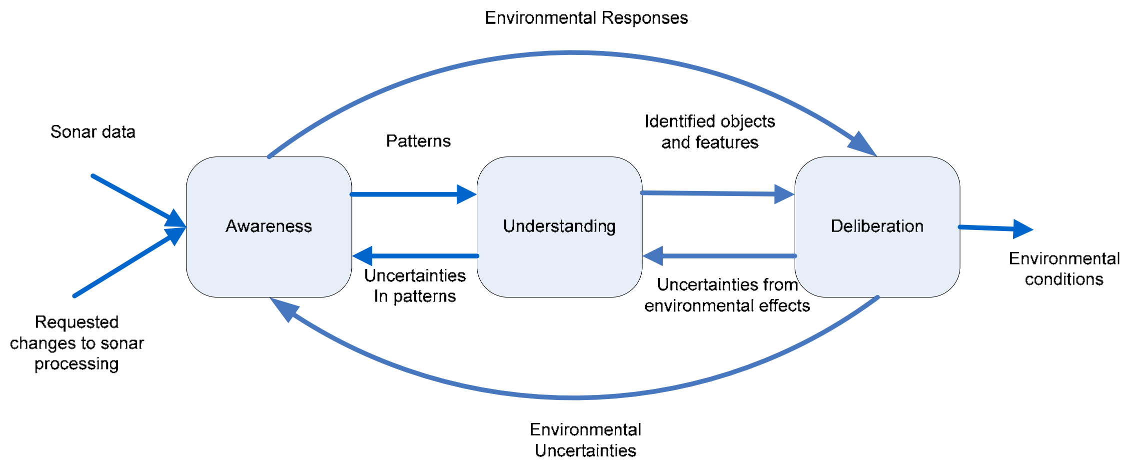

Figure 43 Cognitive focus of SC

There were two sonar controllers who were responsible for managing the sonar to reduce the environmental uncertainties in the processed the sonar data.

The team view

If we join the individual role diagrams together we have a view of the legacy system human team.

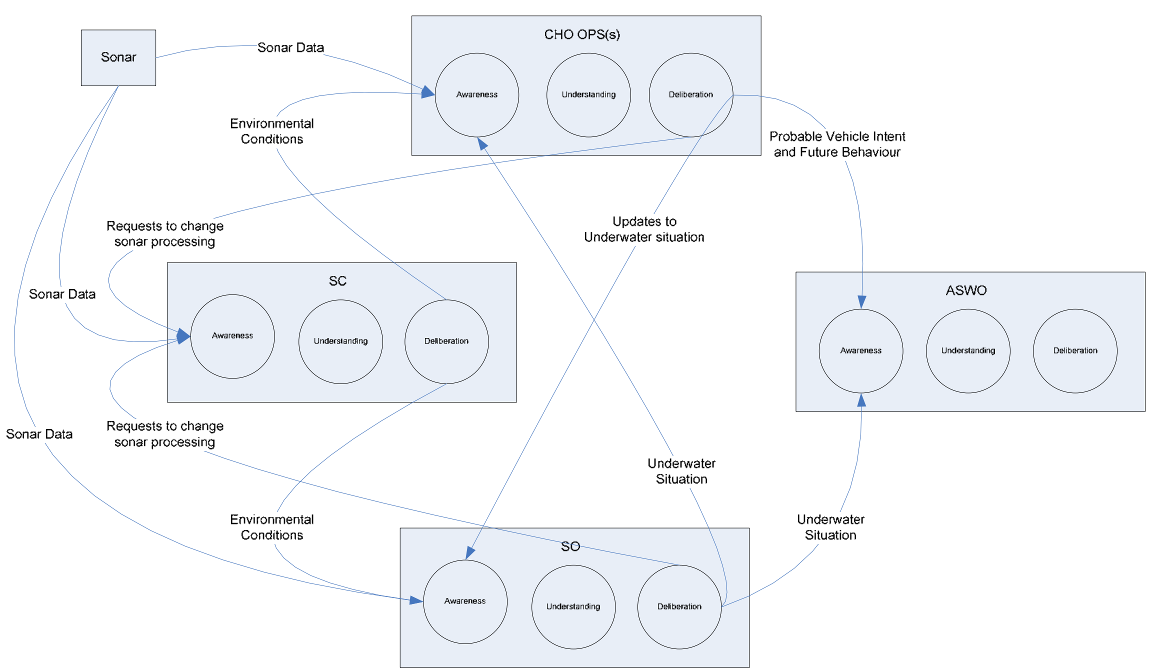

Figure 44 Legacy human team model

Note: the vehicle engagement data flow would feed into a separate system, so has been excluded from this model.

6.3.2 The current system

The current system consists of threes roles the AWSD, the AcPS and the SC.

Anti Submarine Warfare Director (AWSD)

The AWSD is responsible for the defence of own ship from possible attack from submarines using the available anti-submarine weapons. They will probably[31] be the most experienced anti-submarine war fighter on the ship.

To do this required that they were aware of the underwater situation; they gain this from studying the underwater tactical picture, on the combat system, that has been compiled by the AcPS and combining it with their own knowledge and experience.

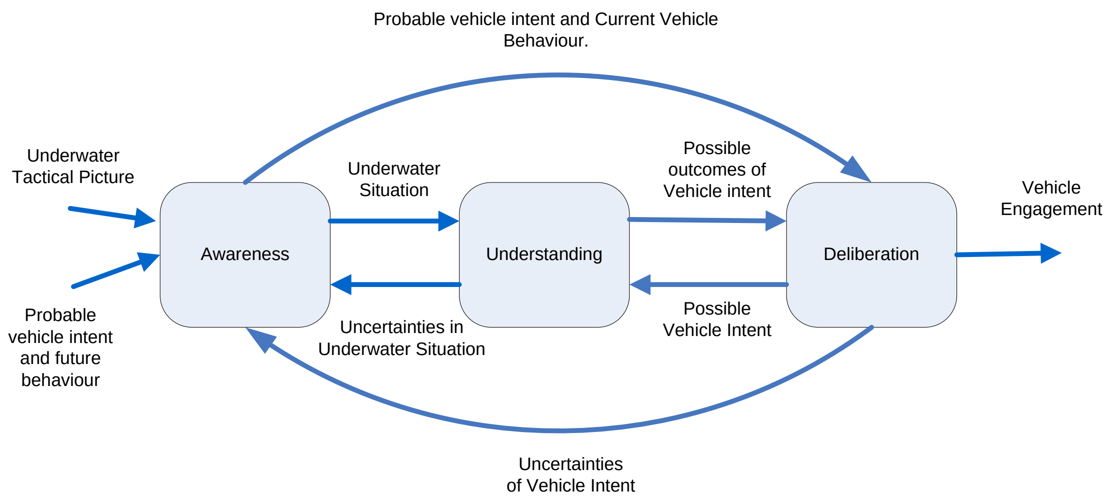

Figure 45 Cognitive focus of AWSD

Like the ASWO in the legacy system, their primary interest is, for any identified submarines, to be able to predict the outcome of their intent and possible future behaviours to enable them to, if necessary, require a target to be engaged.

Action Picture Supervisor (AcPS)

The AcPS is a combat system operator, as such they do not have direct visibility of the sonar unless they physically get up and go and look at it. The combat system will seek to process any underwater objects provided from the sonar system through a process of track correlation, where the machine is unable to correlate a sonar object with a track the AcPS will have to undertake manual association, when underwater conditions are poor this can be a frequent occurrence.

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[31] Assuming that the CO or PWO did not specialise in ASW.

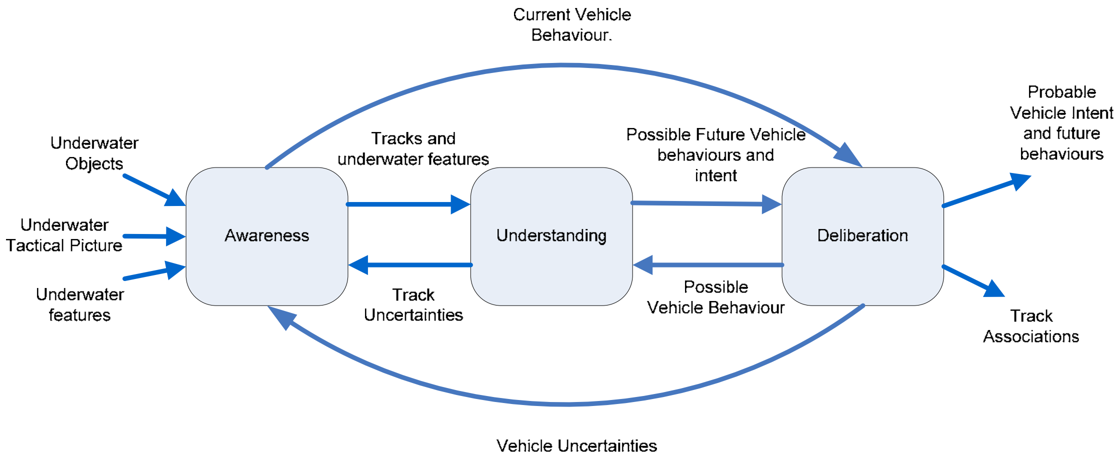

Figure 46 Cognitive focus of AcPS

The combat system automatically provides a historical trace of a number of the latest returns from the sonar, so as to provide an indication of the current direction of the vehicle. Further information or graphics can be added by the AcPS to the tactical picture but they must actively manage that data[32] and remove it, when it is no longer required. As we cannot define what this information may be, it has not been added to the diagram of the cognitive focus.

The AcPS will attempt to predict the future behaviour and intent of any tracks to aid with track associations and provide this information to the ASWD.

Sonar Controller (SC)

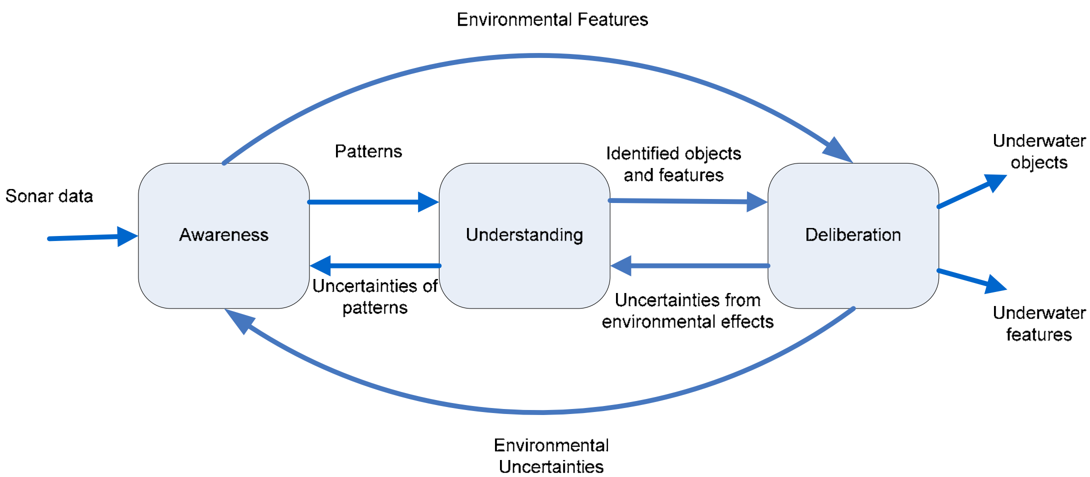

Figure 47 Cognitive focus of T23 SC

[32] Areas drawn on the tactical picture will be geo-static i.e. their location will not be maintained relative to the ship's position.

The role of the sonar operator in this system is to support the sonar processing, correcting where necessary its processing output. The resulting underwater objects are provided electronically to the combat system. The SC will also verbally inform the AcPS of any underwater features but these are not supported by the tactical picture on the combat system.

The team view

If we join up the three roles we can form the human team model of the current system, see Figure 48.

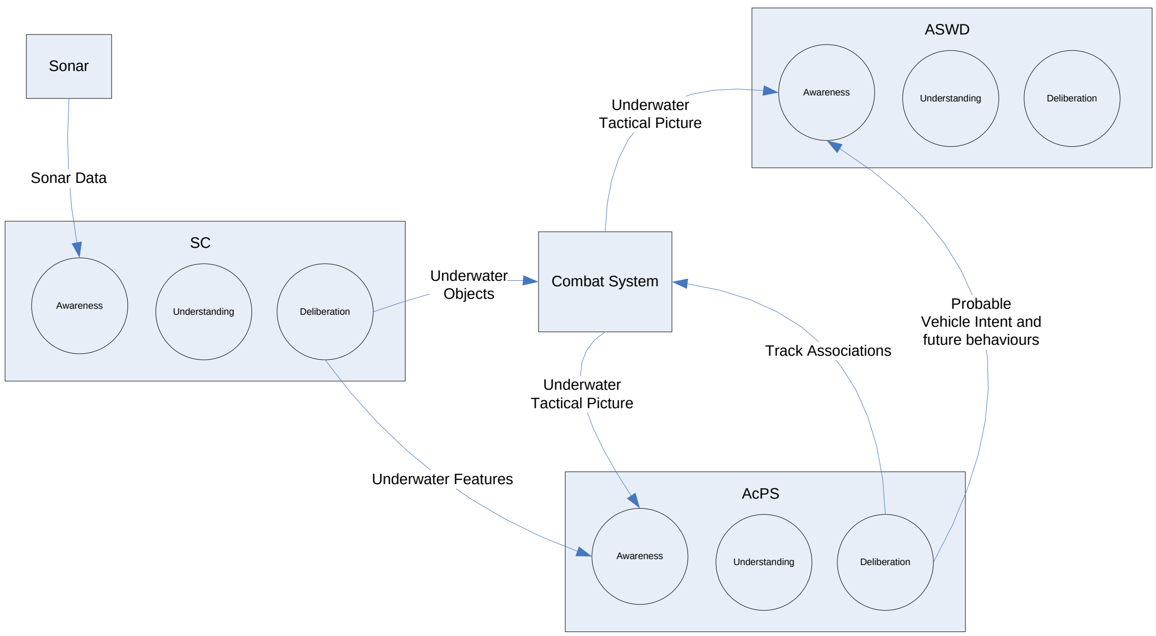

Figure 48 Current human team model of anti-submarine tracking

6.3.3 Comparison of the legacy human system and the current human system

The team view of the current system is much simpler (has less data flows) and uses fewer humans than the legacy system but this simplicity hides the human dependency on machine automation. Machine technology is now providing improved sonar data processing automatic track forming and management of the underwater tactical picture.

Where in the legacy system human knowledge and experience was important, here the requirement is that the human must know the limitations of the machine technology and when its decisions are likely to be incorrect for the evolving context, so that they make the appropriate decisions themselves.

6.4 Operational effectiveness

In this section we consider possible measurements of operational effectiveness and how the human or the machine in the system contributes to this.

6.4.1 Key capability questions

For any system operational effectiveness is all about how well it is able to deliver the system purpose and we normally break this into a set of system capabilities which capture what is required to be achieved. Each of these capabilities requires not only a clearly defined justification but also it must provide an expectation of what constitutes an acceptable level of that capability such as the **effectiveness envelope**. Typically the questions we ask to support the generation of system capability goals (requirements) are:

- How Much? (volume)
- How Well? (accuracy, resolution, confidence level)
- How Fast? (time to completion)
- For How Long? (endurance)
- How Often? (ability to repeat at intervals)
- How Quickly? (responsiveness)
- When? (typically a function of the scenario)
- Where? (typically determined by the scenario)
- At What Cost? (level of training needed, level set-up required, levels of stresses and strains, durability of system)

These performance parameters provide us with an understanding of our possible operational effectiveness. To understand what they mean in reality it is necessary to apply them to the system at hand.

6.4.2 "Effectiveness" in an anti-submarine tracking system.

The requirements for our anti-submarine tracking system is to provide the ability to identify, predict the movement of and anticipate the goal of submarines such that if required the decision can be made to engage them. We can use the three attributes of our engineering framework to understand the system effectiveness challenges:

6.4.2.1 Awareness

Our initial challenge of the identification of submarines focuses around being able to identify underwater tracks and features from the returned sonar data. The challenge is to identify and localise objects, from amongst the environmental effects **in a timely manner**. The localisation needs to be of **sufficient accuracy** that if required it is possible to observe the objects movement and speed.

Effectiveness in the legacy system

In the legacy system the CHO OPS(s) and three SO worked together to form the underwater situation. We can think of this team as being four processors working in parallel to understand the sonar data, each of them will be bringing different knowledge and experience and by communicating together they are actively reducing the uncertainty in the recognised underwater situation, which they are presenting manually on the bird table.

Alongside these are the two SCs who are not directly responsible for contributing to the recognised underwater situation but are dedicated to managing the sonar settings to provide the best possible sonar returns against the evolving environmental conditions.

Where new underwater features are identified that is not on the current underwater charts the data will be added manually to those charts.

Effectiveness in the current system.

In the current system the single SC is supporting the automatic sonar processing, using their knowledge to recognise if different predetermined processing settings can provide better object extraction. These objects are then passed on to the combat system which will filter out the static objects and attempt to correlate moving objects with existing tracks.

The tracks formed by the combat system and the moving objects are then presented to the AcPS for them to improve the underwater tactical picture by identifying track associations where the automatics had failed to correlate tracks.

6.4.2.2 Understanding

When the system has identified an object, it then needs to be able to predict its behaviour and intent, this requires the ability to observe a number of the target's actions and to map those actions on to a known (defined) pattern or tactic.

To be effective the system needs to provide sufficient resolution in object localisation and tracking that it can identify individual actions of the target. The nature of the underwater domain means that this is difficult as it is highly likely that we will have intermittent returns which the system will have to "fill in the gaps" in the sensed actions, consequently the key effectiveness measure for this part of the system is its **ability to maintain tracking over time**.

The requirement to be able to predict behaviour requires the ability to capture sufficient of the track history to be able to compare the actions to known action sets to identify possible target tactics or behaviours. The reduction in uncertainty, as to which behaviour is more likely to be correct will be achieved by predicting future behaviours and comparing the expected actions with those observed. The **achieved accuracy** of these predictions, for any given environment, is a key performance measure.

The focus of behaviour prediction is over the shorter term, longer term prediction is required to identify the targets goals.

Effectiveness in the legacy system.

In the legacy system the CHO OPS(s) and the three SOs will be working together in maintaining the underwater situation on the bird table. Each time they update the current contacts there is a tendency to discuss “what is it up to and where is it likely to go next”. The fact that there is a team working on this means that they are likely to identify many alternative future behaviours but equally to be able to identify reasons why that specific interpretation may not be valid.

These discussion will be audible to the ASWO who will be effectively be overhearing what the team thinks and why.

Effectiveness in the current system.

Within the combat system the automatics maintain a small number of returns for each track on the underwater tactical picture and a linear projection of the possible future path of the vehicles being tracked. Any longer term behaviour needs to be maintained in the head of the AcPS and the ASWD.

The AcPS will in discussions with ASWD, identify what they believe the intent of any submarine is and its likely future actions. This information could be entered into the combat system as manual data but generally because the AcPS already has a high workload entering track associations, this additional data is maintained in their heads.

6.4.2.3 Deliberation

To be able to understand the goal or identify the possible impact that a target submarine may have on our ability to deliver our own military goal, requires that the system extracts the intentional behaviour, which delivers the higher level intent from the more immediate contextual behaviour. This requires the mapping of the observed behaviour of the submarine to both the physical context and that of the evolving military operation. This requires the system to extract actions associated with navigation in the underwater environment, with that which delivers the goal. This is a difficult processing challenge as actions which may seem to relate to avoiding the underwater landscape may actually relate to deliberate actions to avoid detection.

The key effectiveness measure is the **speed and accuracy** that the system can **predict when <u>and</u> why a target is going to change its behaviour and to identify what that future behaviour may be.**

Effectiveness in the legacy system.

In the legacy system the likely intent of a submarine is identified by discussions between the CHO OPS(s) and the ASWO over the bird table, on which has been drawn the underwater situation on top of maritime charts. These charts ground the tracks into the context and provide the means of extracting contextual from intentional behaviour.

Effectiveness in the current system.

In the current system the ASWD will discuss with the AcPS the likely intent and behaviour of any submarines. To aid them understanding contextual behaviour, from intentional behaviour, the combat system is able to present the underwater tactical picture overlaid over the maritime charts.

6.5 Observed operational impact

In this section we capture the military specialist's observations of the consequences of the deployment on system effectiveness. In this comparison we have to recognise that the operational context, against which the current system is required to perform, has evolved.

6.5.1 Improvements

We can identify two major areas where the modern system is meeting the modern operational challenge better than the legacy equipment:

> 1, The introduction of improved machine processing has enabled anti submarine tracking to be undertaken by fewer people.
>
> 2, The use of alarms enables the machine to attract the human's attention when it identifies a contact. This removes the requirement for a dedicated human operator to oversee the equipment and minimises the impact on the human's workload when no contacts have been detected.

6.5.2 What has not improved

We can also identify a number of areas where the modern system is not meeting the modern operational challenge potentially as well as the legacy system may have:

> 1, Humans can achieve the sensing to decision making processing of data faster than a machine. A human operator could identify directly from the sonar audio if a target is changing behaviour; for instance: slowing can be interpreted by a change of frequency from the target's propeller return[33]. The result of greater reliance on automatic processing degrades the human operator's ability to recognise changes in a target's behaviour

[33] This change in frequency indicating a change in direction is not captured by the machine's automatic processing.

2, In the legacy system there were multiple human operators who each brought their own knowledge and perspective on the tracking problem. In the circumstances where new types of contacts are made this multi perspective processing is more likely to be able to identify the new or unusual targets and their actions

3, In the modern operations room we are asking human operators to interact with many pieces of equipment, no longer are they immersed in a specific domain. The point at which the machine attracts their attention to a possible contact requires them to rapidly form a detailed awareness and understanding of the underwater environment, beyond that supported by the machine.

4, In a combat situation the engagement of air contacts takes priority over underwater due to the required response times. In such a situation the ASWD will be distracted from observing the underwater picture. As the machine only provides visibility of the current underwater tracks there is the potential for gaps in the human's observation of the target's behaviour. This can result in delays to the human's ability to recognise and predict the behaviour the target.

5, Machines show track history over a short period of time, the recognition of intent requires a longer term observation and the mapping of that behaviour in the context. Contextual behaviour, as well as needing information about physical environmental data, requires information about own forces and their behaviour: e.g. the target may be positioning itself in respect to one of the ships in the fleet, either for avoiding detection or to gain combat advantage. The challenge of predicting target behaviour is thus likely to also impact the recognition of intent.

6.6 Using the framework to identify changes to the design that should improve effectiveness

In this section we use our understanding of the human's cognitive contribution, formed through use of the engineering framework, to consider potential changes to the current system that could help overcome the identified negative operational impact(s). These are theoretical changes to the system, which have been validated through peer review with a military specialist to understand the potential effectiveness of the proposed changes.

With unlimited funding, time and applicable technologies it should be possible to enhance the machine part of the system with all the functionality to overcome all the negative effects identified in 6.5.2, however practically we need to consider what could be done relatively cheaply in a reasonable time scale, without requiring major redesign to the existing equipment.

6.6.1 Opportunities to improve awareness

During object assessment a number of returns will relate to environmental features, such as wrecks, underwater shelves etc. These features are not normally included in the underwater tactical picture but if they were could be used to improve the existing chart data against which to extract contextual from intentional behaviour.

The identification of underwater features and the creation of a model of the sea bottom features are becoming increasingly practical. Techniques like simultaneous localisation and mapping (SLAM) could be applied to form a map of the undersea edges and provide object recognition. The range at which the existing transducers can provide sufficient resolution is likely to be the limiting factor to this technique.

6.6.2 Opportunities to improve understanding

One of the main criticisms of current tracking systems be they for air, surface or underwater is their inability to recognise that if a vehicle (track) had been identified and subsequently lost, then, unless the vehicle has been destroyed, it is still out there. Simple techniques such as maintaining "*furthest on circles*"[34] for lost tracks would seem a very simple aid to helping the human maintain tracking. We can recognise that as time progresses the accuracy of these furthest on circles will diminish but that the fact that there had been a recognised contact does not change and remains a key piece of operational information. The implementation of furthest on circles to assist in the tracking of lost contacts is likely to be the most basic to implement as it requires a simple calculation of the maximum distance travelled since the last contact to be overlaid on the tactical display. It should also be relatively simple to provide machine processing to correlate a new track, identified within the circle, to be the previously tracked vehicle and to define for it a level of certainty relating to its ID.

Where it can be recognised that a vehicles goes behind a known obstruction (an application of our model of the underwater landscape) the likely area over which the target may have travelled since the previous contact can be further refined and if a new contact identified that is within the expected distance that the previous contact could have travelled providing the option to automatically correlate the contact with the previous track. This would reduce the AcPS's requirement to create and maintain manual associations.

Machine tracking systems normally seek to provide details of the current track and a few prior contacts. In an environment where maintaining tracking is challenging, let alone future projection, the ability to retrieve additional historical data relating to a track should help to fill in the gaps in a human's awareness caused by other operational "distractions". Modern plot fusion engines use earlier plots in their filtering and record all returns, so the data for earlier history should be already available. In considering the implementation we need to consider how such data should be displayed as track data is normally centred on

[34] Furthest on circles are, based on the known maximum speed of the observed target, the circle representing the maximum distance that a target could have travelled from the last contact in the time since that response.

one's own ship in the tactical picture[35]. Processing would require that earlier plots would need to be referenced to a world reference and then translated onto the current tactical picture. This would need to be recalculated as own ship and the centre of the tactical picture moves.

6.6.3 Opportunities to improve deliberation

The identification of the intent of a submarine is currently a human activity with machines providing little if any support to the process. The challenge for the human is to conceive the behaviour of the observed target in terms of military tactics in order to identify the target's possible intent. For instance, to recognise that the target has been following the fleet, would need the inferer to filter out both contextual behaviour and behaviour related to avoiding detection.

One of the difficulties of understanding another's intent is that it requires observation over a relatively long duration, which in a busy operations room can be difficult to achieve. The addition of machine processing that would enable the high level classification and display of this conceptual behaviour would seem appropriate.

The identification of contextual behaviour and intentional behaviour requires that the observer understands the targets behaviour, not relative to their own ship, but relative to the current military operation. The contextual understanding would thus require viewing the current situation as if from a distance, observing not only the targets behaviour but also of other ships etc.

How could we do this? The recognised maritime picture or wide area picture provides a geo-located view of the maritime domain. If we took a similar view and displayed the track history of the contacts in the locality it would be possible not only to observe ones own ship or fleet's behaviour but also of any target submarines. How much history and the choice of what details to display of specific vessels would be a contextual decision.

To aid the operator we could consider enhancing the machine processing to do behaviour identification. There are a number of research activities underway that are intended to enable a machine to do high level fusion, including behaviour identification. These technologies are intended to provide indications of the probable behaviour but do not currently seek to explain why they came up with that answer, a requirement which will be needed to justify any automatic identifications allocated to command.

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[35] The tactical display is centred around the ship to aid the human understanding and covers the ships sensing area, the "world" moves around the ship on the display. Where as the wide area picture is geo referenced.

6.6.4 Conclusion

Through using our framework we have found a number of possible machine processing enhancements that could be developed and deployed that would support the human by helping them build their awareness, understanding and to deliberate in a timely manner. The simplest and most cost effective of which would be to provide furthest on circles and the ability to display historical track data.

This study has only skimmed the surface of the challenge of anti-submarine warfare and it is likely that there are machine enhancements already being deployed that may well address some of the shortfalls identified.

6.7 Review of the Engineering Technology

The primarily purpose of this study was to explore the use of the engineering framework and supporting process. In this section we review their use.

6.7.1 The framework

The engineering framework consisting of the three attributes of awareness, understanding and deliberation, has been successfully used to capture a conceptual model of the cognitive system and the individual human roles for both the legacy and the current systems.

The same three attributes have been used to consider the effectiveness of the system and how the humans contribute towards it. The level of detail of system effectiveness captured in this document has had to be left at a high level due to the potential security implications of providing actual system effectiveness information. Even so the use of the framework enabled us to identify where changes between the current and the legacy systems were likely to change the potential human contribution to the system and hence have implications on system effectiveness.

In this system most of the consequences of the introduction of automation have influenced the human's ability to form awareness, in future studies we need to look to investigate using the framework to investigate *understanding* and *deliberation* in more detail.

6.7.2 The process

In this case study we have undertaken an analysis of an existing system using the engineering framework. The first stage of the process required that we seek to understand the challenges that the system had to meet and the human roles that participated in it. We then captured a conceptual model of the system first as a linear process, then identified the dynamic influences on that system and finally mapped that model onto our engineering framework, from which we created a conceptual cognitive model of the system.

We then turned to creating models of the cognitive focus of each of the human roles in both the legacy and the current system, providing descriptions of their contribution towards delivering the system purpose. These individual role models were then successfully joined together to form the team model which effectively gave us a high level model of the cognitive functions and their relations within the system. It was whilst creating this team model that the flow of the sonar objects from the SC through the combat system to be provided to the AsWD as the underwater tactical picture became very apparent. This transformation was reducing the amount of information available and consequently altering the potential interpretations the AsWD could make of the data.

The fourth stage of the process was to understand what constitutes effectiveness for this system. We took the classical system capability questions and considered them in light of our system purpose. The use of the three attributes to focus our consideration of effectiveness proved useful and enabled us to avoid the temptation to consider the system implementation, instead they forced us to focus on the human roles and how they contributed towards system effectiveness.

The final stage of the process was to make use of the human team models and the identified system effectiveness to see if we could identify system changes that could improve the human effectiveness. The resulting changes have been identified by a third party reviewer as obvious changes. If these changes are so obvious, we need to ask ourselves why they were not implemented when the automation was introduced.

6.8 Conclusion

The use of the framework to guide the engineering analysis delivered a different understanding of the system than would have been achieved using more conventional means. The capture of the conceptual system as a cognitive system model with all its complex feedback paths, provided us with a view on the system and its decision making that provided a good grounding from which to investigate the human contribution.

The capture of the human roles as separate models of their cognitive focus and joining them together, provided us with a new understanding of the information flows within the human team that would lead us to question the impact of automation as the data flow from one human role changed before it reached the next role.

This piece of work has focused on use of the framework to identify possible ways in which to improve the machines ability to deliver the required information to support human awareness, enabling them to understand the situation and make the right decisions. Future work needs to investigate its applicability to helping a human form understanding and to identify or make the appropriate decision.

7 THE APPLICATION OF HCSE TO UNDERSTANDING THE DEPLOYMENT OF MACHINE TECHNOLOGY INTO A HUMAN SYSTEM

In this second study we apply the engineering framework and process to understand an existing military capability that is currently delivered by a human team working seamlessly together as a cognitive system. Into this human cognitive system the intent is to deploy advanced machine decision technology to enable the military assets to be used in a more effective manner.

The aim of this study is to understand how systems engineers can use the engineering framework to capture the cognitive aspects of a system as a model and at a lower level to capture the cognitive focus of individual humans within that cognitive system. Then to use these models to investigate the potential deployment of machine technology by focusing on how that deployment relates to a human's ability to form awareness, create understanding and to deliberate.

This section shows how the engineering framework and process have been used to undertake the engineering analysis and design:

Section 7.1.2 captures the first stage of the engineering process identified as *Understanding the technical challenge*. It introduces the military capability of Force Threat Evaluation and Weapon Assignment (FTEWA)[36], presents a number of different ways in which military assets could be allocated to meet that challenge and which of these techniques are addressed by the algorithm. It also introduces the Naval roles associated with FTEWA[37].

Section 7.2 captures the second stage of the engineering process *Understanding the system.* To understand the FTEWA system it starts by presenting a simple linear system that gathers instantaneous data from the situation, calculates a deployment plan, which is then understood in light of the situation and the assets told to deploy. It then considers the dynamic process, where the context is changing, our assets are moving, the identity of the threats may change (due to resolution of uncertainties), missiles are used, threats may or may not be destroyed and how the tactics used may differ from those expected. It then overlays the dynamic system model onto the cognitive framework.

Section 7.3 investigates the human's perspective in the system. It uses the framework to undertake an analysis of the cognitive focus of the individual human roles, identifying their information needs and the information they are providing. By bringing all of the roles together we capture a model of the existing human team as a single rich model of the team.

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[36] We are using the term FTEWA rather than FTEAA (Force Threat Evaluation and Asset Assignment) as existing Naval convention is to use the terms PTEWA (Platform Threat Evaluation and Weapon Assignment) and WTEWA (Weapon Threat Evaluation and Weapon Assignment) for platform and weapon respectively.
[37] Whilst the operational concept of FTEWA is entering into other military domains, the Naval domain was chosen due to the maturity of the requirement and potential for timely exploitation.

By applying a set of system capability questions section 7.4 considers the effectiveness measures for the FTEWA system. We then focus in on how the human contributes to the system effectiveness and examine the likely areas where the man or machine implementation could have an impact on system effectiveness.

The final part of the engineering process is captured in section 7.6 where using the human system model captured in 7.3 we identify the information flows that relate to the algorithm, using this to compare with the human information flows to identify who within the team may need to interact with the algorithm. We then use our framework to force us to take a human centric perspective and to consider the likely impact of the deployment of the algorithm on each of the associated human roles awareness, understanding and deliberation abilities, which enabled us to identify additional human information needs. We then propose a possible deployment of the algorithm into the human cognitive system and present the idea of a "wrapper" to provide the additional information needed to effectively engage the humans with the algorithm. Finally the design was independently reviewed to consider the potential impact of this system design on the overall system effectiveness.

In section 7.7.2 we consider the outcome of a parallel study into the same FTEWA system undertaken by a human factors team comparing the outcomes of their work with the output of this study.

In section 7.8 we return to developing the engineering tool aspects of the framework it reviews where and how the framework was used during the engineering process captured in this section. We make recommendations for improving the effectiveness of the process and consider the actual cost of using the framework and process.

This section concludes with considering if the application of the framework and process provided anything useful and practicalities of their application.

By doing this it will enable the development of the framework and process to enable engineers to:

- Understand the cognitive functionality provided by the humans in the system and how that functionality is delivered through the human's awareness, understanding and deliberation.
- Recognise the human cognitive contribution in delivering system effectiveness.
- Be able to understand the potential impact of the deployment of the low level machine technology(ies) on system (Human + Machine(s)) level effectiveness.
- To make system design decisions that will seek to make best use of the humans within the system.

7.1 Introduction

The system chosen for the second study is that of Naval Force Threat Evaluation and Weapon Assignment (FTEWA). This system is responsible for the real-time planning and management of Combat Air Patrol (CAP) aircraft to defend an area from incoming threats. The management of the CAP aircraft is currently a manual activity which due to the number of aircraft involved is too large for one human to plan and manage on their own.

In the current system the approach taken to this problem is to divide the operational area up into segments for which the responsibility of defence is held by different ships that have been allocated part of the airborne CAPs to conduct that defence see Figure 49.

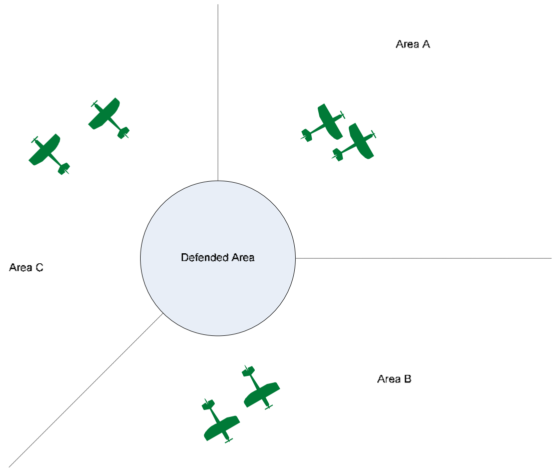

Figure 49 FTEWA using Area of Responsibility Allocation

This type of allocation minimises the number of aircraft that each ship is required to manage thus reducing human workload. However classically when an attack occurs the incoming threats are likely to appear from the same direction as shown in Figure 50

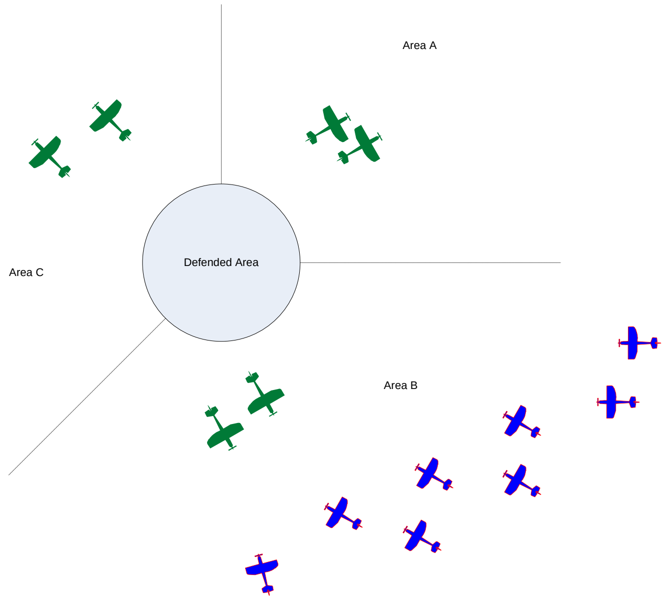

Figure 50 Incoming threats normally arrive from the same direction

In this type of attack one ship has the total responsibility for engaging the incoming threats with the assets that it has been allocate with. The result is that the few assets that they have will be heavily loaded with tasks and there is a higher probability that the threats will get through than if the assets allocated to other ships had been also tasked with the defence. But such a change in system operation requires the introduction of technology to aid the humans[38].

The machine decision technology that is being investigated for deployment is intended to allow all of the airborne assets to be used against the incoming threats. The algorithm has the potential to be able to improve engagement planning not only increasing the probability that all incoming threats will be engaged but also the probability that the engagement will succeed. For these potential benefits to be realised it is necessary to undertake an engineering study into the existing system and to consider the implications of the deployment of the technology on the human contribution in delivering system effectiveness.

7.1.1 Limitations of this study

This research is to develop the engineering framework and process associated with understanding the cognitive aspects of a system; as such the captured design and proposed implementation is not the key deliverable.

This investigation has been limited to a specific military challenge that of FTEWA, undertaken on a single ship. We recognise that in a military operation the dynamic engagement plan will need to be provided to other ships for them to undertake PTEWA planning and that FTEWA is but one of the military capabilities that the human cognition is concurrently contributing to.

The first challenge represents a team human cognitive model and the second a system of systems cognitive model. As we expand the system boundary the technical challenge that engineering needs to address will become more complex and how the use of the framework scales to these other types of challenges is a major area of research that is beyond the scope of this research item.

7.1.2 Understanding the technical challenge.

This section introduces the military challenge and a number of different strategies that could be used to meet it and the authority and responsibility structure in which the system capability is achieved.

7.1.3 The system purpose

The aim of Threat Evaluation and Weapons Assignment at the Force level is to provide the effective defence of High Value Units while maximising air co-ordination across the deployed force.

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[38] It would also require changes to the concept of operation and possible changes to rules of engagement but that is outside the scope of this study.

The FTEWA system provides:

- Evaluation and ranking of all air threats to the Force (Force Threat Evaluation (FTE))
- Generation of plans for the defence of the Force against the air threat using the available force anti air warfare assets.

Force assets for the purpose of this system are the allocated Combat Air Patrol (CAP) aircraft both airborne on station and on deck at alert or standby. These aircraft may be manned or unmanned (UAVs).

7.1.4 Types of force asset allocation[39]

It is possible to tackle the challenge of force asset allocation within the FTEWA plan in a number of distinctly different ways, each of which have their own advantages and disadvantages for different operational scenarios:

7.1.4.1 Area of responsibility

The simplest technique for defending a force is that of area of responsibility. In this scheme individual platforms (ships) are given responsibility for a specific area and assets with which to engage targets within that area. This limits the number of assets that need to be considered in any engagement plan, making it in theory a more manageable problem.

The disadvantage is that normally threats will arrive from the same direction causing local saturation problems. The few assets available will need to be re-tasked and will quickly use their available missiles leaving threats to be engaged at the platform level.

7.1.4.2 Coverage

In this engagement scenario the totality of the force's assets are considered to ensure that all the threats are engaged. To do this requires centralised command but the natural tendency for a human is to allocate the closest asset to each threat, without consideration to capability or to achieve coverage.

In the situation where there are more threats than assets with which to engage it is highly probably that at the end of their initial engagement that the defending assets will no longer be able to catch up with the remaining threats and they will need to be engaged at a platform level.

[39] These types of force asset allocation have been captured from discussions with Mr Bob Clark Type 45 Combat System Leader.

7.1.4.3 Optimal coverage

An alternative to coverage is to calculate if it is possible for each asset to engage a number of threats, one after another, identifying where and when those engagements could occur. The advantage of this type of allocation is that there is the potential to engage a greater number of threats with the same number of assets.

The challenge is that to gain this expanded coverage may require that the “pilots” are asked to engage targets that may not be the first that they encounter: the natural tendency, for a human pilot, being to engage anything hostile within their sensor range.

7.1.4.4 Optimal allocation

Within both our own forces and the incoming threats we can recognise differences in capability: platform fight ability, weapon payload, available flight time or the individual pilot’s combat skill. By extending the challenge of asset allocation to include some of these additional parameters we have the potential to improve the probability of successfully engaging the current wave of threats.

In this type of allocation it is possible that not all of the assets will be required to engage at any point in time and that other assets will have been allocated multiple engagements. The result is that this is the first of the allocation types that provides solutions that are highly likely not to be intuitive to the human observer.

With the change to aircraft allocation (potentially some with no allocations and others with multiple) the command engagement of the pilots with their task will become an important system challenge. Task allocation to pilots needs to be timely to inform the pilot when to proceed to a specific location for an engagement such that they arrive at the calculated time to conduct their engagement, but not timed such that it distracts them during a current engagement.

With this type of allocation there is a requirement to change the concept of operations as we may find aircraft allocated not only to cross the flight path of threats but also of other force assets. With human pilots this is likely to be a physiological barrier which must be managed by command. The UAV’s programming will need to take this into account as this type of flying is likely to break the flight safety rules required for UAV flight certification.

This is the type of allocation that can be achieved using the algorithm developed under SEAS DTC research item MP001 [Papadakos et al. 2008].

7.1.4.5 Dynamic optimal allocation

During combat missiles will be used, threats may change their course or be destroyed, changes to priorities for engagement and our own assets may be lost. To meet this we can extend the concept of optimal allocation to that of Dynamic Optimal Allocation where we re-optimise based on the evolving situation. We use the same parameters used in optimal allocation but their values will be the instantaneous values during the engagement.

Such a re-optimisation needs to take into account the real time asset re-orientation challenge, e.g. if a pilot who is currently undertaking an engagement is re-tasked this will require time for the pilot to understand what is being asked of them. During such a re-orientation they are more vulnerable to attack, so it is more appropriate to plan to re-task for future tasks for human piloted assets rather than current engagements.

In this type of allocation it may be that part of the original plan remain valid, so there is little to be gained by changing them. So we could consider dynamic optimisation to be plan repair. This type of optimisation is being considered under the SEAS DTC research item MP017.

7.1.4.6 Game theoretic optimisation

The allocation of assets using a game theoretic approach requires that we correctly identify and understand the strategies of the opponent. We then use this to calculate for any defensive move that we may consider, how the threat may react and in turn how we would use our assets to counter that theoretical future move.

The resulting allocation of assets will be based on changes to the current situation, actions by the threats, which have not yet occurred, which makes this type of allocation very difficult for a human to understand.

This type of allocation is a stretch challenge under the SEAS DTC research item MP017

7.1.4.7 Chosen allocation type

For the purpose of this paper we are considering the FTEWA optimal allocation implementation identified under 7.1.4.4. as implemented by Imperial College under the SEAS DTC research item MP001 "Uncertainty software programming Applied to Mission Planning, Decision Making and Design Optimisation for UV Operations"[Papadakos et al. 2008]. We will also consider the dynamic challenge that is being addressed by the SEAS DTC Research Item MP017 "Dynamic Restructuring of Decisions and Games under Uncertainty"[40] [Papadakos et al. forthcoming].

[40] The current intention is that both MP001 and MP017 will use the same parameters for their algorithms. As the work on MP017 progresses this may change.

The MP001 algorithm in its calculation of the optimal engagement takes into account the following parameters:

Area being defended (area enclosing the high valued units).

For current threats:

Location,

Speed,

Direction,

Priority for engagement

For the available assets

Location,

Speed,

Direction

Number of missiles available

Available flight time.

It can optimise to minimise the number of threats reaching the defended area, time to defeat all threats, minimise the number of missiles used or to seek to maximise the survival of the assets.

The algorithm uses an engagement parameters matrix to provide information relating to potential engagements:

Kill Probability: the likelihood of success of a specific asset type defeating a threat type.

Re-Engagement time: if the first engagement attempt fails, how long the asset will need to carry out a second engagement.

Missiles per engagement: The likely number of missiles the asset will use to engage the threat.

Asset survival probability: the likelihood of the asset surviving the engagement with the threat

These parameters are defined during the framing problem stage of the FTEWA process, the results of which are then provided as an engagement plan giving: asset identifier, expected number of missiles needed, probability of success, engagement matrix (threat number, time of engagement, location of engagement), see Figure 51.

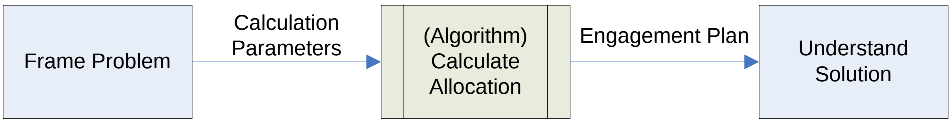

Figure 51 Application of the Optimisation Algorithm

The application of such an algorithm into a system requires that the host system supports both the framing problem process and the understand solution process. To understand who is going to do this we need to investigate the human roles associated with FTEWA.

7.1.5 The existing naval roles and their relationship with the delivery of FTEWA

To define the context of the FTEWA capability we need to understand its relation with the military system, specifically the human roles and responsibilities in that system. The duties relating to FTEWA were included as part of the Type 45 destroyer roles [UK MoD 2001], which identified the following operational tasks[41]:

Commanding Officer

Is legally responsible for the actions of his ship and all subordinate assets.

Key Operational Tasks:

- Responsible for the performance of own ship and any assets allocated to his tactical command.
- Approval of engagement plans

Anti Air Warfare Commander (AAWC)

Key Operational Tasks:

- Defence of the force from air attack.
- Conducting AAW planning: defining appropriate dispositions and stationing of aircraft to ensure timely warning and engagement of threats.
- Conduct of the real-time air battle management.

Force Marshal

Key operational tasks:

- Real-time safe management of airspace in the vicinity of the force.
- Management of aircraft joining or leaving the force

[41] Note this is an unclassified definition of the operational tasks.

Air Co-ordinator

Key operational tasks:

- Real-time Monitoring of group’s airspace.
- Planning functions associated with aircraft management.

Fighter Controller One (FC1)

Key operational tasks:

- Exercise Force Duties as directed.
- Appreciation of Tactical Situation
- Control of assigned Aircraft.
- Maintain status of aircraft within combat system.
- Airspace Co-ordination and Air Traffic Control safety procedures.

Where multiple separate groups of aircraft are being managed a second Fighter Controller role may be occupied.

In addition we need to consider the platform roles of:

Principal Warfare Officer (PWO)

Key operational tasks:

- Exercise Force Duties as directed.
- Platform Capability.
- Operational conduct of subordinate units, including aircraft.

Anti Air Warfare officer (AAWO)

Key operational tasks:

- Exercise Force Duties as directed.
- Appreciation of Tactical Situation
- AAW defence of own ship and others.
- Effective Operational employment of aircraft under own-ship control.
- Safety of all aircraft under ship’s direction.

Each of these roles has distinctly different responsibilities contributing towards delivering the FTEWA subsystem, roles that form part of the higher level military system. Any machine technology that is deployed to assist in the delivery of FTEWA will need to be engineered in such a way as to meet all of their needs.

7.2 Understanding the system

This section considers the conceptual system process needed to deliver FTEWA, initially as a simple linear problem then as a dynamic problem.

7.2.1 A conceptual FTEWA system

In the previous section we introduced the challenge of FTWEA and different ways in which we may solve the allocation challenge, a specific machine technology that could calculate the allocation and the humans who are involved in delivering the existing military capability. We now seek to bring these elements together to capture the conceptual FTEWA system.

7.2.1.1 Simplistic FTEWA process

If we seek to draw our FTEWA system[42] we could consider it as a simple process as shown in Figure 52:

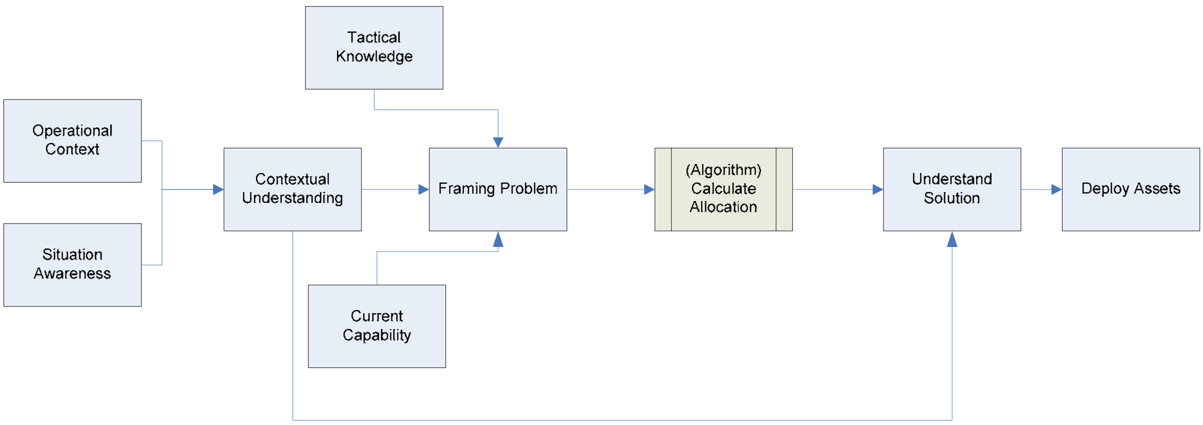

Figure 52 FTEWA process

Each of these boxes captures stages in the process, we could consider that the blue boxes capture human functions and the green box the function provided by the algorithm. If we follow through each of the steps in turn:

The FTEWA process requires that the system uses knowledge of the operational context (e.g. the type of operations, intent of the "other side", capability or tactics of the other side, political situation etc) and the current situation awareness to form its current contextual understanding. It is this understanding that is used to identify probable aircraft types, interpret behaviour and intent of any contacts in the tactical picture, enabling their classification

[42] This model was captured as a result of discussions with Mr Bob Clark, Type 45 IPT Combat System Leader.

(threat, suspect etc) and prioritisation for engagement. This is the first stage of the process known as threat evaluation.

Having identified threats the second stage is to seek to allocate the available assets to engage those threats. To do this, using an optimal strategy, the system needs to apply tactical knowledge of the probability our own aircraft's ability to successfully engaging the opposition's aircraft type, with the available missile types and the current capability of the aircraft available. The tactical knowledge and the assumptions made in the contextual understanding can be considered to be subjective or to have probabilities associated with them. The current capability could potentially, if radio contact is available, be real data or may be an on ship assessment of the likely current capability.

This set of parameters can then be used to calculate the engagement plan. Whilst the engagement plan defines a possible engagement solution it only takes into account this specific engagement problem, in the real world it is necessary to consider future engagements both in the short time frame (attacks normally come in waves, just as you are completing the engagement of the first wave a second appears…) and in the longer time frame (there are only limited resources available the loss of which changes the possible future engagement options). As such the understanding solution and subsequent decision to use that solution takes into account spatiality, temporality and alternative possible futures, placing the proposed solution into the higher level military plan.

We could consider this stage to be taking a 4 dimensional plan (3D spatial plus temporal) and then placing it in the much greater dimensional military decision context. It will be necessary to review how it changes both immediate combat options and possible future options. It is only once the decision to use that plan is taken, the system must then decide when and where to task our assets to undertake the engagements.

7.2.1.2 Dynamic FTEWA process

But FTEWA is a real-time dynamic problem: as the engagement progresses the problem space changes and the system needs to be able to identify when it is appropriate to change the planned engagement. To understand this we need to extend our process diagram to include what is happening in the engagement, see Figure 53:

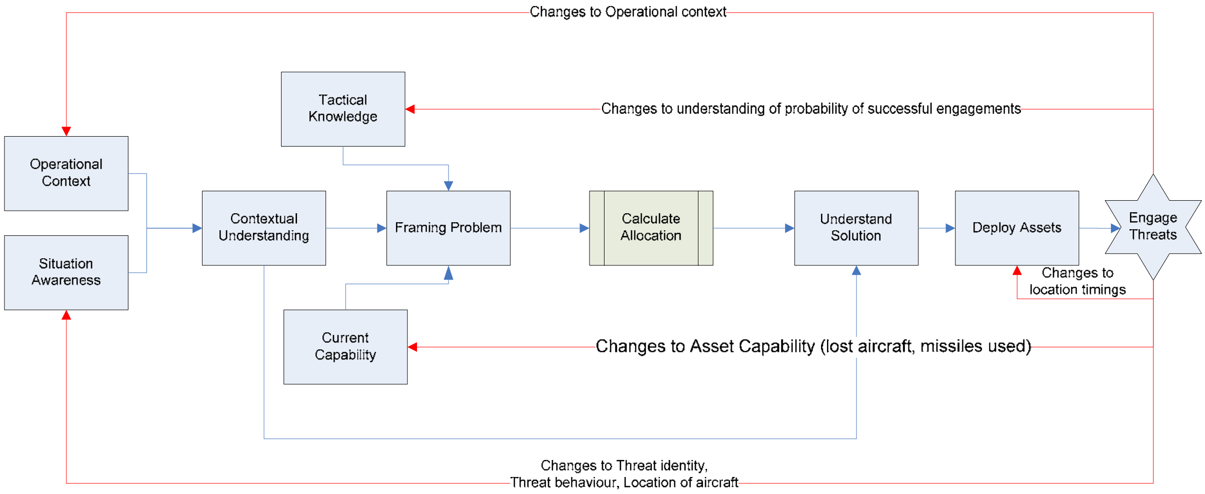

Figure 53 Dynamic FTEWA with feedback

As a consequence of engaging the threats we can recognise that most of the parameters used to frame the engagement problem are likely to change:

- During engagement missiles will be used,
- Assets may be lost,
- Threats may not be destroyed.
- It may be recognised that our tactical knowledge of the probability of successful engagement is incorrect.
- Our identification of the threats may be wrong: a fighter may have been incorrectly identified as a bomber etc. Changing both the priority for engagement and the tactical knowledge we need to apply when considering an engagement.
- The threats may not behave as anticipated, resulting in them not being where we expected them to be for an engagement.
- Our assets may not be where we anticipated they would be in order to undertake future engagements.
- New threats may appear that need to be engaged.
- The operational context may change; we may recognise that the opposition’s intent is not as initially anticipated.

This would imply that the FTEWA system is a nested closed loop system. But the system also needs to consider the consequences or implications of the outcomes of the evolving engagement in light of the higher level military plan.

7.2.2 Understanding the FTEWA system as a cognitive system

To understand the higher level processing we need to move away from classical control engineering techniques and to capture the problem as a cognitive system. If we use our engineering framework to map the three key cognitive capabilities of awareness, understanding and deliberation onto our FTEWA system we get the mapping shown in Figure 54.

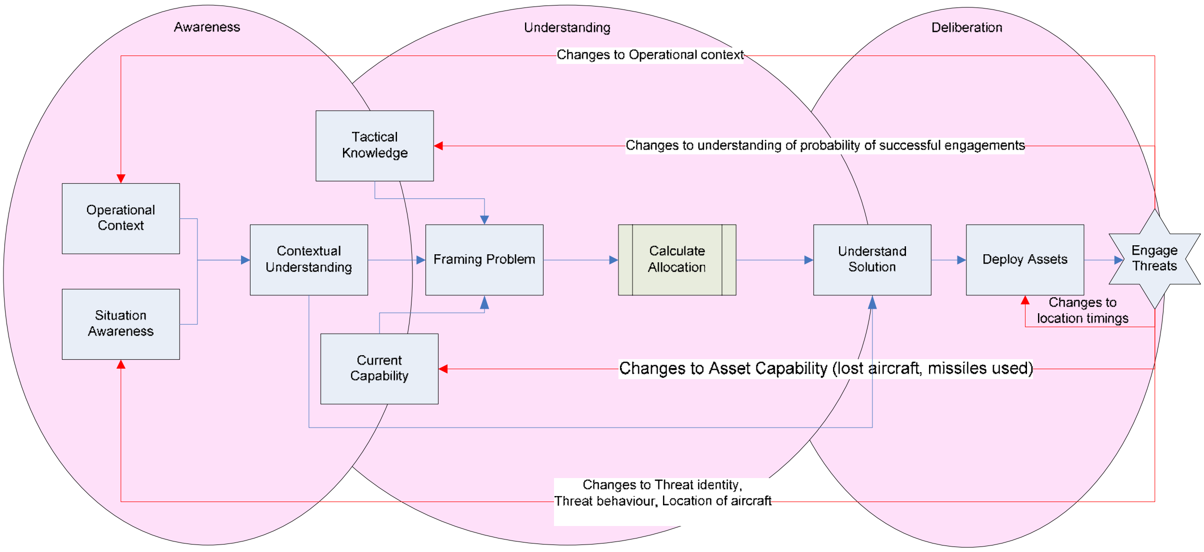

Figure 54 Mapping of framework to FTEWA system

By mapping the engineering framework onto our system we can see that awareness is focused on gathering and forming the information that is required to create understanding. Through the use of tactical knowledge the system can build on its observations to create understanding, which is used to frame the problem and to understand the solution. The understanding provides ability to place the proposed solution in the "n" dimensional military context and deliberation the ability to make choices that will influence the likely outcome of the engagement and the future military capability.

If we capture the FTEWA system in the form of a data flow diagram showing the flow of information between the three cognitive capabilities we could represent the system as shown in Figure 55. The construction of this diagram requires that engineer make explicit some the information items that are implied by the FTEWA process by doing this the engineer is able to draw out the uncertainties, possibilities and priorities associated with the three key capabilities.

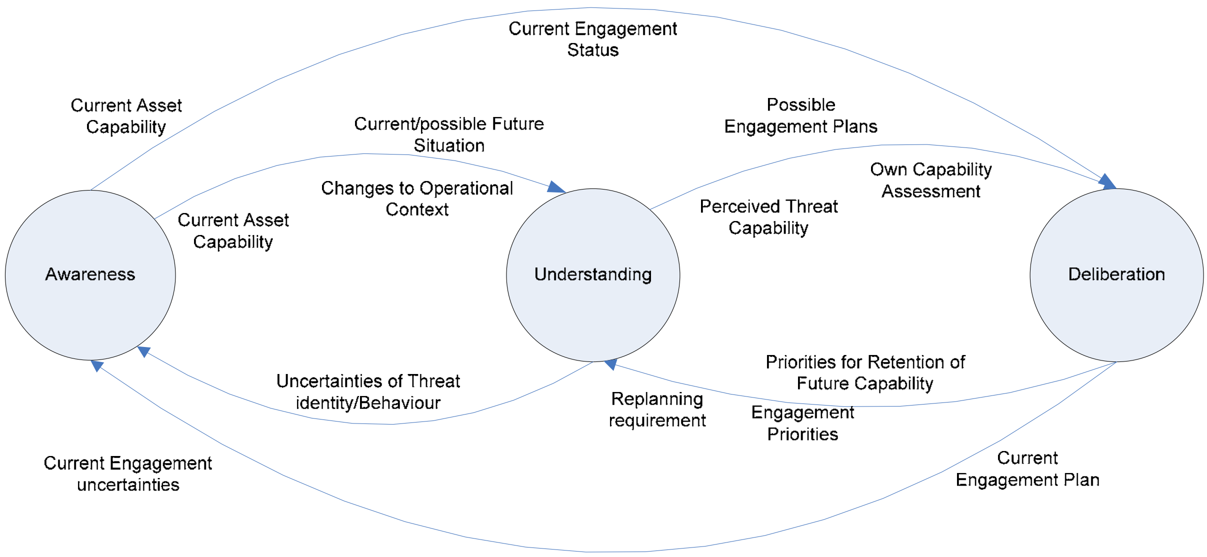

Figure 55 Conceptual information flows in the cognitive system

If we start at the left hand side of this diagram and consider the awareness capability. Awareness takes the responsibility of perceiving the current operational context in light of the system's purpose and delivering the information required to support the understanding and deliberation capabilities. This means that it needs to be able to report on the current asset capability, the current and projected future situation so that the system can understand if the current plan is still feasible. In addition there may be changes to the operational context such as changes to the rules of engagement that changes the contextual space in which the understanding is seeking to recognise possible choices for engagement. There is also a requirement for much faster reaction time from the decision making component if the current engagement is not achieving what was as planned, such as we are losing more assets than was anticipated and where that will have a longer term impact on future capability. This will trigger the need to change the engagement plan.

The understanding capability needs to take the evolving situation, comparing it with the anticipated evolution and make changes to the plans as needed, this will constantly change the available choices for engaging the threats and recognising what those engagement plans will mean for future asset capability. As part of this activity it is mapping observed threat actions onto behaviour to enable the recognition of intent (what is it trying to do). The intention of a threat, along with any corrections to its identity (e.g. aircraft type) will change the attributes of the threat changing the perceived threat capability which will change the deliberation space, which may trigger changes to the engagement priorities and require a replan.

The deliberation function thus is making both short term decisions and longer term decisions based on what it is being provided from the system's awareness and the understanding the system has formed. The chosen engagement plan is provided to the awareness to focus the way in which the situation is observed and subsequent information formed for use within the system. In interacting with understanding, deliberation is not only defining the priorities for engagement at the current time but also prioritising what capabilities need to be retained to maintain military capability for future engagements, which may mean that certain assets are not considered for inclusion in the current engagement.

This conceptual diagram (Figure 55) of our system exists at a high level, by breaking it down and mapping it onto the defined human roles, we can identify their individual awareness needs, the understanding that they will form as part of the system and the deliberation challenge that they undertake for us.

7.3 Understanding the Operator's Perspective

We now use the engineering framework to undertake a detailed analysis of the human roles in our system, then joining those roles to form a team model of the human system.

7.3.1 The FTEWA system

The current FTEWA system consists of seven different human roles working together to deploy the available assets to engage current threats. They are supported in doing this by what we can consider to be external devices such as the tactical picture, information sources and communication devices (which will be used to control or command the assets). The assets used to deliver the evolving solution are also external to the system in that they are at the other end of the communication devices. For our purposes we will define the system context to be:

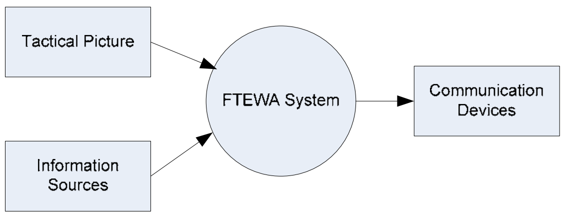

Figure 56 System Context

Internal to the system we currently have our seven human roles see Figure 57:

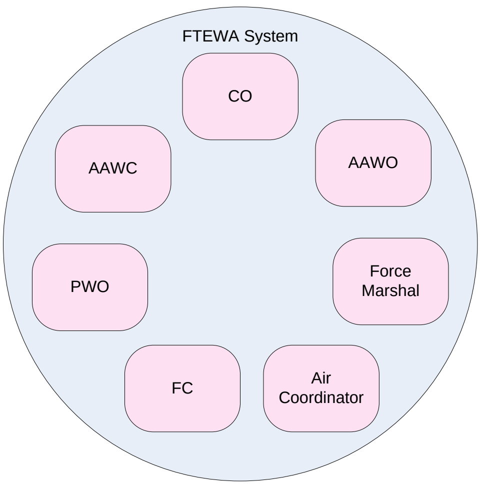

Figure 57 System Components

To understand the relationship between these components we can use the definition of the human roles associated with the FTEWA defined in 7.1.5 to provide the engineer with the first view of the cognitive functions provided by each of the humans and the possible awareness, understanding and deliberation requirements within our system:

Role	Task or function	Awareness requirements	Understanding requirements	Deliberation requirements
CO	Maintaining performance of Assets under direct command	Operational Context Potential engagement plans Current Engagement Status Current Asset capability	Future Military capability requirements Possible Future Force Capability	Prioritising or Maintaining future Military capability Approving or overriding engagement plan
AAWC	AAW planning Air Battle Management	Operational Context Current Operational situation	Tactics likely to be employed by threats Current tactics being used by threats	Deployment of aircraft to meet operational context. (to FC) Prioritisation of engagement based on current treat tactics (to AAWO)
Force Marshal	Safe Management of airspace Safe management of aircraft joining or leaving force	Aircraft Status and locations Threat locations Engagement plan	Current aircraft behaviour Threat behaviour Future aircraft locations	When and where to route aircraft.
Air Co-ordinator	Aircraft Management	Current Operational situation	Current aircraft tactics Threat	Aircraft tasking.

Role	Task or function	Awareness requirements	Understanding requirements	Deliberation requirements
		Engagement plan	behaviour	
PWO	Maintaining Force Capability[43] Conduct of subordinate aircraft	Operational Context Tactics being employed by Threats Current Asset capability Available engagement plans	Future Asset capability requirements Possible intent of threats Possible Future Asset Capability	Prioritisation of threat engagement Prioritising or Maintaining future Asset capability When or how to move to PTEWA
AAWO	Effective Operational employment of aircraft	Aircraft or Threat Location & Capability Status of current engagement against plan	Ability of aircraft to meet future planned engagement needs. Probability of engagement success	Effective deployment of aircraft: Engagement Plan
FC	Control of Assigned Aircraft	Aircraft or Threat Location Aircraft tasking requirements	Current own aircraft tasks, actions or behaviour	Aircraft tasking (when & where to inform)

Table 1 System cognitive functions provided by human roles

This table provides the basic identification of the cognitive focus of the individual roles involved. We can look to use this information to interview subject matter experts who have held these roles to enable us to capture the necessary information to be able to create models of the individual roles cognitive focus and information needs.

[43] We are using the term Force Capability rather than platform capability to imply the overall capability of the force. This includes ship borne assets as well as the airborne assets such as defending and refuelling aircraft.

7.3.2 Understanding the cognitive focus of the individual roles

In this section we consider the cognitive focus of each of the human roles[44] and the information flows that they require to be able to conduct those roles. This capturing of their cognitive focus is purely focused on the FTEWA challenge in reality each individual will have multiple concurrent foci which are beyond the system being examined, as such they do not form part of this analysis. The information flows have intentionally been left at a high level as the nature of the implementation of the flows will be context dependent and further detail was seen to be unlikely to add value for the purpose of this evaluation of the engineering framework.

Each of the roles will be considered in turn, initially a textual description of their responsibilities has been captured and then a data flow diagram, using the format of the engineering framework, to show their possible cognitive process.

CO

The CO has overall responsibility for the performance of own ship and for any assets allocated under his tactical command. Using the ship's manoeuvrability, sensors, weapons and assets the CO seeks to effectively fulfil the tasked mission. Once plans have been made and disseminated, the CO will normally control the ship and assets through the actions of his immediate officers. In the case of FTEWA this will be the AAWC. This allows the CO to take a higher view point on the engagement observing how the situation is evolving and to understand the changes to assets capability.

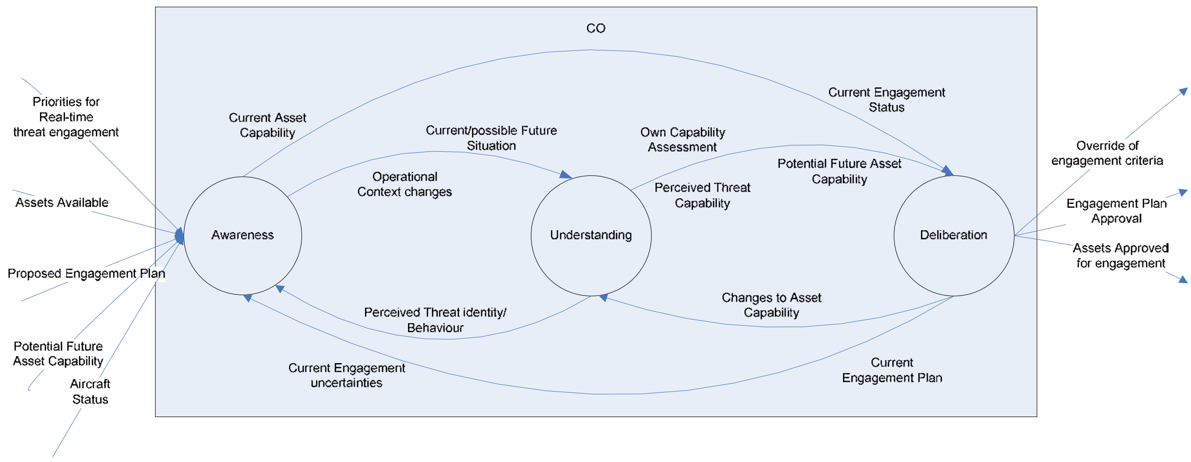

Figure 58 CO cognitive focus

They will be open to recommendations from their officers for re-prioritising engagement, enabling them to understand how the current and any proposed engagement plan relates to overarching military operation and to make decisions focused on the longer timeframe, see

[44] In normal activities this will be achieved by interviewing people who have held each of the roles but due to the constraints of this activity only a retired AAWO with responsibility for defining the original T45 FTEWA problem was available.

Figure 58. It is this viewpoint that provides the basis for them approving assets to use in an engagement, approving and overriding engagement plans.

AAWC

The AAWC has responsibility for planning the deployment of the force's air defence assets and for conducting the real-time air battle management.

To do this the AAWC needs to maintain a detailed awareness and understanding of the assets under their command, what they are currently capable of and when they will need to be refuelled etc. The AAWC's timescale of attention is the current engagement and the immediate subsequent operation. With this view they will decide which assets can be made available to engage the threats. As well as understanding what can be done with our own force assets the AAWC will apply their knowledge of tactics in interpreting the behaviour of any threats to understand what they are attempting to do and to prioritise their engagement.

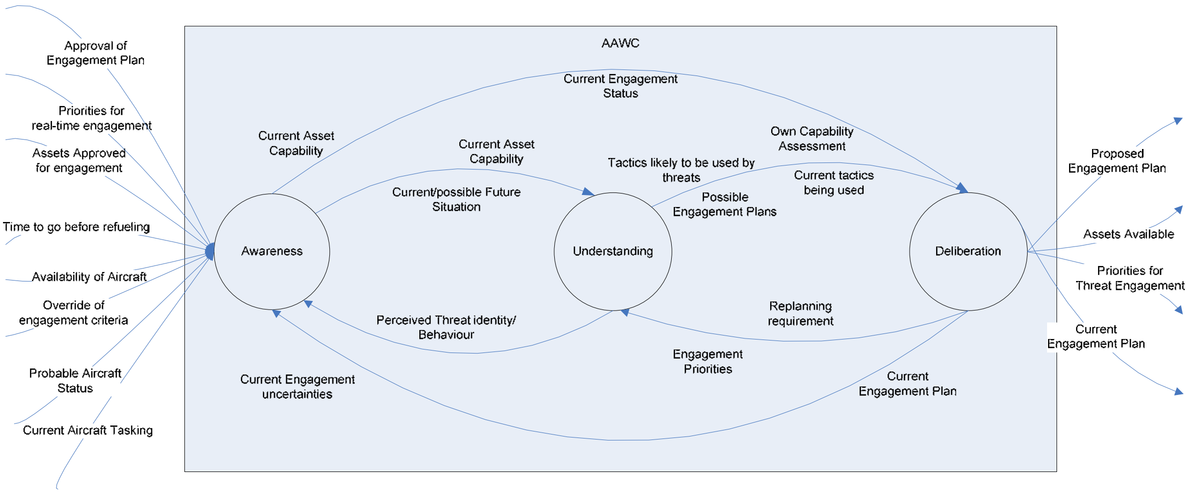

Figure 59 AAWC cognitive focus

If we look at the model of the cognitive focus of the AAWC, see Figure 59, we find that the diagram is very busy, so we can anticipate that there is a good probability that they will have a very high workload.

Air Co-ordinator

The Air Co-ordinator is a specialist in air traffic control and undertakes a significant role in the non combat tasking of the assets. They will take responsibility to task assets that are not planned into the current engagement to maintain their safety.

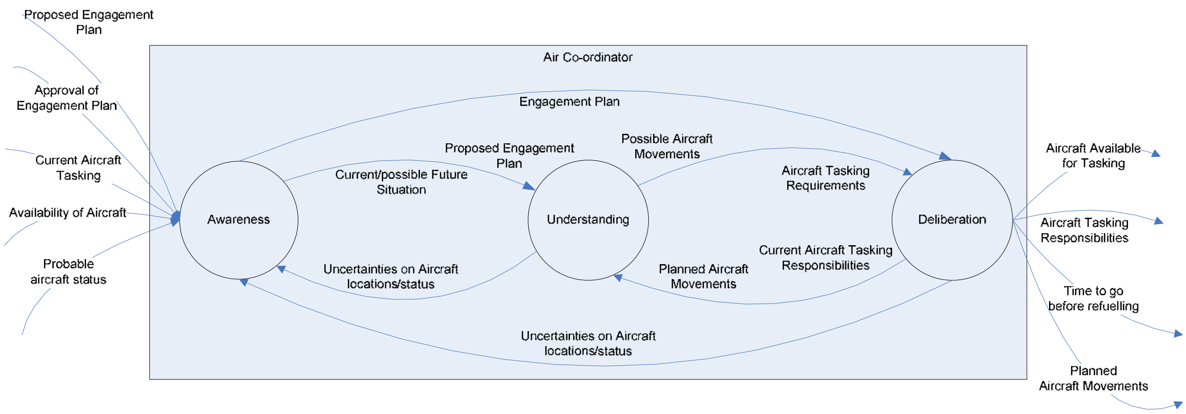

Figure 60 Air Co-ordinator's cognitive focus

To do this they need to be able to maintain a 4D model of the tactical situation, of all the current assets, how their position or status will change over time and of which Fighter Controller is controlling which aircraft at any point in time, see Figure 60.

Force Marshal

The key task of the Force Marshal is to process aircraft joining or leaving the force. In doing this they are required to have an understanding of the current tactical situation, to enable them to be able to plan when or where to bring new assets into the force and when or where to task them for leaving the force, without affecting the force capability, see Figure 61.

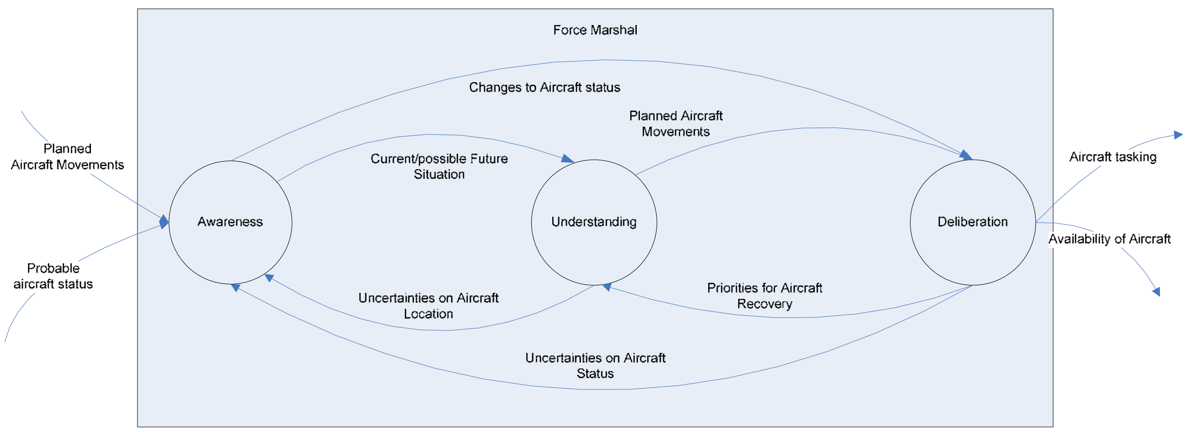

Figure 61 Force Marshal's cognitive focus

PWO

The PWO is responsible to the CO for the operational conduct of the ship and subordinate assets. The PWO is the command's primary adviser and is principally responsible for the ship's overall fighting effectiveness and safety. As such the PWO is responsible for initiating platform threat evaluation and weapon assignment (PTEWA) against any threats that are not planned to be engaged by the air assets or that fail to be destroyed in the air engagement.

For the PWO to know when and where it may be necessary to move to Platform engagement requires that they actively monitor the real-time air engagement and the progress against the engagement plan. The result is that they are monitoring the same types of information as the AAWC but it is to support a different set of decisions.

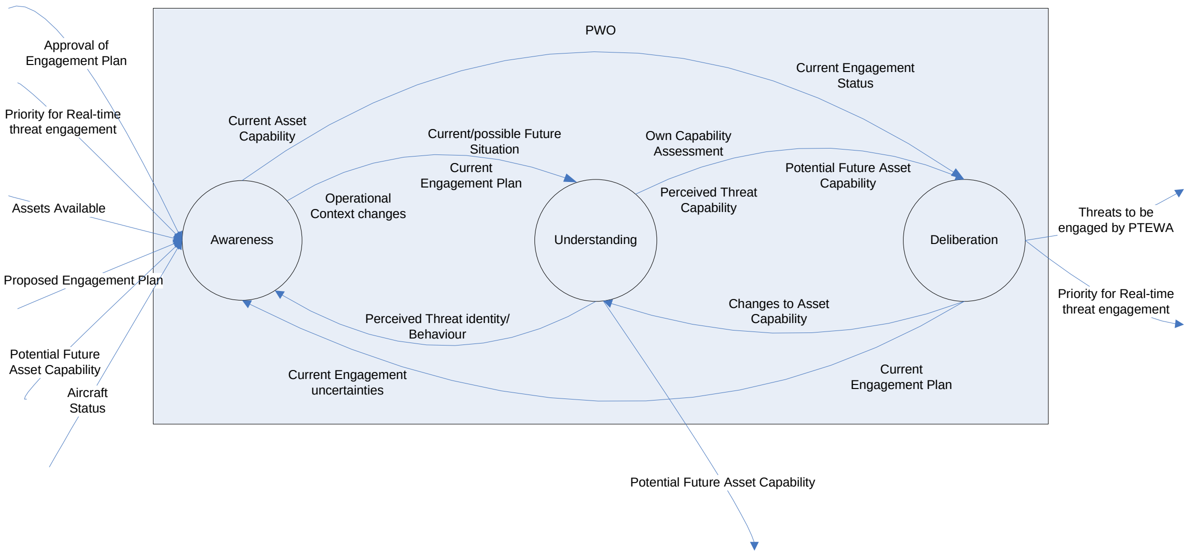

Figure 62 PWO cognitive focus

Even after it has become necessary to move to Platform engagement of a specific threat, where the platform is unable to engage a threat the PWO may request to reprioritise the air engagement plan to include it. If approved by the CO this asset will then form part of the PTEWA system running concurrently with the FTEWA system, under the same air management control used for FTEWA.

AAWO

The AAWO is responsible to the CO and PWO for the defence of own ship and the safe and effective use of air defence aircraft under own-ship control. This requires the AAWO to appreciate the tactical situation and the current engagement plan. The focus of the AAWO is the immediate and subsequent engagements for all aircraft against the engagement plan.

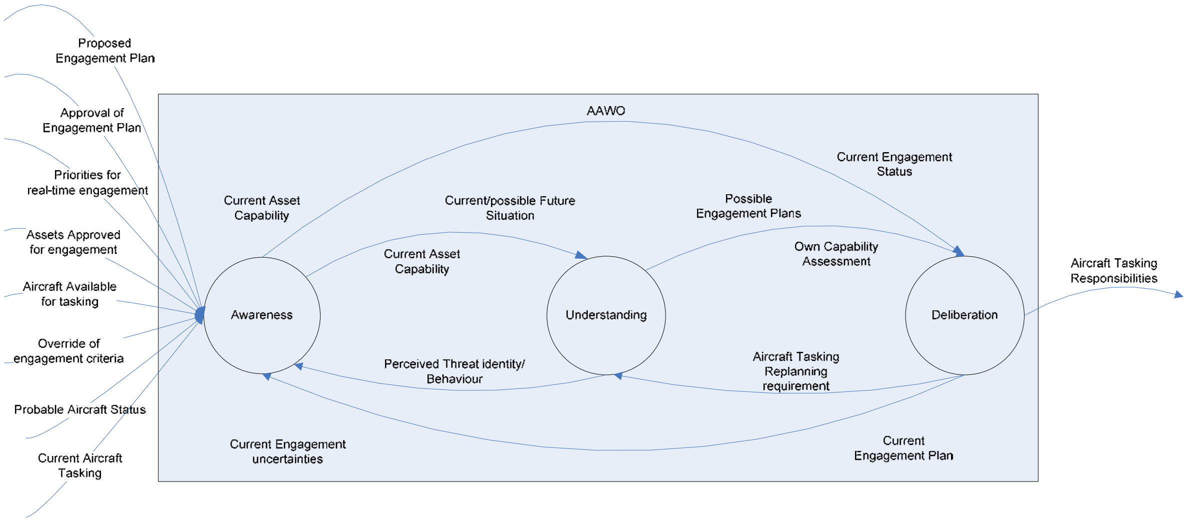

Figure 63 AAWO cognitive focus

In real-time the AAWO will allocate certain aircraft from the engagement plan to individual FC's for them to task for their next engagement. The AAWO would be responsible for the management of the transfer of aircraft control between FCs.

FC

The FC is responsible for the real-time control of their assigned aircraft: passing tasks at the appropriate time to assets and for monitoring their progress against those tasks. Where the FC's awareness is very much focused on the assets, where electronic status update is not available, they will be responsible for providing their estimate of the probable aircraft status including available missiles, fuel, damage etc to the wider team.

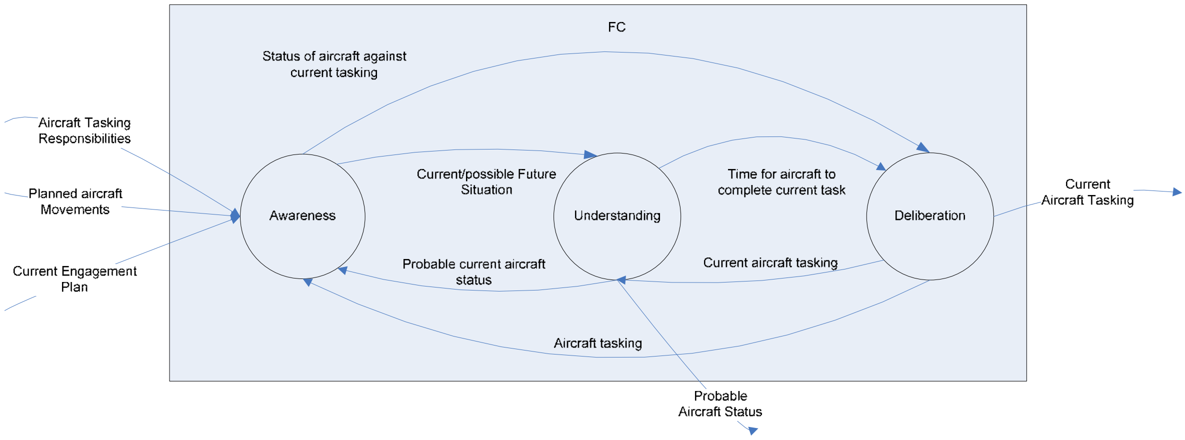

Figure 64 FC cognitive focus

Each of these seven roles work together to deliver the FTEWA system. To understand the complexity of the system we need to bring them all together and model them as a single team model, showing each of the information flows between the individuals:

7.3.3 The Team FTEWA Challenge

If we combine all of the human roles and information flows together on a single diagram[45], see Figure 65, we begin to get a better understanding of the dynamics and complexities of the FTEWA system[46].

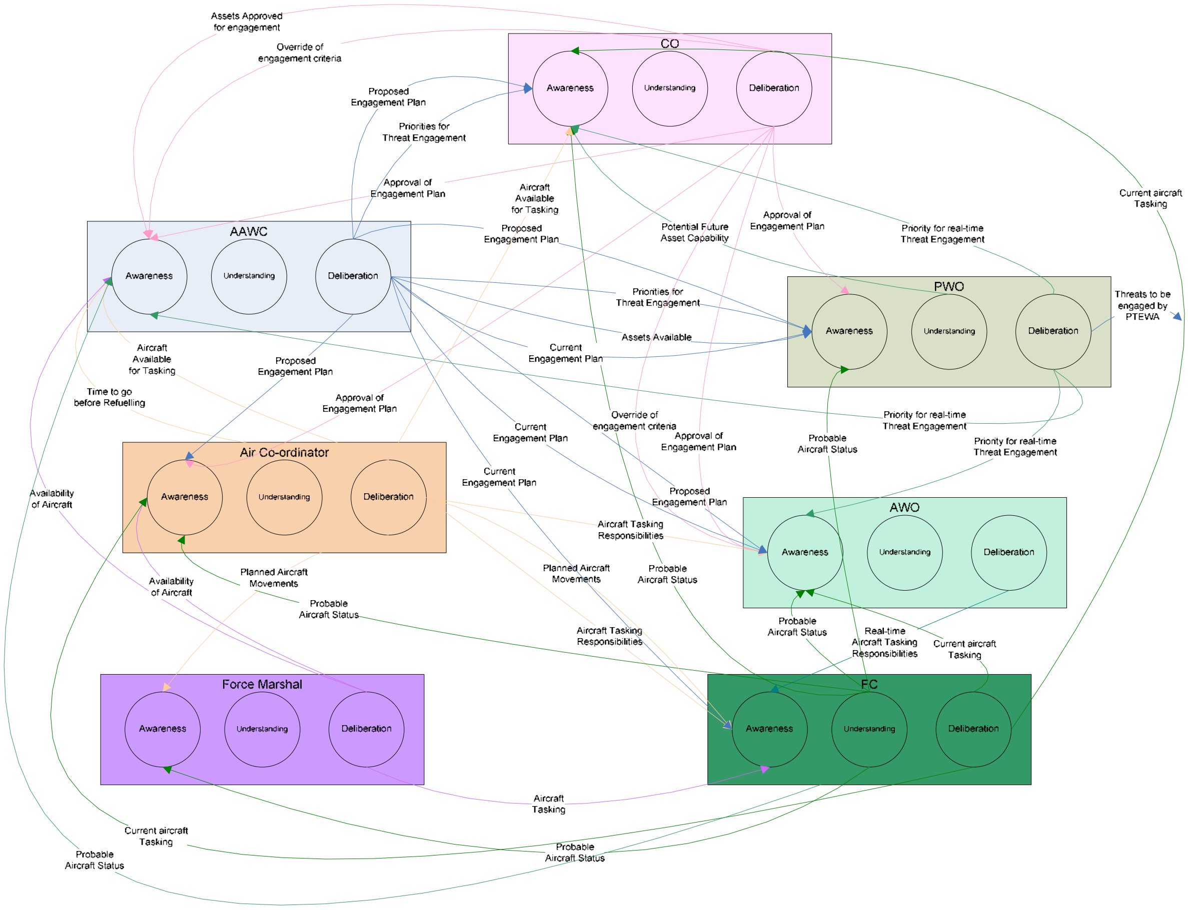

Figure 65 Human team model with Information flows colour coded for individual roles

An alternative means of capturing the information flows within the team may be to use a simple table such as in Table 2:

Role	Information Requirement	Source
CO	Priority for real-time threat engagement	PWO

[45] It is recognised that the paper version of this diagram is difficult to comprehend, in engineering teams such models are created, manipulated and viewed in an electronic tool.

[46] Note: This model captures the team model for a single platform (ship). In reality there are questions about how the plan should be communicated to other platforms and their interaction, which form part of the higher concept of operations. For the purpose of this work this has been excluded from this study but forms a key challenge for future studies.

Role	Information Requirement	Source
	Priorities for threat engagement	AAWC
	Assets Available	AAWC
	Proposed Engagement Plan	AAWC
	Potential Future Asset Capability	PWO
	Probable Aircraft Status	FC
AAWC	Approval of Engagement Plan	CO
	Override of Engagement Criteria	CO
	Assets Approved for Engagement	CO
	Priorities for real-time Engagement	PWO
	Time to go before Refuelling	ACO
	Availability of Aircraft	FM
	Probable Aircraft Status	FC
	Current aircraft Tasking	FC
PWO	Approval of engagement Plan	CO
	Priority for threat engagement	AAWC
	Assets available	AAWC
	Proposed Engagement Plan	AAWC
	Probable Aircraft Status	FC
Air Co-Coordinator	Proposed Engagement Plan	AAWC
	Approval of Engagement Plan	CO
	Availability of Aircraft	FM
	Current Aircraft Tasking	FC
	Probable status of aircraft	FC
AAWO	Proposed Engagement Plan	AAWC

Role	Information Requirement	Source
	Approval of Engagement Plan	CO
	Assets approved for Engagement	CO
	Override of Engagement Criteria	CO
	Priorities for real-time Engagement	PWO
	Aircraft Available for Tasking	ACC
	Probable aircraft Status	FC
	Current Aircraft Tasking	FC
Force Marshal	Planned Aircraft Movements	ACC
	Probable aircraft Status	FC
FC	Aircraft Tasking Responsibilities	AAWO
	Engagement Plan	AAWC
	Aircraft Tasking	ACC

Table 2 Information flows in the human team

Whilst this table has provided us with all the information items, their sinks and sources we must recognise that it does not capture the temporal or concurrent aspects of the information flows. To understand the system dynamics we must also recognise that the aircraft planning and management information flows will be present prior to the appearance of any threats, which is effectively before the FTEWA system is initiated. As the aircraft management information flows and the appearance of the threat(s) are contextual, it is meaningless for us to attempt to define a static instance of them.

It is meaningful to use the model to understand how the individual roles awareness, understanding and deliberation combine together in a cognitive system to create and execute the FTEWA plan. This model gives us a base line which we can use as an engineering tool to consider how and where we should deploy the algorithm. As well as the likely impact of that deployment on the potential cognitive contribution of the individual humans involved in our system and on that of the overall system.

7.4 Operational effectiveness

We next need to seek to identify the effectiveness measures for this system and examine the likely areas where the man or machine deployment and implementation may impact the achievable system effectiveness.

7.4.1 “Effectiveness” for a FTEWA system.

If we start by considering the overall system, we can recognise key effectiveness measures based on the system capability goals, from section 5.2.4:

> How Much: This could be the number of threats that can be planned to be engaged in any one plan.
>
> How Well: The percentage of threats that can be successfully engaged (this is a scenario specific measure).
>
> How Fast: The time needed to create, understand and to gain approval of an engagement plan. It could also be a measure of the time needed to successfully engage all of the threats.
>
> How Long or Often: Can a plan be created and from it continue to generate new plans with an acceptable probability of engagement success over time.
>
> How Quickly: What is the time required to replan, understand and gain approval to use that plan.
>
> When: The ability to recognise the need to replan.
>
> At what cost: The impact of defining the engagement problem on current operations. The resulting military capability for use in future engagements. The impact on human workload.

These measures can be applied to the human system captured in the previous section and we can also make use of them when we consider the deployment of the algorithm.

7.4.2 Delivering “effectiveness” in the FTEWA system

The effectiveness measures identified for the existing system are a result of the individual human’s abilities and the dynamics of the information flows within the system. We must first recognise that the human’s abilities are an emergent property of their training, knowledge and experience, which are specific to each individual; consequently it is only appropriate for us to consider them in general terms. The second item, the information flows, are more useful as they can be defined and are something that we can through the system design process change and measure the consequence of that change.

We can recognise two types of information flow: push (broadcast) and pull (requests). The effectiveness of both of these types of information flow can be measured: for information push we can measure the time it takes the other members of the team to recognise and make use of the information. In certain circumstances there may also be temporal decision windows in which the information may be required, where earlier or later delivery may not be appropriate. For information pull, the time it takes the respondent to provide the information that has been asked for. We can also measure the amount of wrong information that is being used. Where wrong means that the data could be out of date, incorrect etc.

One of the challenges of measuring the effectiveness of the current system is that the engagement plan does not exist as a tangible item. The plan is a virtual plan in the minds of our people, which is being rapidly adapted as the situation evolves. But this lack of a tangible plan itself impacts the system effectiveness as time is required for the team to discuss the engagement, for them to each form a mental model of the engagement plan and to reduce errors in their understanding. This challenge has encouraged the use of simple (and hence easy to understand) engagement tactics, which has the disadvantage that if we can easily understand them, then .it is probable that the threats will find it easier to anticipate them, which itself is a reduction of system effectiveness.

7.5 Understanding how our system design contributes to human operational effectiveness

As we look towards the deployment of the MP001 algorithm we need to consider what shape the new system may take, irrespective of the implementation of the design, we can identify that the algorithm can influence a number of the system effectiveness measures as well as the human's abilities to form their awareness, understanding and deliberation.

How much, How Well, How Fast:

> If we consider the challenge of calculating a plan to engage threats, it is highly likely that the machine will be able to calculate solutions quicker and for much bigger problems than a human can. But this efficiency will need to be balanced with the time required for the human to understand the offered solution and to approve it.

How Long or How Often:

> We can recognise that the machine will be able to continue to calculate answers for as long as is requested, far into the time frames where humans will be suffering from fatigue when their error rate will have increased. Whilst we can recognise that the machine may be creating valid solutions, we need to recognise that human error may be affecting the definition of the problems that they are presenting to the machine, their ability to understand any solution and their ability to recognise when to replan.

How quickly, when and at what cost.

> The real-time engagement challenge requires not only someone to know when to create a new plan but for the remainder of the team to become aware of it, for command to understand it, approve it and then for the rest of the team to understand it in light of the evolving situation so that they can run with it.

The algorithm can also optimise on one of three different specific criteria,:

> The time to complete the engagement.
>
> To minimise the number of assets that may be lost during engagement.
>
> To minimise missile usage.

Each of these criteria has different consequences and changes the option space for the higher levels of the military planning. At the lower level they provide the criteria against which members of the team will decide when it may be necessary to replan if the engagement is not evolving as anticipated.

If we look across all of the system effectiveness parameters the key challenge is to successfully engage multiple humans in the machine generated plan. In the next section we will investigate where it may be possible to deploy the machine technology in the human team and the information that it needs to provide to each of the humans.

7.6 A Potential system design

Using the team model developed in section 7.3.3 and by using the framework we now investigate a potential system design that includes the use of the algorithm and consider how the associated design decisions may affect the human's cognition.

7.6.1 The Context and Top level system diagrams

The introduction of the algorithm does not alter the System Context and the diagram in Figure 56 is still valid. The top level system diagram is modified to include the algorithm, see Figure 66:

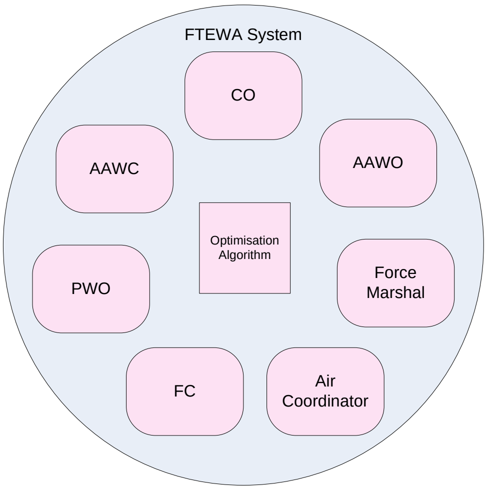

Figure 66 System Components including the Algorithm

7.6.2 Understanding the information flows interacting with the algorithm

We can now look to capture the information flows into and out of the optimisation algorithm:

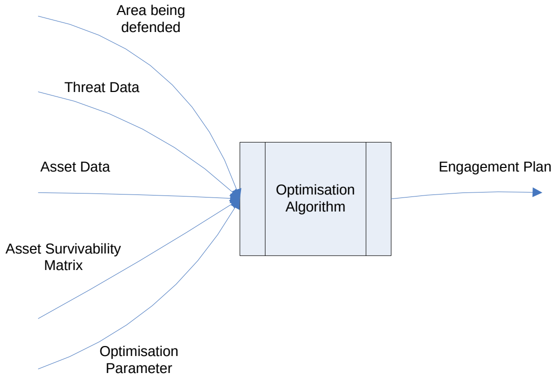

Figure 67 Information flows for the optimisation algorithm

Clearly these information flows do not directly match the human information flows, somehow we need to map between them and not all of the data required by the algorithm needs to come from members of the human team. Some of the data sources that the humans are using will be directly accessible by the machine technology. In this instance we can recognise that the combat system (CS) Tactical Picture data is being used to form the human's awareness of the situation and is directly available to the algorithm.

With this view we can identify a possible mapping of the information items as shown in Table 3.

Algorithm Information label	Data Item	Human Information flow that contains elements of the data item	CS or Role associated with that information item
Area Being Defended	Area Being Defended	-	CS
Threat Data	Location	-	CS
	Speed	-	CS
	Direction	-	CS
	Priority for engagement	Priorities for Threat Engagement	CO, AAWC
Asset Data	Location	-	CS
	Speed	-	CS
	Direction	-	CS
	Number of Missiles Available	Probable Aircraft Status	FC or CS
	Available Flight Time	Probable Aircraft	

Algorithm Information label	Data Item	Human Information flow that contains elements of the data item	CS or Role associated with that information item
		Status	FC or CS
Asset Survivability Matrix	Probability of a specific asset type successfully defeating a threat type	Tactical Knowledge	CO, PWO, AAWC
Optimisation Parameter	Cost or Time or Remaining Assets	Override of engagement criteria	CO
Engagement Plan	Matrix containing: Asset number, threat for engagement, engagement location, probability of success	Proposed Engagement Plan	CO, PWO, AWO, AAWC
Area Being Defended	Area Being Defended	-	CS
Threat Data	Location Speed Direction Priority for engagement	- - - Priorities for Threat Engagement	CS CS CS CO, AAWC
Asset Data	Location Speed Direction Number of Missiles Available Available Flight Time	- - - Probable Aircraft Status[47] Probable Aircraft Status	CS CS CS FC or CS FC or CS

[47] This information may be able to be provided electronically via the CMS if adequate communications exist if not then the FC will have to estimate the value and enter it into the machine.

Algorithm Information label	Data Item	Human Information flow that contains elements of the data item	CS or Role associated with that information item
Asset Survivability Matrix	Probability of a specific asset type successfully defeating a threat type	Tactical Knowledge	CO, PWO, AAWC
Optimisation Parameter	Cost or Time or Remaining Assets	Override of engagement criteria	CO
Engagement Plan	Matrix containing: Asset number, threat for engagement, engagement location, probability of success	Proposed Engagement Plan	CO, PWO, AWO, AAWC

Table 3 Information exchanged with the algorithm

This table has enabled us to identify that five of the human information flows map well to five of the algorithms data requirements. The CS is able to provide automatic access to situation data (location of the defended area, threat or asset dynamics or location). We also have a new item the "asset survivability matrix", which is equivalent to the human's tactical knowledge, which is providing information about the probability of a specific type of asset being able to successfully engage a threat type.

If we look back at our model of the information flows across the human team, **Error! Reference source not found.**, we find that many of the information flows do not directly flow through the algorithm, e.g. whilst the PWO identifies the priority threats for real-time engagement, the CO needs to approve those priorities, which places this flow outside the scope of the flows interacting with the algorithm.

7.6.2.1 Mapping the information flows onto the cognitive system

If we go back to our human team system model from **Error! Reference source not found.**, we can identify those flows that are going to be **directly influenced** by the introduction of the algorithm. To aid our understanding in Figure 68 the flows that are going to be influenced by the algorithm have been identified in red, those left in blue should be unaffected. :

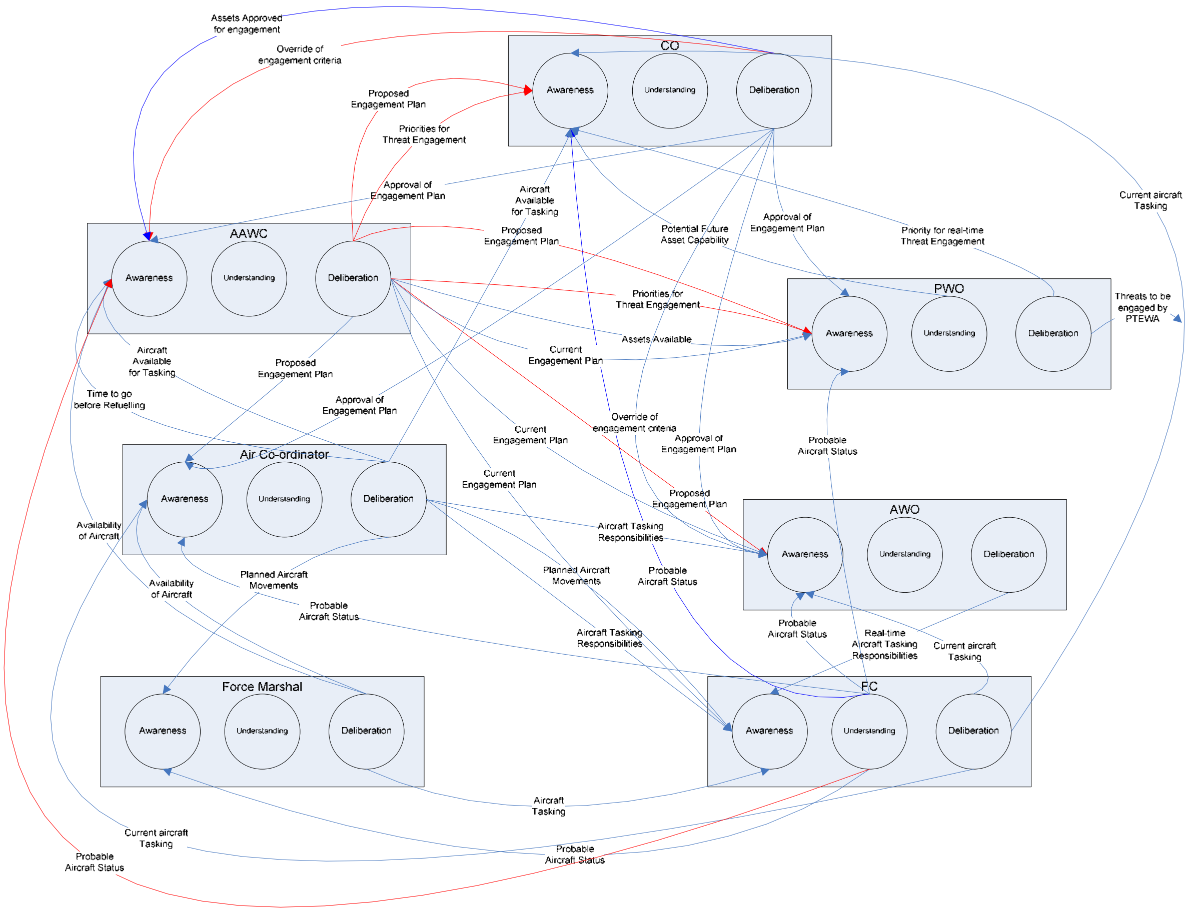

Figure 68 Information flows that interact with the algorithm

From this we could assume that the most appropriate individual to control the execution of the algorithm will be the AAWC. We can also recognise that one of the required information flows originates within the AAWC.

To consider the deployment of the algorithm we also need to consider those flows that help **shape the problem**, these are the data flows that correspond to the input adapt items for the algorithm. So we are interested in the data flows that define the assets that are available and those associated with the approval to use those assets, see Figure 69:

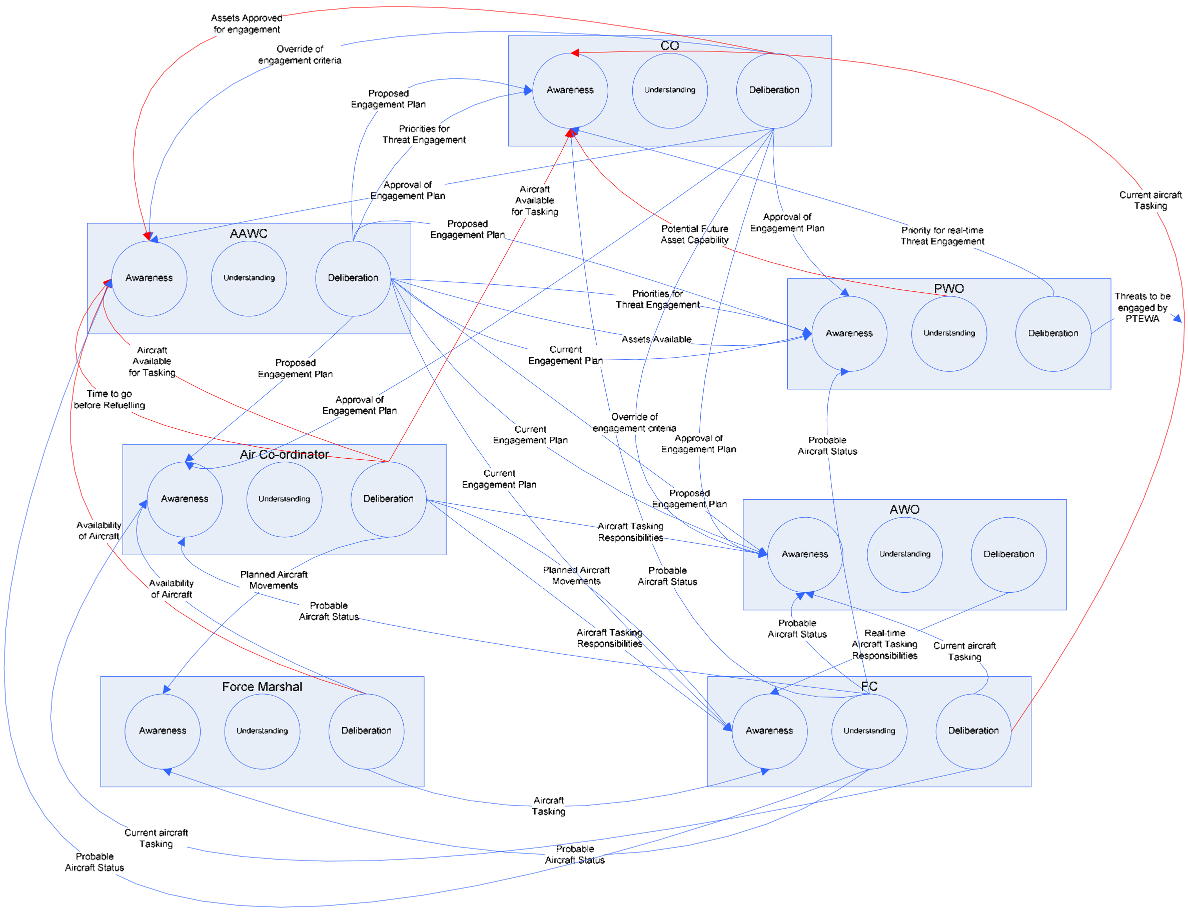

Figure 69 Information flows that help frame the problem

We also need to recognise who needs access (**delivery of the result**) to the engagement plan that will result from the use of the algorithm, both prior to approval and once it is approved, see Figure 70:

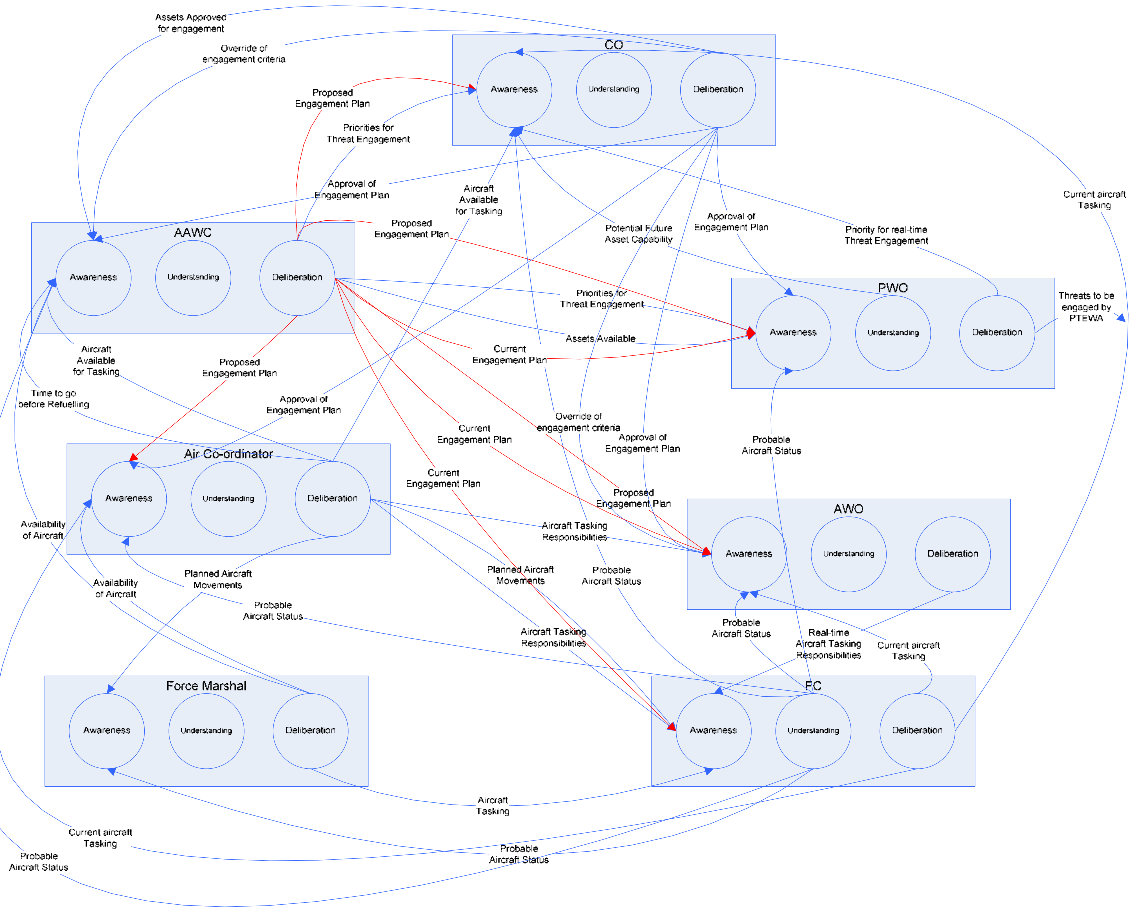

Figure 70 Delivery of information from the algorithm

If we extract all the individual human roles and the information flows that relate to the algorithm we will end up with a much simpler data flow diagram, see Figure 71:

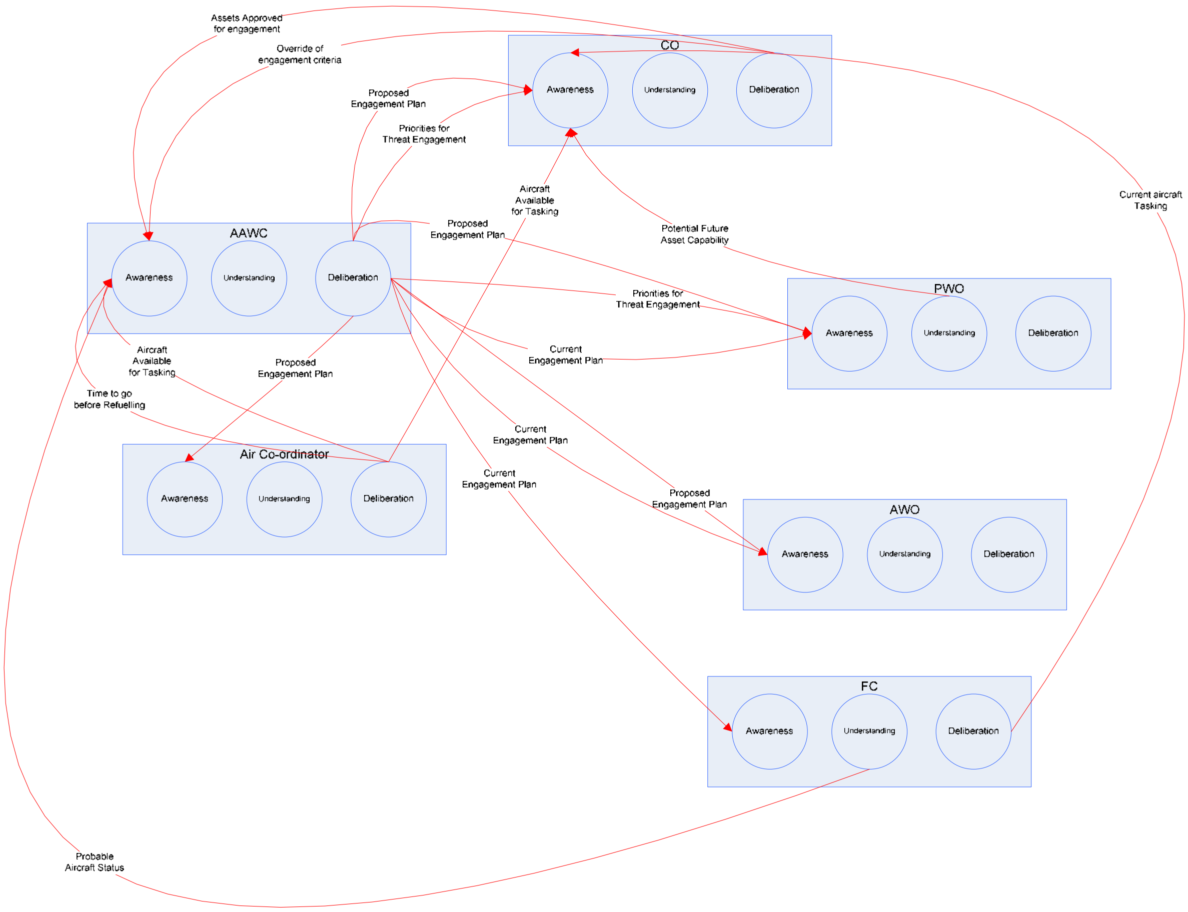

Figure 71 Information flows needed to support the algorithm

This diagram provides not only the information flows between the humans and the algorithm but also the immediately related flows within the human team. It is this diagram that we will now use to investigate the deployment of the algorithm.

7.6.3 Human Centric System Considerations for the deployment of the algorithm

To understand where to deploy the algorithm we must seek to understand the potential impact of the machine technologies capability on each of the involved human roles. A basic principle that we need to take into account is that we want to minimise the impact of the deployment on the human team as much as possible, because whilst we are only looking at the FTEWA system, the humans in our system are concurrently involved in other systems and any major changes are likely to have knock on consequences in those systems as well.

If we consider what the algorithm does, we can seek that its deployment has the potential to influence the human's cognitive contribution and what we need to do is to identify where any miss matches may occur, their form and how it may be possible to meet the human's cognitive need. If we take each of the key cognitive capabilities in turn:

Awareness: The algorithm is effectively going to be the information source used to form some of the human role's awareness. Whereas with a human as the information source they can be questioned to provide additional information, we must consider the full human awareness needs as part of the deployment challenge and to predict what addition information may be needed.

Understanding: Understanding uses an individual's knowledge to interpret and project based on their current awareness. In Table 3 we identified that the algorithm is "using" a type of knowledge which we have called tactical knowledge, this is the same knowledge item that was identified in Figure 52 and knowledge that the CO, PWO and AAWC are using. Consequently the deployment of the algorithm has the potential to erode the need for these roles to learn or form this type of knowledge and in the longer term may influence their ability to form understanding and change the results of their deliberation.

Deliberation: The algorithm is only going to calculate an answer based on the information that is provided to it. So by deploying the algorithm we need to add an addition human cognitive task to review the data going into the algorithm and to decide how to change it to meet the evolving situation. It is this human modification that is going to define the optimisation parameters and potentially, if the plan is enacted change the available future military capability (remaining assets).

We also need to recognise the risks associated with the deployment of such an algorithm: human's having recognised that a machine is capable of doing something have a natural tendency to "let the machine get on with it". This behaviour towards this type of technology is not appropriate as the algorithm only optimises against the criteria and values given to it. The algorithm has no way of recognising if the contextual circumstances change so it will always remain dependant on the humans to define the appropriate problem each time a solution is required. Human complacency will cause the algorithm to deliver inappropriate plans to the combat situation.

7.6.3.1 Understanding the awareness needs.

If we first consider the human awareness needs. The algorithm is producing an engagement plan which consists of proposed locations or times for specific assets to engage specific targets and a probability for success. The CO, AAWC, PWO and AWO need access to the proposed engagement plan, they will use the plan to form their individual awareness of how the current situation may evolve if that plan was approved.

What they will do with this awareness (i.e. form understanding) is different for each of them and this may effect the supporting information that should be provided with the plan or how it is presented to them:

The CO needs to be able to understand:

- Is the proposed engagement likely to be successful?
- What is the likely situation after enacting the plan (Where are both my own and the oppositions assets likely to be).
- When will it be appropriate to move to PTEWA?
- If the plan is approved what military capability will be available in the future?

The AAWC needs to be able to understand:

- Is the proposed engagement likely to be successful?
- When or where any engagements may take place.
- Where the assets will be in the future and their potential capability (number of missiles remaining for engagements, time to go), in order to plan future engagements
- When and why it may be necessary to create a new engagement plan.

The PWO needs to be able to understand:

- Is the proposed engagement likely to be successful?
- What threats may be left to be engaged by PTEWA?
- When could PTEWA safely start threat engagement? (Without endangering our own assets)
- If specific remaining threats cannot be engaged should an alternative FTEWA plan be requested?

The AAWO needs to be able to understand:

- If the plan is approved, how to task the FC's.
- When and against what, to commence PTEWA planning.

If we take an abstract view of these understanding requirements we need to deliver three things:

1, The ability to gain very quickly the likely outcome, potential remaining assets and probability of success.

2, The ability to fast forward the planned engagement showing the aircraft movements and probabilities of success in each engagement.

3, The ability to identify potential decision points for replanning.

We now need to consider how the engineering design could meet these additional requirements. Whilst we can recognise that a human factors specialist may find better solutions, in seeking to find that solution they may have not considered these requirements or that these requirements lie with more than one individual involved in delivering the purpose of the system.

7.6.3.2 Understanding the understanding needs

Human understanding in our system is all about enabling the humans to go beyond what is being observed through their awareness and to be able to recognise possible future evolutions of the situation. We can consider that this is achieved through them applying their knowledge. We have also identified that the algorithm requires tactical knowledge to be able to calculate the probability of any specific asset type being able to successfully engage a specific target type, which is called the asset survivability matrix for the algorithm. Both the humans and the algorithm are potentially using the same knowledge item and there is the possibility that if the humans become reliant on the algorithm they may no longer retain this knowledge (or the ability to apply it to the situation), clearly this is undesirable. So we can define a requirement to seek to actively engage the human in use of this knowledge to maintain their abilities.

But what of the knowledge item that we are to provide the machine? Is it a static piece of knowledge or dynamic? So long as both sides continue to use the same type of tactics we can consider this to be pre-definable, at the very least not something that would normally require changing during active combat. If we consider the potential size of this item of knowledge then we could identify that the number of different aircraft types available to any opponent is actually relatively few, which would imply that this is a relatively small definable item. But the data itself the ability for one type of aircraft to engage another is contextual; we can recognise that the ability for the opponent to successfully use a specific aircraft type in an engagement will vary due to training, e.g. USA pilots are more likely to be able to use a F22 more effectively than say the Iranians. So it would be desirable to be able to, at an appropriate time, alter the tactical knowledge to reflect this, which could enable the algorithm to open up opportunities to plan to utilise less valuable assets to create an engagement plan.

7.6.3.3 Understanding the deliberation needs

The humans in the team are responsible for providing the information that defines the problem that the algorithm solves. The algorithm we are investigating is stochastic, one of the characteristics of which is its sensitivity to changes to its input parameters. This means that small changes in the input parameters are likely to have a large change in the planned solution (although not necessarily in the probability of overall success). So we need to look at each of the parameter: the algorithm is using in turn and who is defining them and on what basis.

The first consideration for the CO is to prioritise the engagement and allocate threat levels for the incoming threats. This allocation will be based on the CO's understanding of the tactics and intent of the opposition.

Having decided upon the level of threat for the current operation the choice is then to decide which of the available assets should be made available for FTEWA and which to retain for other responsibilities. This requires the CO to use their tactical knowledge not only of how this engagement may evolve but of the future tactics and engagements that the other side may plan. The approved assets, which are unlikely to be all of the available assets, are then available for entry to the algorithm.

The final data items required by the algorithm relate to the assets: their location, velocity and their status, which should be available automatically from the Combat System.

7.6.4 A possible deployment of the algorithm

If we look back at the diagram in Figure 71, we can see that the primary roles that are associated with the algorithm are the CO, PWO and AAWC, with the AWO requiring access to the proposed engagement plan.

If we are seeking to minimise the impact on the team we could consider that both the AAWC and the algorithm require the same information feeds from the CO: the assets approved for engagement and override of engagement criteria. In combat situations the CO will have a multitude of considerations and is unlikely to be able to dedicate sufficient of their awareness to maintain a detailed understanding of the individual asset status. We have also identified the AAWC as the officer who is focusing their awareness on the potential evolution of the engagement(s) and who has the responsibility currently for recognising the need to create new engagement plans. It would therefore seem appropriate to associate the algorithm with the AAWC.

We can now look to take our information flow diagram[48] from Figure 71 and insert the algorithm looking at the mapping of the new data[49] items.

[48] We have moved to using the term information flow diagram rather than data flow as the information flowing in this diagram has been processed by the humans in light of the current context.
[49] We are using the term data for flows that go into or are provided by the algorithm because the algorithm is not contextually aware.

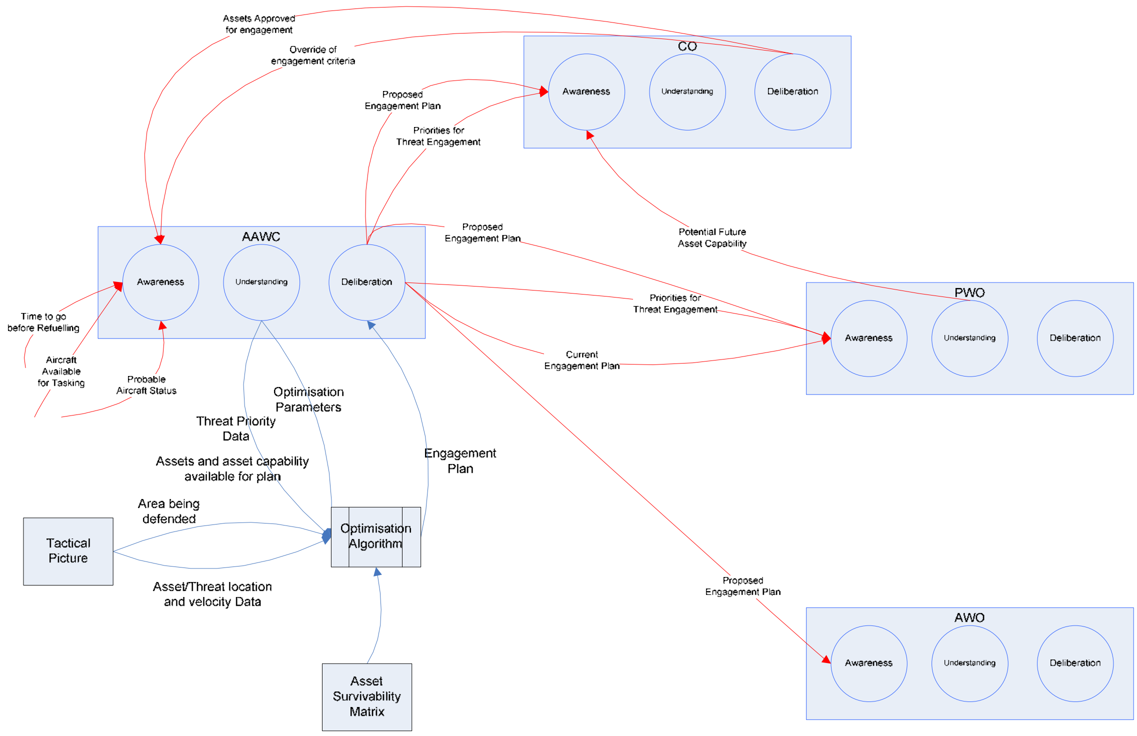

Figure 72 AAWC basic information exchange with the algorithm

We can see that the **information flowing to the AAWC is different from the data required by the algorithm.** For the AAWC to transform the information received from the other crew members into the correct data form for the algorithm, they will need to use some new knowledge which relates to the algorithm and how it may use the data provided to it. They may well choose to modify the data set provided to the algorithm, e.g. reduce the number of assets to be considered further, to minimise the calculation time for the algorithm or to simplify the human understanding of the solution.

This information flow diagram does not capture any of the additional information items that were identified in section 7.6.3 because the algorithm does not support them. These additional information items need to be supported by enhancing the command system functionality which has been shown in Figure 73 as "wrapper" around the algorithm:

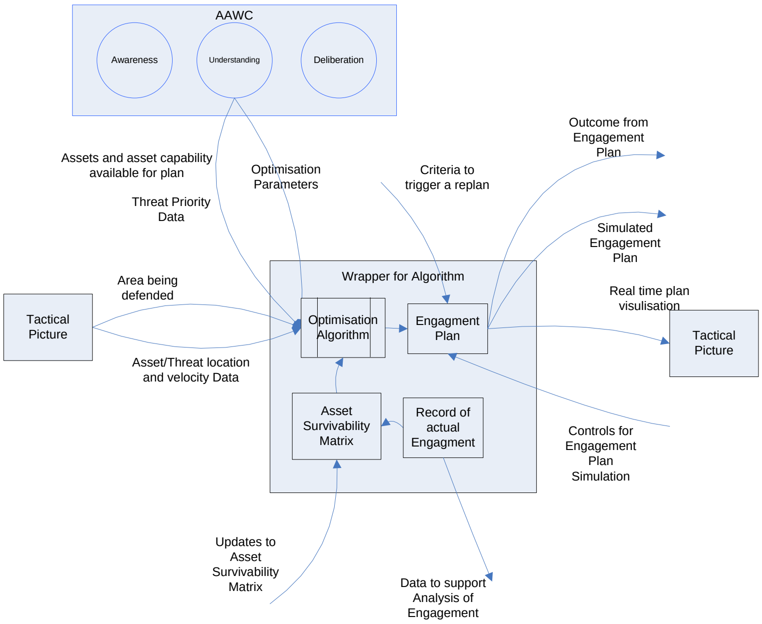

Figure 73 Wrapper for algorithm to support additional information items

The wrapper would provide the interface for the AAWC to define the problem, the means of the team engaging with the engagement plan and for setting up and reviewing the asset survivability matrix.

In Figure 72 there is a single instance of the outcome of the engagement plan, which would be provided to the CO, AAWC, PWO and the AWO. There could be a number of alternative potential engagement plans being considered plus the current plan, but for clarity only one is shown. For the purposes of the humans reviewing and understanding an engagement plan there will potentially be the need to simulate the plan in different ways to meet the needs of each of the individual roles. For speed and efficiency it would be desirable that not only could they share the same simulated plan to gain common understanding but they could also independently simulate the plan to meet their own understanding or decision needs.

To support the human understanding of the evolving situation against that which was planned, for this the engagement plan could be simulated in real time and over laid onto the tactical picture. This would enable the team to visually engage with the plan during the evolving combat and rapidly recognise or respond to needs to change the plan. This real-time over lay could also provide the necessary engagement and support for the FC to enable them to task the assets as required.

At the bottom of the figure in the wrapper we see functionality that supports the recording of the actual engagement and the ability to replay for the purpose of the teams' debrief. It is from this debrief that a member of the team, probably the AAWC, could be actioned to update the Asset Survivability Matrix (tactical knowledge).

Over laying the algorithm and the wrapper onto the human team we can see how the wrapper supports the human cognitive process, see Figure 74.

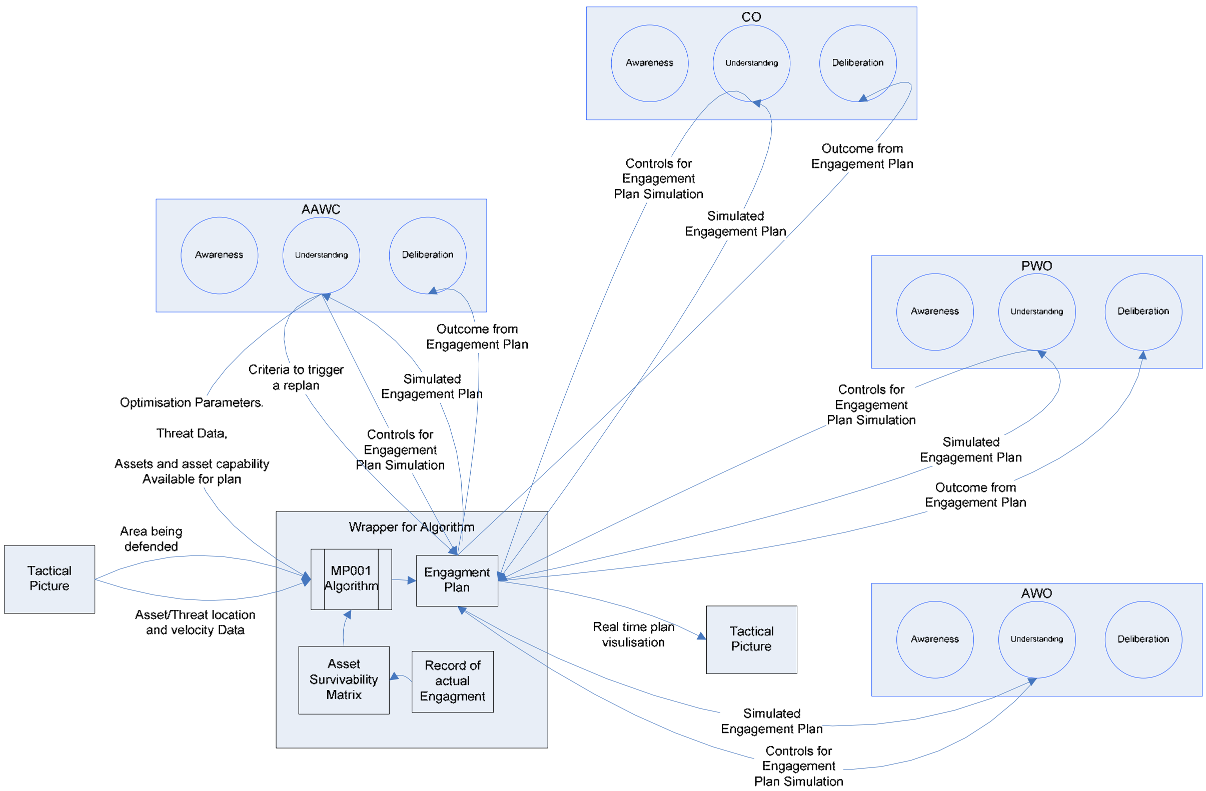

Figure 74 Interaction of wrapper with human cognitive processes

For the purposes of understanding the individual human role's interaction needs with the wrapped algorithm we can use the engineering framework to generate models for each of the human roles.

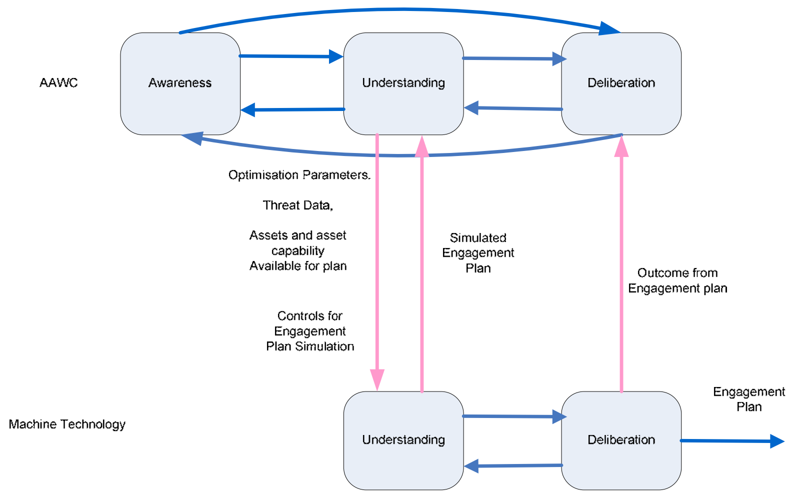

Figure 75 AAWC interaction with machine technology

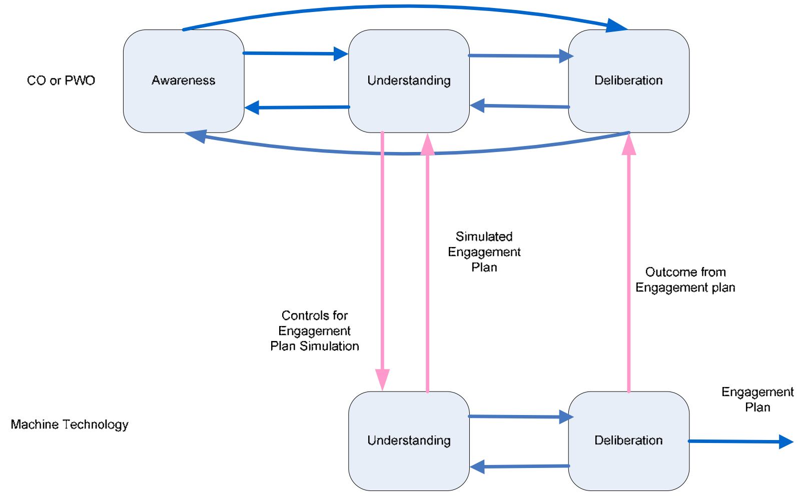

Figure 76 CO or PWO's interaction with machine technology

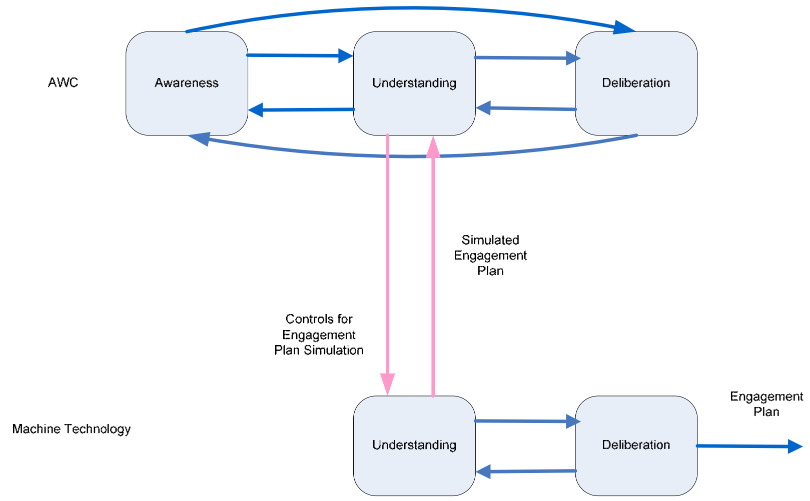

Figure 77 AWC's interaction with machine technology

These diagrams provide a clear indication of the new human cognition support requirements that can now be provided to the human factors team to be considered as part of their design of the HMI.

We should note that the choice of wrapping the algorithm in additional machine functionality, rather than modifying the algorithm, is purely an implementation choice. It enables the optimisation algorithm to remain generic and would allow the generic algorithm to be maintained independently of the system design, whilst the wrapper itself can be designed to embrace the culture of the system into which the algorithm is being deployed.

Without seeking to implement this design and conducting evaluation experiments just how effective this design is, means the effectiveness of the result is open to conjecture. But what we can do is to compare it with the recommendations resulting from a human factors study that was conducted concurrently to this work. This will enable us to better understand the different focus of human centric systems engineering to classical human factors.

7.7 Comparison of this study to Human Factors study of the same problem.

The system and algorithm used in this study are currently being evaluated within the SEAS DTC. It was recognised early on that the human interaction with such complex machine technologies would be a challenge so a human factors study was funded to investigate the command (human) engagement problem. This work completed in December 2008 and is captured in the SEAS DTC report [MacLeod 2008] entitled *"Understanding the Command Engagement Problem for the Deployment of Complex Machine Decision Technologies"*.

7.7.1 Engineering process used by human factors team

In this section we examine the engineering process used by the human factors team, recognising the briefings they were provided with and their results.

The Human Factors (HF) team before commencing this work were briefed by the T45 Combat System lead on the challenges of FTEWA and why it was so different from the current combat model. This was specifically undertaken to ensure that the human factors team understood that the proposed system was a substantial change to current concepts of operation not only at the system level but also the Warfare level. They were shown the operation of the algorithm, the data it used, where that data would have to come from and the output data. They were also shown a simple graphical representation of the output plan, similar to that shown in Figure 78.

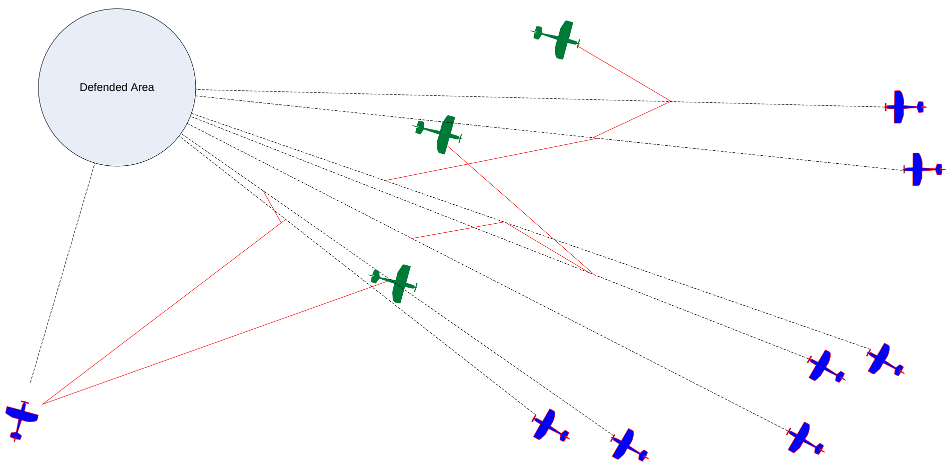

Figure 78 Simple graphical output of algorithm

At the commencement of this work the HF team were given two aspects of the command engagement problem that they need to address:

> 1, How should the decision maker or user initially interact through the system with the algorithm in order to ensure that engagement goals are supported in the required timeframe?

2, How can we ensure that the decision maker or user comprehends the command decision solution presented at the HCI in order for them to approve and then act on that recommendation in a timely manner?

To solve this, the HF team undertook a number of activities:

Activity 1: They considered the purpose and the properties of the algorithm, capturing the input and output data. They then considered the general challenges of automation and how that affects the human computer interface.

Activity 2: They discussed the challenge of usability, recognising that the algorithm was intended to supplement or replace human cognitive activities. They recognised that the use of the algorithm would need to be easy and that additional functionality may be required to support usability, what this maybe or why it may be needed was not provided. They discussed general frameworks for usability.

Activity 3: They described possible influences on command and control related decision making, specifically:

- They discussed the challenges of the military decision making.
- They identified the issue of the legal responsibility for decision making that may deter use of the algorithm.
- They recognised that there are human issues associated with the dynamics of multiple target engagement.
- They recognised that current models and theories that try to address the human processes relate to past actions and indications of influences on possible future actions, rather than decision making.
- They recognised that the use of the algorithm would change the user's work.
- They looked at types of information and their relationship to control of dynamic systems.
- They discussed of the concept of time, the need for timely feedback
- They discussed the importance of trust.
- They discussed the challenge of Human error.

Activity 4: HCI correspondence with automation. For this they provided guidelines for algorithm HCI Design and then interviewed two fighter controllers[50] to get their views on the

[50] The Fighter Controller had been the role identified by the combat system engineers as the person responsible for tasking aircraft. It was not recognised by either the systems engineers,

utility of the algorithm. They then focused on the existing user's views of the algorithm without realising that the Fighter controllers were not responsible for the type of planning being provided by the algorithm.

Activity 5: Based on the views of the Fighter Controllers they identified a need to undertake algorithm demonstration and prototyping to seek to resolve some of the issues raised. The aim of the proposed demonstration and prototyping would be to *"promote the quality of a product, or to investigate associated concepts, by resolving uncertainty"*. Their recommendations for the demonstration were:

1. The simple demonstration should be restricted to coverage of the existing functions of the Algorithm. It should focus on an in-depth approach where possible.
2. The seeding of the algorithm should be automatic at each initiation.
3. Operating area boundary restrictions should be applied as constraints to each asset's permitted operation[51].
4. The results[52] of each initiation should be saved for later examination.
5. Good HCI principles should be applied.
6. There should be an ability to declutter the HCI by removing symbol annotation or by changing the graphical situation display scale.
7. Colour use should kept to a minimum: e.g. Red for targets, Blue for Assets and own forces.
8. The baseline HCI should be restricted to a simple graphical interface using one Graphical Window, for a graphical situation display, and a TOTE displaying engagement information contained in a second Window.
9. Command inputs for control of the demonstration should be kept to a minimum and only exist if they are needed to assist explanation.
10. There should be an ability to temporarily display simulated static graphical representations of the algorithm's optimised engagement solution in a second window accompanied by a truncated TOTE display (this representation considering a selected Asset or all Assets) whilst retaining the situation display in the first window as per the baseline HCI.

Following a review with the author of the HSCE technique the human factors team viewed their work and added an eleventh point to address the 4D aspects of the plan:

11. There should be an ability to shown a simulated greater than real time static or dynamic rehearsal of the assets' engagements of targets in one window (depicting a

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the human factors specialist or the Fighter Controllers that what the algorithm was doing was at a higher level that the role they investigated.

[51] Note: this is a legacy requirement for area of responsibility type of allocation not optimal allocation and is not supported by the algorithm

[52] But for some reason not the automatically entered input data.

selected single asset or multiple assets) and an updating TOTE on the engagement in the second part of the Window.

In conclusion they claimed that:

The problem space had been investigated and captured.

That they provided an argued and evidence backed understanding on how the two given aspects could interact with and gives support to user's awareness, their understanding of the command engagement situation, and could allow the user an ability to recognise if the solution offered by the Algorithm was appropriated to an evolving situation.

7.7.2 Comparison of the Human Centric Systems Engineering and the Human Factors study.

If we compare the human factors study and the Human Centric Systems study we can see that they have each approached the challenge in a different manner:

Human Factors	**Human Centric System Engineering**
Focused on interaction of a single role, the FC as previously defined by the combat system engineers, with the algorithm	Considered the appropriate deployment of the algorithm within the human team. Placed the immediate responsibility of commanding the algorithm with the AAWC.
Identified the algorithm's input and output data.	Created a human team information model, examined algorithm's data flows and created a correlation of the two. Identified the potential redistribution of knowledge from the human team members into the algorithm and made recommendations to maintain the human abilities.
Recommended that the input data for the algorithm should be automatically seeded.	Investigated the human roles responsible for providing the input data require by the algorithm and understood how the cognitive focus of those individual roles was likely to seek to define it and change during the engagement.
Provided general guidance of the human issues.	Provided specific guidance associated with the deployment of this algorithm on human cognition and how it could impact system effectiveness.
Excluded any consideration of the need or utility of the solution to other members of	Identified other team members who needed to know and understand the plan so that they

Human Factors	Human Centric System Engineering
the team	could undertake their own role both in this system and others (PTEWA)
Assumed that the FC had the authority to approve the plan.	Recognised that the plan required approval from the CO and that the CO had a different perspective on the engagement than the AAWC who use the algorithm to create the plan.
Did not provide a solution, proposed further demonstration or prototyping without guidance on the starting point.	Identified requirements for supporting the human cognitive processes and provided an information or data flow model of the required interaction between humans and machine technology.
Explicitly removed the 4D planning challenge[53] by reducing the displayed plan to the first two legs.	Made high level recommendation for engaging the team in the 4D plan and during the operation.
Assumed current concept of operations of area of responsibility rather than embracing force optimal use of assets.	Did not constrain the design by assuming defined constrained rule set, hence increasing the likelihood of system flexibility and agility.

Table 4 Comparison of human factors[54] and human centric systems engineering

From Table 4 we can see that the human factors team have focused on the individual human's interaction with the specific machine technology, whereas the Human Centric approach has provided an integrated human team or holistic viewpoint, which can be seen in the results:

The deployment chosen by the combat system engineers for the algorithm was to give the Fighter Controller responsibility for interacting with the algorithm and the human factors engineers did not question this allocation or consider that other roles would need to be involved in the operation of the algorithm. The system analysis resulting from the use of Human Centric Systems Engineering placed the algorithm with a different team member the AAWC, who is two levels higher up the command chain and has identified additional requirements to integrate the use of the algorithm into the human team.

[53] Which was only recognised as a result of the briefing on HCSE. It should be noted that by reducing the 4D plan to only 2 legs the proposed solution is denying the human the ability to understand the future option space.

[54] It should be noted that the human factors team chose the level at which they chose to undertake their analysis of this problem.

7.7.3 Conclusion

From this basic comparison we claim that the human centric systems engineering approach is providing additional information that would not have otherwise been generated that are a useful input to system engineering activities in that it is improving the engineer's understanding of the appropriate deployment of advanced machine technologies and has enabled the identification of additional requirements for engaging the human factors team in the system problem.

Discussions with the human factors team showed that the use of HCSE and specifically the human team model has the potential to better engage the HF team in the wider system problem.

7.8 Review of the Engineering technology

This second validation study has used the framework and associated engineering process to enable us to investigate the deployment of a new machine decision making technology into an existing human system.

7.8.1 Use of the framework and process

In this report we used the same framework as in the previous study but modified the engineering process as shown in red in Figure 79.

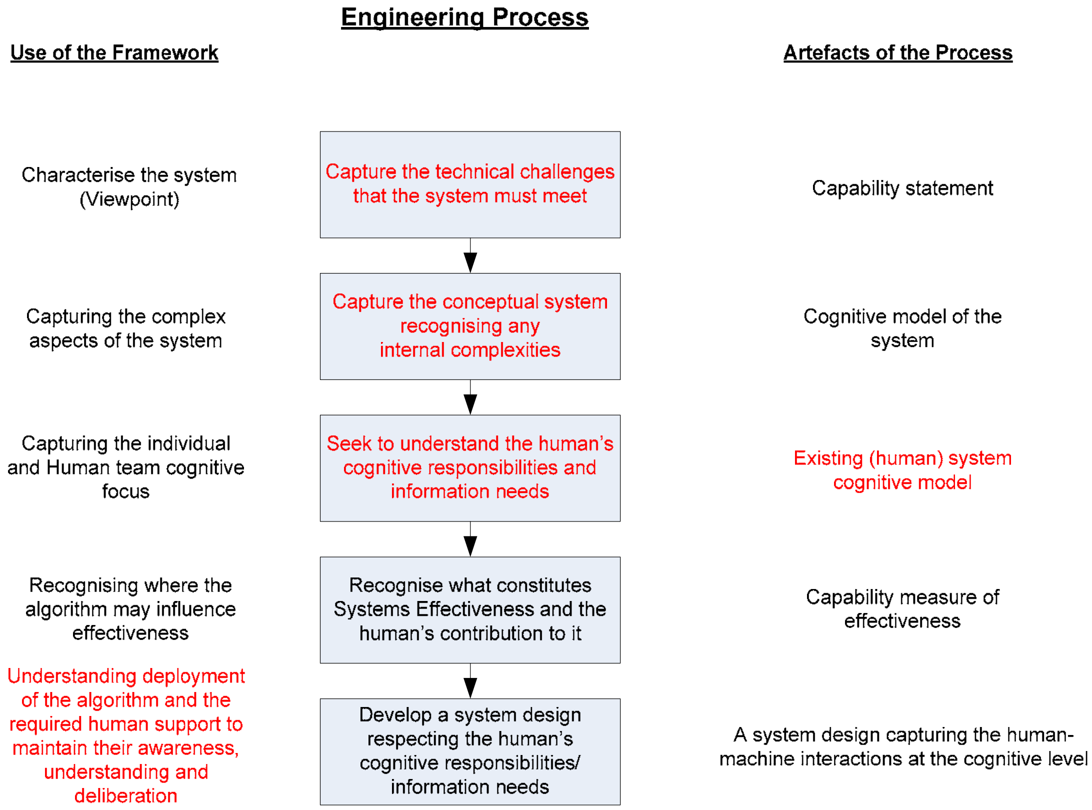

Figure 79 Engineering process used in study 2

The first stage in our updated engineering process we captured the capability statement of what the military required, the technical challenges that the system needed to meet and recognised potential constraints that the system must comply with. This provided the baseline for the subsequent engineering analysis.

In section 7.2 we used the second stage of the engineering process to capture a conceptual model of the system. The initial work in section 7.2.1.1 captured a linear model of use of the algorithm the development of which was a relatively simple exercise that was undertaken using classical control engineering methods, but once the dynamic flows that existed in the environment were added the system become complex and more difficult to understand. We then overlaid the cognitive functions of awareness, understanding and deliberation on to the dynamic model and used this to create a top level cognitive system model of the system. This forced us to consider the data flows between each of the cognitive elements and add them to the model, which proved to be relatively easily identifiable from the dynamic model Figure 54.

In section 7.3 we followed the third stage in the engineering process and investigated the human cognitive focus using the role responsibilities information from section 7.1.5 to guide the work. For each of the roles, the responsibilities were used to investigate the individual's awareness needs, what they may be trying to understand and their deliberation challenge. This gave us some high level requirements for each of their cognitive functions which were then used to identify possible information flows both internally to the individual human roles and the external flows.

Intentionally we kept these cognitive functions at a very high level, when we attempted to gain more detail the exercise rapidly degraded into implementation detail which would have meant that the context independent applicability of the model would have been lost.

We then brought together each of these cognitive focus information flow diagrams to form the team cognitive model. In joining the model together a few loose information flows were identified that required the re-visiting and update of the individual's cognitive focus models.

The operational effectiveness of the system was derived using classical system engineering prompts but our focus on the human aspects of the system forced us to measures that recognised reliance on the human's abilities to deliver their cognitive functions. This understanding was in turn used to recognise how the deployment of the algorithm may influence the human's ability to perform.

In section 7.6 we returned to system modelling and mapped the algorithm's information needs onto the human system in order to recognise which roles may be influenced by the deployment of the algorithm. We considered for each of the algorithm's information flows their relation with the human roles requirements for awareness, understanding and deliberation and the potential ways in which the system design could meet those needs. In doing this we recognised that to be able to effectively deploy the algorithm additional information items would be required to support the human roles.

By investigating the information flows and consideration of the human responsibilities beyond our own system we identified a single role that would seem to be the most appropriate individual to be responsible for framing the problem and initiate a plan calculation. The additional information items needed to support the human cognitive focus, identified in 7.6.3, would require additional machine functionality that did not form part of the calculation so it was proposed to deliver this through a wrapper layer that would both maintain the genericity of the algorithm and be able to meet the cultural needs of the human system.

Concerns over potential human complacency and the possible degradation of the human knowledge led to the recommendation to actively involve the human with the review of the "asset survival matrix", the one information item needed by the algorithm that had been recognised as machine knowledge.

The engineering review suggests that the proposed algorithm deployment captured in this document is likely to deliver improved system effectiveness over that being currently developed for evaluating the algorithm using normal systems engineering techniques.

7.8.2 Recommendations for improving the effectiveness of the engineering method.

It was found that the framework and process provided a useful tool to not only understand the cognitive focus of individuals in the team and their information needs but to capture the overall information flow in the human team. The number and complexity of the information flows made comprehension of the team cognitive information exchange diagram difficult, colour coding of the flows made the challenge of understanding different not necessarily easier. The use of an electronic tool to access this model would seem a more appropriate means where the information flows for individuals could be independent layers which could be turned on and off.

The use of a drawing package to create the diagrams contained in this paper was not optimal and even the few updates or corrections needed took time that could have been avoided through the use of an engineering tool. The alternative presentation method to use a table, see Table 2, failed to portray the complexity of the system and to have attempted to consider the deployment of the algorithm using only the table would have risked the engineering activity overlooking some of the important aspects (emergent properties) of the cognitive system.

7.8.3 Assessing the cost of using the framework and process.

We need to ask are the benefits of doing this type of analysis worth the amount of time and effort of doing it?

The analysis contained in this document took 15 days to undertake but this timescale needs to be considered in light of the practitioner undertaking the task who has over 20 years experience[55] in various engineering modelling techniques and was knowledgeable in the area of military capability examined. It is likely that someone with less experience or who did not have the background knowledge in the military capability may take two or three times the time to do the analysis. If we consider the cost of this investment in light of the cost of integrating the algorithm into the combat system, subsequent system verification & validation and the requirement to undertake sea trials of the upgraded command system, the time used in this engineering analysis or design activity is insignificant.

The nature of this type of advanced machine decision technology is such that an inappropriate deployment or the operators failing to setup or understand the resulting plans could potentially reduce system effectiveness. The analysis in this paper points to the conclusion that the deployment of the algorithm being currently evaluated by the SEAS DTC is not optimal and would have not gained full benefit of the technology. We can also recognise that this inappropriate deployment may also in the future lead to the users not actually making use of the algorithm, which would negate the investment made in it. As a result of the study captured in this section the proposed deployment of the algorithm has now been changed to that of the AAWO and a future human factors study commissioned to investigate engaging the associated roles in the algorithm's solution.

If we take a systems view of cost, then we are balancing the pound notes or analysis time against the benefits which are measured as the change to system effectiveness. Whilst we have seen that effectiveness can be measured as time to successfully destroy threats, it also relates to maintaining military capability; which is all about seeking to engage in such a way as to minimise the number of aircraft lost, targets that need to be engaged at the platform level and currently, safeguarding lives of the pilots who fly those aircraft.

7.9 Conclusion

This second evaluation study has used the framework and process to analyse and model a system that currently consists of a human team. We saw in section 7.3.2 how the framework could be used to capture the cognitive focus of individual roles participating in the FTEWA System and how those individual models could be joined together to form a rich model of the system.

In section 7.6.3 we identified that the algorithm was using a form of knowledge in the form of the engagement matrix. Such a redistribution of system knowledge could have influenced the human team's decision making so it was recommended to seek to maintain this human

[55] This is less than the human factors engineer who did the study in section 7.7

knowledge. The result of this work was to define a means of on going engagement of the humans in shaping and defining the machine knowledge. This would enable them to know the parameters that the machine was applying and when the evolving operational context went beyond the valid application of the current machine knowledge[56].

The rich system model provides for the engineer a combined view of the cognitive system that enables them to see beyond the individual to how they contribute to the higher system purpose. This same rich system model enabled us to recognise in seeking to deploy the machine technology how changes in one part of the system could impact the cognitive contribution in other parts of the system. This resulted in additional requirements being defined to support the human cognition as part of the proposed deployment of the algorithm.

As part of this second study we have also compared the output of a human factors study to the outcome of using a human centric viewpoint. The comparison showed that human factors focus on the individual human's interaction with the specific machine technology, whereas the human centric approach provides an integrated human team or holistic viewpoint. From this comparison it was identified that the human centric systems engineering model could provide a better baseline for the human factors engineering work, in that it identified a more appropriate deployment of the algorithm and additional requirements to support the humans which the human factors team could then consider as part of their design activity.

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[56] To use Qvortrup's classification of types of knowledge; the human in this instance would be applying fourth order knowledge, one of the hardest to form.

8 ASSESSMENT OF HCSE AS AN ENGINEERING TOOL

In the preceding two sections the engineering framework and process have been applied to real military systems enabling us to understand their potential utility to an engineer. During the studies the initial process was refined enabling an improved understanding of the contribution of the human team. In this section we revisit both the framework and the process, capturing the updated view of the process.

We start by reminding us of the beginning of this journey when we recognised the challenges faced by system engineering and why it is necessary to consider seeking to address them. We then revisit the framework and the process updating them to reflect the knowledge gained through the conduct of the studies, presenting them in a format that should be immediately exploitable for the systems engineer.

This section then reviews the key achievements of this work and whether the use of the engineering technology met our expectations identified in section 5.3 and the cost of that achievement. As a final contribution section 8.4 considers the practicalities of deployment of this engineering technology.

8.1 Background

In section 5.1 we recognised that system engineering had intentionally left the human contribution to delivering the system purpose outside the bounds of the system that they were considering. This viewpoint was chosen because it seemed to simplify the systems engineer's task, as they did not need to worry themselves about the complexities of the human. But it had an unintentional side effect in that the systems engineers often ignored the human cognitive contribution to delivering system purpose. Instead there was a tendency to define the human as some sort of automaton following blindly predefined tasks, with defined decision needs.

Over the decades decisions that are simple enough to find a solution to have often been automated by the engineers designing the system, whilst those that are more difficult have been left for the human to solve. To aid the human we are now seeing the development of advanced decision making machine technologies that go beyond automation and make contextual decisions, something we have chosen to call autonomy. These machines will be providing some of the *cognitive functionality* currently provided by humans and with it, they will need to apply knowledge, to form awareness, create understanding, to recognise the appropriate decisions based on how they change the context and to make those decisions. Consequently today's systems engineers are being asked to solve even harder problems than before, problems that are complex. Because it is impossible to define all the possible permutations of system and environment in these complex problems we accept that we will be unable to define the specific problem that machine autonomy will have to solve. Therefore for the foreseeable future the system will remain reliant on the human to provide the real-time system adaptation. The problem being that the deployment of the machine technology will itself change the role of the human in the system and their potential cognitive contribution. To enable the engineer to understand the system challenges we have developed the engineering framework and associated process.

8.2 The engineering framework and process

Section 5 introduced an engineering framework and process for applying it to analyse the cognitive aspects of a system. We now we revisit them, capturing what has been learnt as a result of undertaking the studies.

8.2.1 The framework

The engineering framework provides the engineer with a means of thinking about and capturing the relevant aspects of the human cognitive contribution to delivering the system purpose. It provides a means of communicating with subject matter experts (people who may have held the roles) that is sufficiently abstract but that speaks in their language that enables the engineer to capture the roles cognitive responsibilities in the system of interest. The framework consists of the three cognitive capabilities: awareness, understanding and deliberation. Between these three capabilities we have identified information flows that provide specific support to the functioning of those cognitive capabilities, see Figure 80.

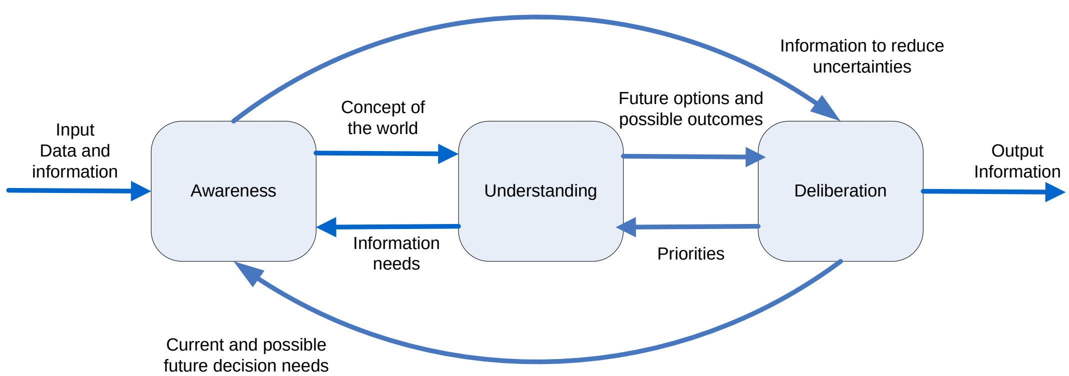

Figure 80 the Cognitive framework with the purpose of the information flows identified

The three capabilities provide the individual human roles with:

> Awareness provides the ability to **conceive or perceive the current operational context**, in a way that is **meaningful to the current system purpose**.
>
> Understanding provides the ability to recognise the **relationships in the operational context and their significance or affordance** in light of the system mission or purpose.

Deliberation provides the ability to make suitable choices taking into account the **n dimensions that can alter both the temporal and spatial future**, with the aim of changing the future to deliver the system purpose, whilst conforming to the constraints imposed upon it.

The information flows between these three cognitive capabilities enables the engineer to recognise the individual role's information needs and provides an indication of the types and importance of the knowledge being applied to form this information. From this it is then possible for the engineer to deduce the role's required input data and the output data.

The joining up of the individual role models provides a team model that enables the engineer to recognise the sources and consumers of information see Figure 81.

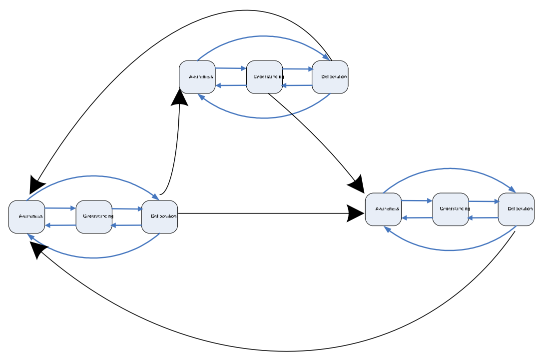

Figure 81 Team information model

This team information model enables the engineer to identify how individuals are actively aware of other team member's responsibilities and that they may choose to change their own choices to better support other roles by providing them with different option and decision spaces.

The nature of the information flows within the team model will give the engineer an indication of where responsibilities have been spread across the team in order to reduce an individual's workload e.g. a linear information flow across a number of individual models. And where there are supervisory or command roles who are taking a different viewpoint on the problem space. These two types of relation give an indication of the nature of the knowledge being applied by the roles: at the lowest the knowledge will be mainly procedural, through tactical to the highest strategic.

Whilst the joining up of the individual roles provides the engineer with the information flows across the team, it is also worth the engineer considering if there are other potential exchanges or influences between each of the three cognitive functions in individual roles see Figure 82:

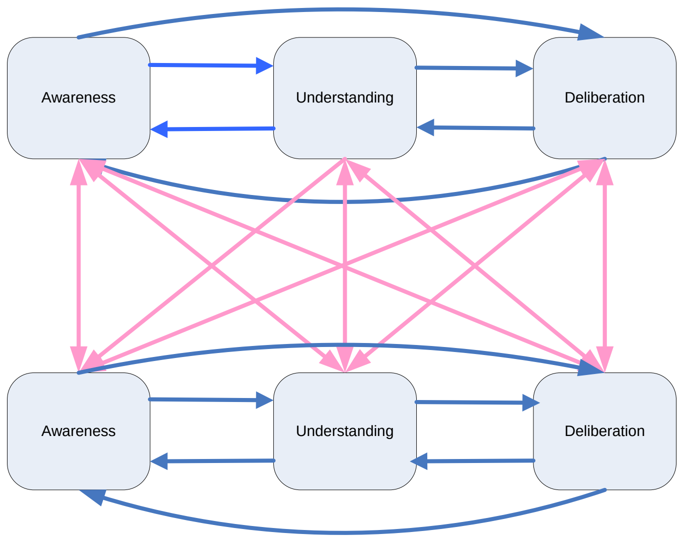

Figure 82 Potential influences across cognitive models

The engineer needs to recognise which of these flows or influences are possible and which may be useful to understand as they may have system value. The engineer needs to understand:

- Are the information flows delivering what they think they are delivering?
- What is the impact of the flow? E.g. what are the consequences of timeliness on system behaviour and performance?

This framework is not intended to be used to capture every last detail of either the individual or team model, as it is likely that would quickly degrade into capturing implementational or context specific data, but it represents an adequate framework for gaining additional understanding of the human contribution in the system.

The framework can also be applied to understanding advanced machine technologies, to give an indication of the level of context sensitivity of the technology and to enable it to be included in the human team model to form a rich system model, which will enable the engineer to understand the potential influences of the machine data flows on the human team.

8.2.2 The engineering process

In section 5 we presented an initial process model for the engineer to use the engineering framework to think about the cognitive aspects of systems. In this section we revisit that process model updating it in light of the two studies, capturing the associated guidance to make it available as a coherent process.

For each activity stage in the process we have used the BAES Lifecycle Management Guide [BAES 2006] definition of the requirements for defining a stage of an engineering process to capture:

- Purpose: Describes the purpose of the stage in the process and what the engineer will get out of doing it
- Inputs: Identifies the information required to undertake this activity.
- Outputs: Identifies the key deliverables from the activity.
- Verification: Potential means to verification of the stage
- Guidance and notes.

The use of an existing format for defining an engineering process should aid early exploitation. The final engineering process is shown in Figure 83, with the last update shown in red.

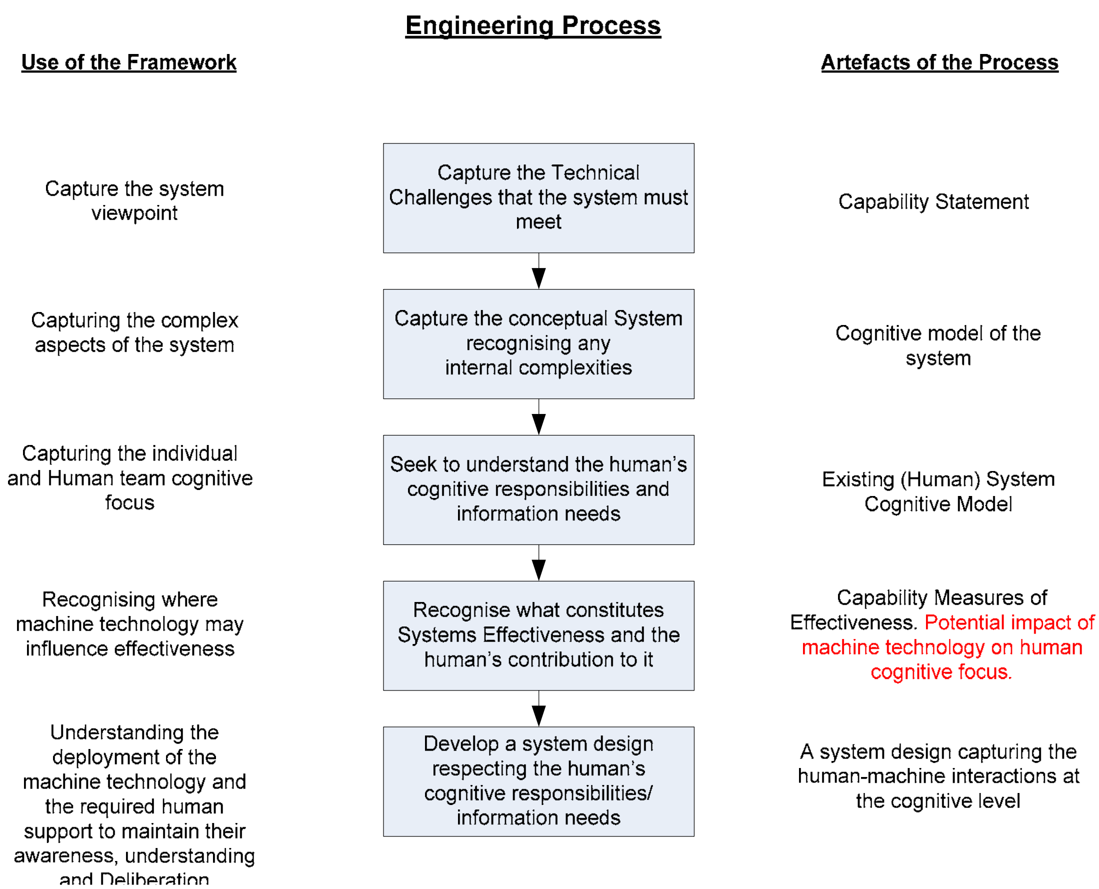

Figure 83 Engineering process, final

8.2.3 Activity 1: Capture the technical challenges the system must meet

Purpose:

To capture the system purpose in such a way that fully embraces the human contribution.

Inputs:

- Capability requirements,
- Existing human role responsibilities and authorities,
- Constraints including any constraints imposed by technology being used and external constraints that may restrict the freedom by which to execute the design.

Output:

- Capability statement. This captures what the system is to achieve, the existing human role responsibilities relative to the capability statement and the generic problem space solved by any technology being investigated.

Verification.

The outputs of this activity should be reviewed by the both the purchaser and the human "commander" who will be responsible for the outcome of the system in deployment. The focus of the review is to confirm that the engineer has fully understood the system capability requirement and sufficiently the likely challenges of the problem space.

Guidance and Notes

This first stage forces us to think about the system in an abstract manner: *What does it achieve?* Captured as a textual description this will drive the subsequent process stages providing the engineer with an implementation independent view of the system.

In many systems there may well be a number of potential solution spaces that could be chosen[57] what they may be and their relationships need to be recognised as they may change the concept of operation, human roles, responsibilities, etc. in the system.

Where the system in question may exist in some form the recognition of the relevant responsibilities of the existing human roles provides an initial identification of the individuals for whom it may be necessary in subsequent activities to capture their cognitive focus as part of the rich system model.

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[57] E.g. The types of allocation identified in the FTEWA case study.

The capture of any technological constraints before considering any modelling forces the engineer to capture what the technology does, rather than seeking to find solutions for using it.

External constraints may exist that need to be identified. Many of these will be implicit, e.g. to "*make a country safe*", implicitly includes the requirement to seek to minimise damage to civilian infrastructure. This may be obvious to the system participants but because the engineer is highly unlikely to be an expert in the context for deployment it will be necessary for them to be aware of aspects that may restrict the system solution space in the future.

8.2.4 Activity 2: Capture the conceptual system

Purpose

To capture a conceptual process model of the static and dynamic system, recognising within it the key activities associated with awareness, understanding and deliberation, before capturing the system as a model using the engineering framework. This model is independent of underlying technology, so does not consider if a human or machine may be seeking to solve aspects of the problem.

Inputs

- Capability description,
- external constraints.

Outputs

- Linear system process model.
- Dynamic model (showing relevant feedback paths).
- A conceptual model of the system based around the cognitive framework.

Verification

The resulting model should be reviewed by the human "commander" to confirm that the linear and dynamic process models have captured the key stages of process and information flows and that these are correctly reflected into the top level cognitive system model. The review will also confirm that the textual description of the processes and information flows are consistent with the "commanders" expectations of the cognitive activities.

Guidance and Notes

The first step is for the engineer to identify a simple model of the system process, which must include recognition of any contextual influences in an abstract way. The inclusion of abstract context influences is important as it is something that the human has catered for when systems have been deployed but now because we are considering the humans in our system we need to recognise those contextual influences as part of the engineering process. By intentionally keeping this to a linear model it enables the key stages in the process to be identified and simplifies the task of describing what they are there to achieve.

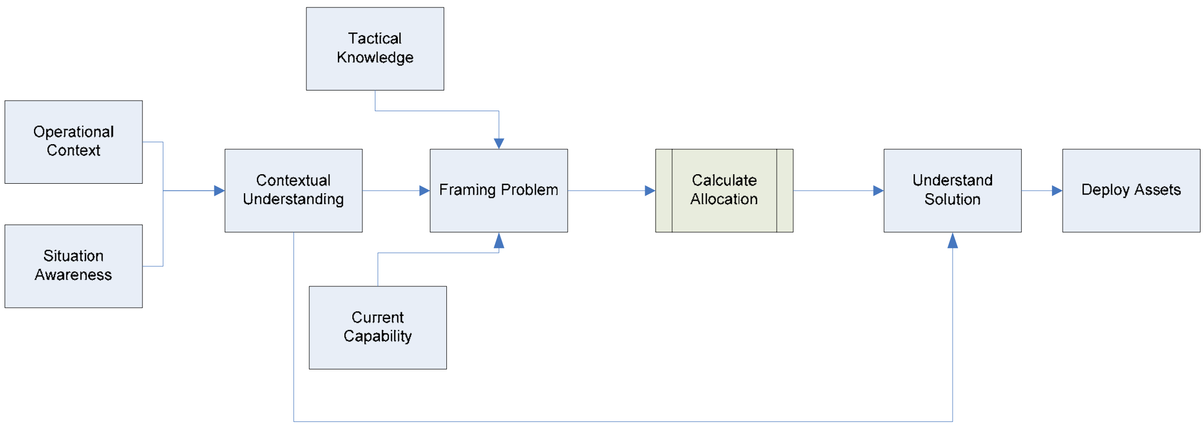

Figure 84 Example simple model of the system processes

This simple model of the system processes can then be used as a basis for capturing the dynamic system process model. To do this we add the feedback loops that exist external to the system within the environment that change the problem space for the system. These feedback paths represent things that the humans would normally become aware of and change the way in which they choose to interact with a system.

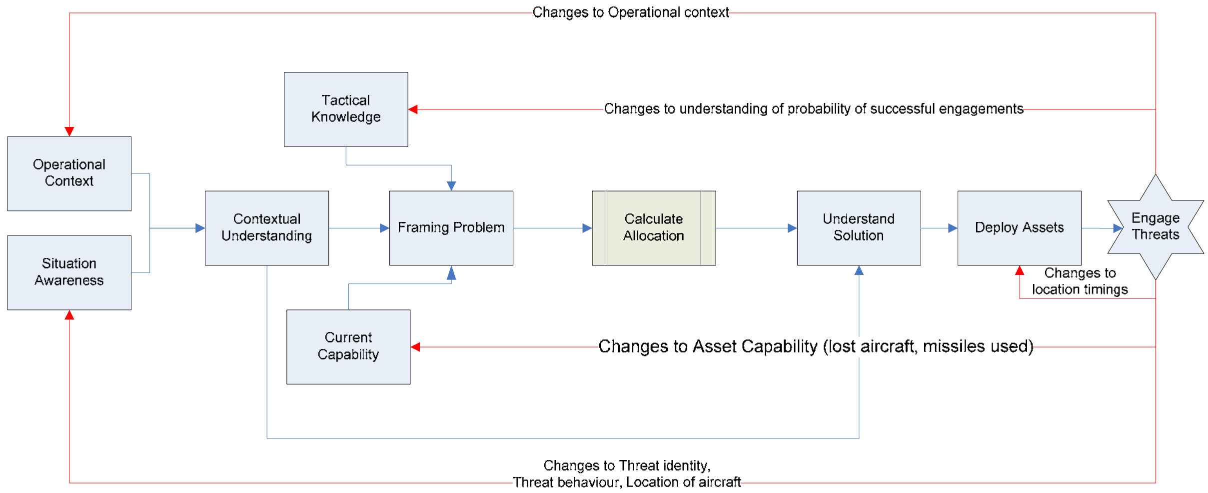

Figure 85 Example dynamic model of the system processes

The third system process model maps the dynamic model onto the cognitive framework.

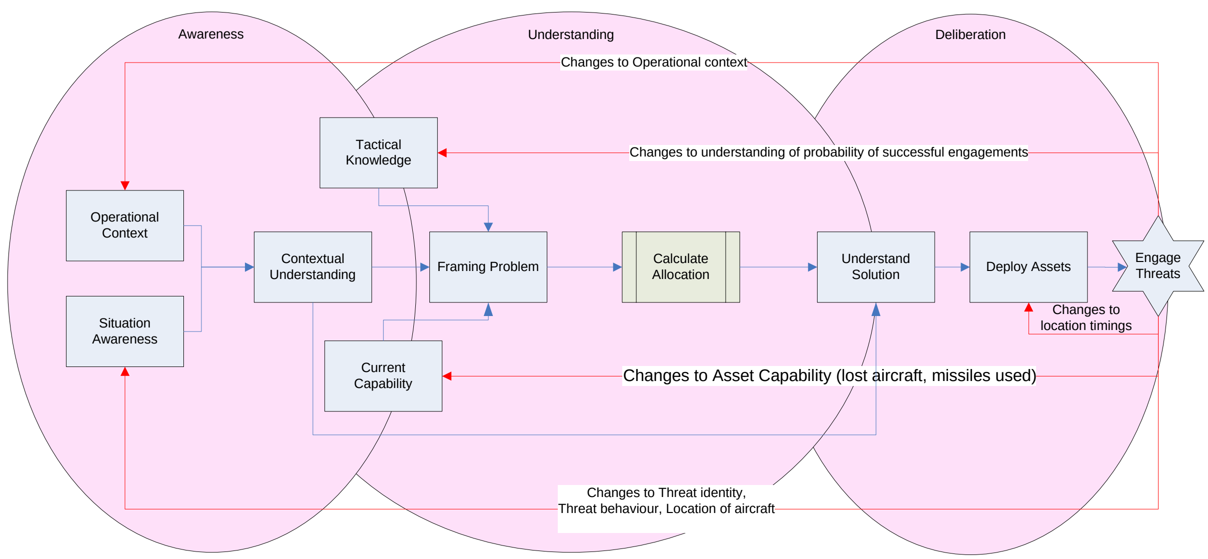

Figure 86 Example mapping of cognitive framework to the system

By explicitly considering the three cognitive capabilities the engineer can draw out the uncertainties, possibilities and priorities associated with the three attributes and capture it using the cognitive framework.

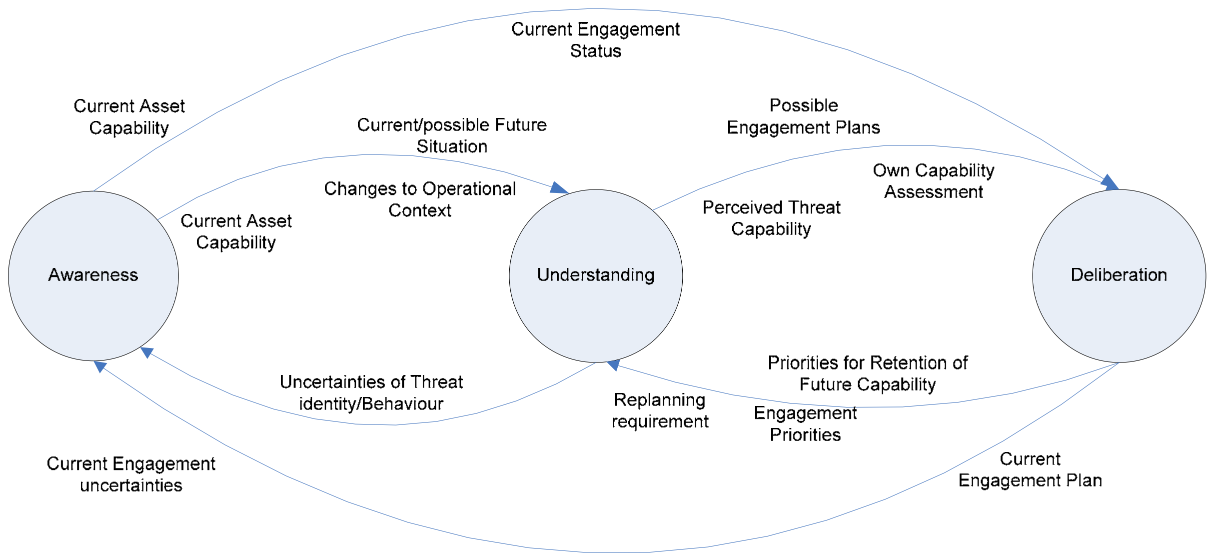

Figure 87 Example cognitive system model

This high level conceptual model of the cognitive system would, in Yourdon or SASD terminology be considered to be the level 1 system diagram.

8.2.5 Activity 3: Understanding the human's cognitive contributions and information needs

Purpose

For each role in the system, to capture their cognitive responsibilities, their information needs and from this create a model of the human team's contribution to the system purpose.

Inputs

- Cognitive model of the system (from activity 2),
- Human roles and responsibilities (from activity 1).

Outputs

- The system cognitive functions provided by the humans, a description and model of each roles cognitive focus.
- A rich view of the system formed by combining together the individual role models as a single human team model.

Verification

Each role model should be reviewed with an appropriate individual who has experience of undertaking that role, to confirm that it contains the information they would expect and that the engineer has understood their cognitive focus.

The rich system model should be reviewed by the human "commander" to confirm that the flows of information meet to their expectations within their team and to identify that all the necessary team members have been included in the model.

Guidance and Notes

For each of the role responsibilities identified in activity 1 map those responsibilities to the three cognitive capabilities to provide an initial idea of their cognitive responsibilities. This can initially be undertaken using a simple table, e.g.:

Role	Task or function	Awareness requirements	Understanding requirements	Deliberation requirements
CO	Maintaining performance of Assets under direct command	Operational Context	Future Military capability requirements	Prioritising or Maintaining future Military capability
		Potential engagement plans	Possible Future Force Capability	Approving or overriding engagement plan
		Current Engagement Status		
		Current Asset capability		

Table 5 Example table for capturing high level role cognitive responsibilities.

For each role use the system cognitive framework and these cognitive responsibilities to ask questions as to their individual awareness, understanding and deliberation, in order to capture a description of their cognitive responsibilities and their cognitive focus. Capture these as a model of the three cognitive capabilities and the data flows between them e.g.

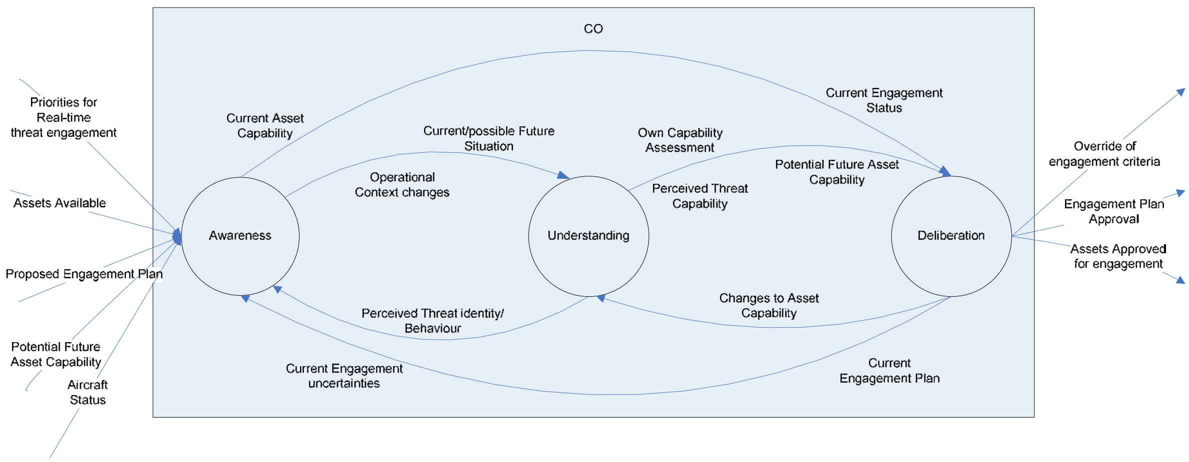

Figure 88 Example role cognitive focus

This basic model is used for interviewing SMEs in order to further refine it. The questioning should first focus around the decision space: “*What are the decisions you are responsible for making*”, this should naturally lead to questions about how the option space is derived at (the understanding) and then focus on the awareness needs, which will, with the internal information flows, identify their external information requirements. The decisions they are responsible for making will provide an indication of the information they maybe providing to others in the team.

It should be noted that whilst we are only concerned with the individual roles responsibilities in this system, the individuals will concurrently be involved in other systems. Such involvement does not form part of this analysis but such recognition needs to be captured as it may form a part in evaluating the possible system solutions and conclusions.

Once all of the individual roles have been captured they can be joined together to form a team view. This joining together acts as a self verification activity as it will identify shortfalls in the models of the individuals where information items may not have a source or consumer. Where shortfalls are identified it is worthwhile revisiting the original subject matter expert to understand if there are other issues that need to be understood.

We can use this team view of the system to identify potential information bottlenecks, or points of high workload, where a number of information flows converge on a single individual before being processed and passed to other team members.

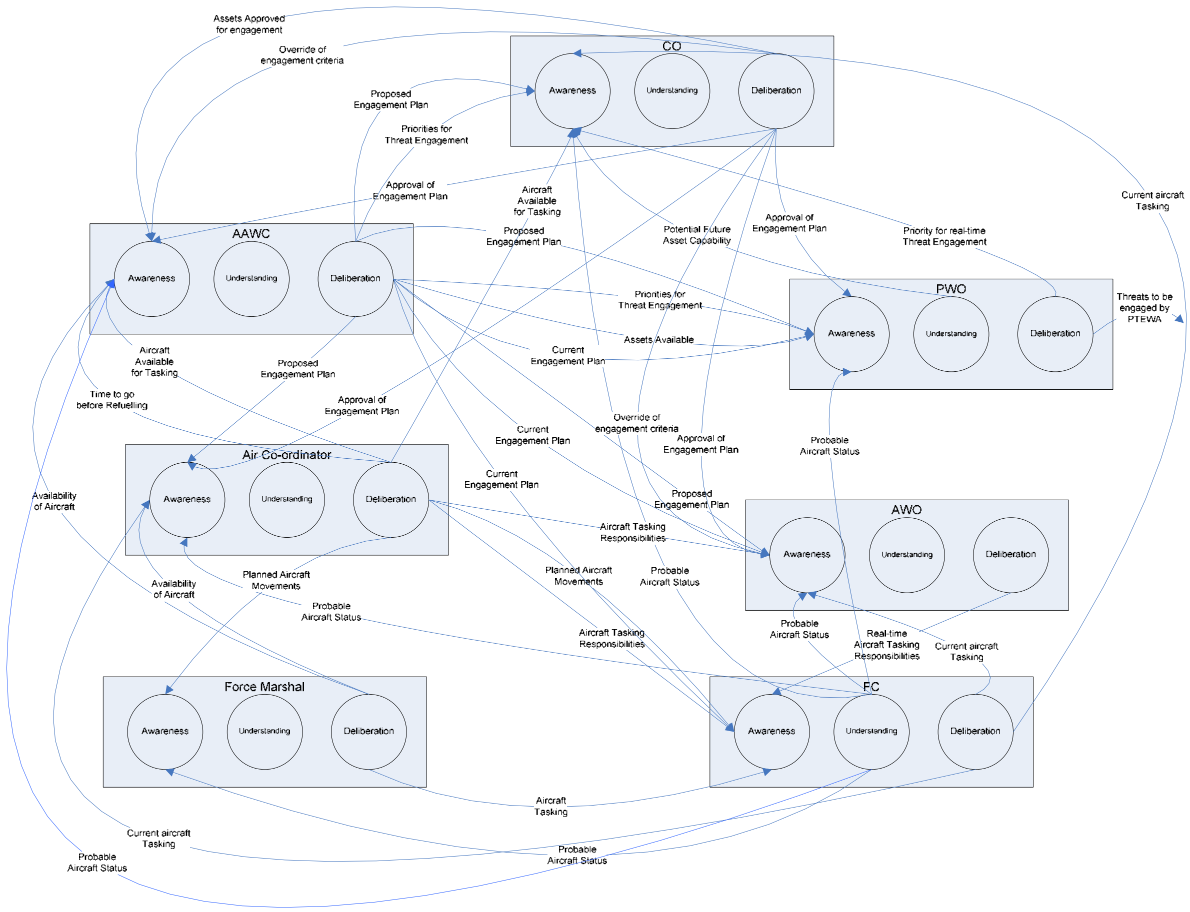

Figure 89 Example information flows across the human team

Using this team view of the system the engineer can now capture the information flows within the system identifying the sources and consumers, as a simple table.

Role	Information Requirement	Source
CO	Priority for real-time threat engagement	PWO

Table 6 Example information flows in the human team

This table provides a much quicker means of initially considering the potential influences of machine technology data needs than the engineer trying to extract them directly from the complex team model, which may risk some being missed. Once these are recognised then it is necessary to return to the team view to understand the complex information problem and potential consequences.

8.2.6 Activity 4: Identifying system effectiveness

Purpose:

To identify what constitutes effectiveness for the system and how the human contributes towards delivering it.

Inputs:

- Capability Description (from activity 1),
- generic description of technology to be considered for deployment (from activity 1)

Outputs

- System effectiveness statements.
- Identification of how the machine technology may affect the overall system effectiveness

Verification

The resulting identified system effectiveness should be reviewed by the human "commander" to confirm that their expectations of all the key performance aspects have been captured, including the contribution of the human team members.

Guidance and Notes

The effectiveness of the system captures how well the humans and the machine technologies working together can deliver the system purpose. To identify potential effectiveness statements the engineer should use the classical systems engineering performance questions to derive these:

- How Much? (volume)
- How Well? (accuracy, resolution, confidence level)
- How Fast? (time to completion)
- For How Long? (endurance)
- How Often? (ability to repeat at intervals)
- How Quickly? (responsiveness)
- When? (typically a function of the scenario)
- Where? (typically determined by the scenario)
- At What Cost? (level of training needed, level set-up required, levels of stresses and strains, durability of system)

Underlying these effectiveness statements will be measures relating to “information” type effectiveness measures, which relate to the transformation of data into information for use in the system.

We can recognise at least two types of information flow: push (broadcast) and pull (requests) [58]. The effectiveness of both of these types of information flow can be measured: for information push we can measure the time it takes the other members of the team to recognise and make use of the information. For information pull the time it takes the respondent to provide the information that has been asked for. We can also measure the amount of wrong information that is being used, be it out of date, incorrect etc.

Using the captured role responsibilities the engineer should seek to identify how key individual role responsibilities contribute directly to the identified system effectiveness measures. This then enables the identification of critical aspects of their cognitive focus that the engineer should keep in mind when they seek to use the rich system model for their design purposes.

8.2.7 Activity 5: Development of the system design

Purpose

To develop a system design that respects the human cognitive responsibilities and information needs.

Inputs

- Capability Description (from activity 1),
- Generic description of technology to be considered for deployment (from activity 1),
- Human team model (from activity 3),
- Identification of how the machine technology may affect the overall system effectiveness (from activity 4),

Outputs

- Rich system model.
- Requirements to support the human cognitive contribution.

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[58] Others information flows include random events, such as “leaks” when someone overhears something but such information “opportunities” will be highly contextual, so we have excluded them from our consideration.

Verification

The potential impact of the machine technology on the human cognitive focus should be reviewed with the "commander" to confirm that the identified potential impacts are valid and no important aspects have been missed.

Special focus should be given to any potential knowledge redistribution to confirm the potential impacts on the human's abilities, where possible not only in this system but in any concurrent systems they may be participating in. Once the potential impacts are agreed the engineer can then seek to deploy the proposed machine technology into the human team model.

The final stage in the verification process is to review the proposed machine technology deployment and the additional requirements to support the other human team members. At this stage further issues may still be identified by the reviewer that may require additional iterations of the considerations of the deployment of the machine technology or human support requirements.

Guidance and Notes

To be able to consider the deployment of machine technology into a human team the engineer needs to first focus on understanding the machine technologies data needs and the outputs it can provide, in light of the system purpose. By capturing a model of the machine technology as a data flow node, or if applicable as a cognitive model, showing the input and output data, prepares it for later inclusion in our rich model of the system. It is also important for the engineer to recognise if the machine technology is utilising any "knowledge" such as look up tables as this will influence how the machine technology constructs its own option space and how its output should be interpreted by the humans.

The engineer should now compare the machine data flows to the information flows in the human team model and identify those that are similar. This enables the engineer to simplify the human team model to only retain those flows that may be influenced by the deployment of the machine technology.

For each of the human roles that have information flows that are similar to the machine technology data flows it is necessary for the engineer to consider how the machine technology could influence their awareness, understanding and deliberation. Specifically we are interested in detecting possible mismatches; as the human information flows are contextual and the machine data flows will not in the main respect context, so mismatches are highly likely, even with flows that may share the same name.

In addition to the information flows the engineer needs to consider the knowledge items that the machine technology is using and recognise how that may influence the humans ability to form awareness, understanding and deliberation. Whilst the machine may be using knowledge, it is not contextualising its use, so mechanisms are needed to engage the humans in that knowledge item so that they can continue to recognise the limitations and applicability of the machine knowledge being employed during system execution.

Where defining the problem and the results of the machine technology are used by more than one individual in the human team, we need to recognise that multiple individuals defining their own problems and solutions will quickly cause awareness synchronisation problems in the human team. It is therefore advisable to seek to identify an individual role who will take responsibility for the management of the technology in the team. A basic principle that the engineer should apply in identifying the individual, is that they should seek to understand the impact of the deployment of the machine technology on the human team as much as possible, because whilst we are responsible for only looking at one specific system the humans in our system are concurrently involved in other systems and any major changes is likely to have knock on consequences in those systems as well. Having identified an "owner role" for the technology, it will then be the responsibility of that role to engage the other team members and make them aware of a new machine solutions and why it was created[59]. The engagement of the other team members with the machine solution will require suitable information flows to overcome any identified data or information mismatches relative to their cognitive contribution in the system.

As a result of this work the engineer will have identified additional information and knowledge engagement requirements for the human roles that may be influenced by the machine technology deployment. It is likely that this will require that the machine technology is augmented to meet the human need and recognising that it is often difficult to modify the underlying algorithms the simplest way may be to provide a wrapper around the machine technology to interface it to the human system. The use of wrappers has much to commend it as it enables the underlying machine technology to remain generic, whilst the wrapper can embrace the human team needs and the culture[60] of the system it has been deployed into.

The final requirement for the engineer is to create an enhanced model of the machine technology and to place it into the model of the human team, to form a rich model of the system. Using this rich model, the engineer can then confirm that the machine technology should not have unforeseen consequences across the remainder of the team.

The resulting rich system model can now be used to support the system design stages. The additional human engagement system requirements can be provided to the human factors team for consideration as part of their human computer interaction design. The investigation of how both of these activities may change as a result of looking at the cognitive aspects of the system is defined as being outside the scope of this thesis.

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[59] In effect they are providing contextualisation of the machine solution.

[60] We can recognise that the way that humans form their cognitive contribution in our system will be influenced by their personal background the emergent collective team culture. This may also influence how the data from the machine will need to be presented to the humans.

8.3 Tailoring the use of the engineering process for other purposes.

In this thesis we have chosen to use the engineering framework to explore the challenge of the deployment of machine technologies into a human team, as was identified in section 5.2.5 we could also use it to analyse potential changes to the human team. To do this we could slightly modify our process as shown in Figure 90.

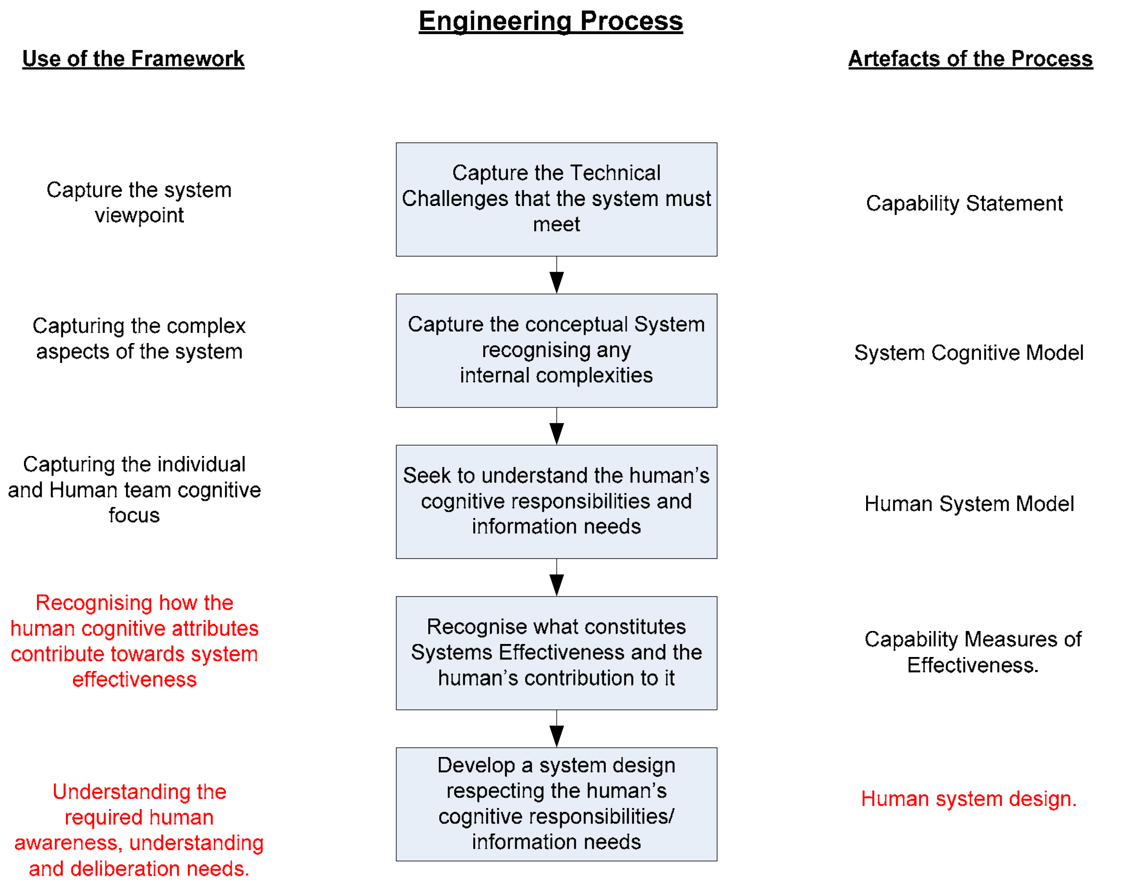

Figure 90 Engineering process modified to support investigating changes to the human team

To investigate potential changes to the human team we would see those aspects of the engineering process that were looking at the machine technology removed leaving the focus on the human roles and their information flows. The requirement would be to generate a human team design that delivered the top level cognitive model but using a different decision responsibility deployment and consequently information flows. How effective this would be and the detailed guidance for the process would require to be investigated as part of a future piece of work.

There is no doubt many different potential applications of the engineering framework and process that can be explored in the future, a few of which are captured in section 9.3

We should also recognise that the engineering technology contained in this thesis could be applied to understand part of a system, rather than the whole. In truth both of the studies in this thesis are only exploring part of the much larger combat system. The requirement to understand part of a system only requires that the practitioner is able to adequately define the system challenge in stage 1 of the process, independently from the remainder of the much larger system.

8.4 Review of the key achievements

To seek to solve the challenge of being able to understand the cognitive aspects of a system in section four we changed our system viewpoint to include the human's cognitive contribution within the system bounds.

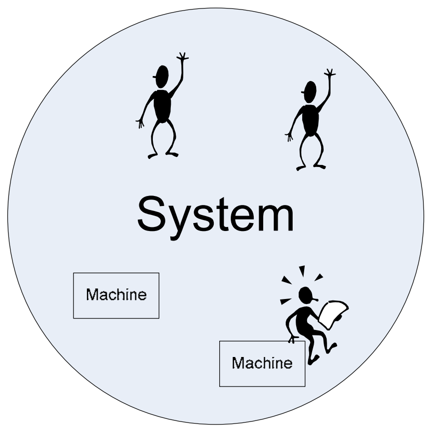

Figure 91 Human cognitive contribution placed within the system bounds

To capture the human cognitive contribution this thesis introduced a three stage framework, consisting of awareness, understanding and deliberation. To guide the engineer on how to use this framework in section 5 this thesis introduced an engineering process that has been subsequently verified in the work captured in sections 6 and 7 [61]. The use of this framework and process enabled:

- The capture of a model of the human cognitive focus or function including their information requirements and information they can provide.
- The creation of a rich system model capturing the information flows and interactions within the human team.

This modelling technique forces the systems engineer to specifically focus on the human cognitive process in support of the system and to ask questions that may otherwise have been overlooked.

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[61] This work still needs to be independently validated.

The use of data flow type models to capture the human cognitive focus was intentional and means that the engineering model captured is familiar to engineers who are experienced in classical systems engineering modelling techniques such as Yourdon (Yourdon & Constantine 1979) and SASD (DeMarco 1978). As a result the human contribution may be flowed into the detailed design stages of the engineering lifecycle, an area of future study that we have defined as being outside the scope of this thesis.

The resulting rich system model has been found to be adequate to understand the possible consequences of the deployment of advanced machine technologies not only for an individual but also the wider human team and enabled the identification of requirements for additional machine functionality to support the human cognitive functions.

8.4.1 The final engineering process

During the three verification phases the process used in conjunction with the framework has evolved. The final version is shown in Figure 83. The changes that have been made from our initial process are:

- We have recognised the need to capture the system view point before seeking to identify the complex aspects of that system.

- The third stage now seeks to capture not only the individual human cognitive focus but also to join those together to form the human team model.

- The fourth stage started by considering what humans contributed to system effectiveness, the final process takes this further and considers where the potential deployment of machine technology may influence that effectiveness.

- To use the human team model and a data flow model of the machine technology, to understand the potential deployment of that machine technology into the human team. From this to identify any additional functionality that may be needed to support the human role's cognitive contribution.

The first three stages in this process provides the rich system model embracing the human team and their information flows, this model could be used for other additional engineering purposes but in this thesis we have used it to investigate the deployment of advanced machine technologies.

8.4.2 Meeting our expectations

In section 5.3 we identified the potential benefits of using the framework and process as being:

> The ability to consider aspects of the human cognitive process within the systems design.

The ability to capture the information flows within the human team.

The evolution of the process over the validation exercises captured in this thesis has been able to deliver both of these expectations.

The framework and process have also delivered additional understanding of the potential implications of the deployment of machine technologies on the human cognition. As a result we are now able to identify new requirements to be included in system design process to support the human cognitive contribution.

The unexpected benefit from using the framework and process for the FTEWA study was that it enabled the engineers to recognise that their original proposed deployment of the stochastic algorithm to the Fighter Controller was to the wrong role. The HCSE analysis showed that the algorithm did not meet the FC role's information needs or responsibilities; as such it was highly likely that if the implementation of the algorithm went ahead it would, like so many "system enhancements", not have been used. Instead it placed the deployment with the AAWO and identified support requirements for other members of the human team that had not been previously recognised.

HCSE also delivered for the second study requirements to support the human engagement in the machine solution both as a plan (4D solution) and as a dynamic management tool. In contrast the original system concept proposed by the combat system engineers which went as far as considering how to display the plan results as a table or a graphics. The human factors solution to this was to undertake a classic "suck it and see" series of experiments building on the combat system engineer's idea to investigate the human engagement challenge. This means of experimental development would have incurred substantial additional costs and in light of the incorrect placement of the technology in the human team investigated an inappropriate solution. But we will assume that as a result of the human factors experiments the appropriate deployment would have been discovered at some time in the future.

8.4.3 The cost

We need to ask are the benefits of doing this type of analysis worth the amount of time and effort of doing it? Cost can be measured in many ways. The most obvious being the financial cost to undertake the engineering exercise. But for systems cost also relates to the achievable system effectiveness and consequences of operation:

1, Engineering Effort

The validation exercises captured in this report were undertaken over a period of one year. This was due to the work being undertaken part-time and the need to wait to have access to the subject matter experts. In a normal engineering development the work would be full time and planned around the availability of the subject matter experts. If we focus on the actual days spent on the study the first validation exercise looking at Anti-submarine tracking took 10 man days and the FTEWA 15 days. In comparison the effort used in developing the human factors report on the FTEWA system was 40 days. Both the author and the human factors engineer had over 20 years experience in their areas of specialisation, so this is a reasonable comparison. Note: the cost of the development of the optimisation algorithm considered in the FTEWA study was 12 man years of effort.

If we were to ask someone with less experience to undertake a similar systems engineering exercise to capture the cognitive aspects of a system it would be reasonable to expect them to take longer than was taken in these studies but we must recognise that they would not be looking to develop the engineering technique concurrently with the modelling. We could consider that it would be reasonable to allow a similar period to undertake the systems cognitive work as was used for the human factors work. . If we consider the cost of this investment in light of the cost of the development of the algorithm, the future integration of the algorithm into the combat system, subsequent system verification & validation and the requirement to undertake sea trials of the upgraded command system, the time used in this engineering analysis or design activity is insignificant.

2, System Effectiveness

We have seen that system effectiveness is a result of the combination of human and machine effectiveness. The nature of advanced machine decision technologies is such that an inappropriate deployment or the operators failing to setup or understand the resulting plans has the potential to reduce rather than improve system effectiveness. The analysis in this thesis points to the conclusion that the deployment of the algorithm being currently evaluated by the combat system engineers is not optimal, consequently the system effectiveness improvement will be less than anticipated. If such a deployment went through to system delivery we can recognise that there is a high risk that, due to the incorrect deployment, the technology will not even be used negating the entire investment made in it.

3, Consequences of Operation

The final consideration for cost is the long term evolutionary impact. The deployment of advanced machine decision technologies will change what our people do in the system. This will alter the baseline against which they will seek to adapt the use of the machine to achieve the purpose of the system. Because adaptation is used to overcome complex problems, prediction is not possible so we cannot predict if this will be successful or not.

What we can surmise is that if they are required to know less then the option space that they will be able to conceive of to solve the problems will also reduce.

8.5 The practicalities

For an engineering technique to be usable it needs to meet a number of challenges. So in this section we look at the attributes needed by the engineer, the potential for tool support and the challenges of working in a legacy customer base.

8.5.1 System engineer: Skills, knowledge and experience

The first challenge is that use of our engineering technology needs to be compatible with the system's engineer skill, knowledge and experience. What are these? The skills of system engineers are developed over many years, because of the specialist nature of systems there are no hard and fast engineering techniques taught. In general most techniques use a type of data flow diagram, so the framework should be familiar to them and with the worked examples contained in this thesis should be able to apply the process to other domains.

What training would be required? The human factor's engineer who participated in the parallel human factor's study of the FTEWA problem was given a briefing in the technique before using the framework to enhance their proposed deployment of the algorithm to better meet the Fighter Controller's cognitive needs[62]. He had no issues over the process and saw it as fully compatible with the Yourdon techniques he was familiar with[63].

The technique has also been briefed to a Battlespace Architect who is responsible for designing military experiments to investigate better ways of working. The feedback was that they saw no problems with what was proposed and that the framework and process was intuitive to follow. In the coming months the intention is to use it to support some of the planned military experiments. From this initial work we can anticipate that training costs will be minimal.

8.5.2 Tool support.

The development of the models captured in the validation exercises used a drawing package; this was not optimum but still worked and the results were useful. In an ideal world there would be a specialist tool to support it, but there is no reason why an existing engineering tool should not be used to capture the cognitive functions and information flows. The ability of certain tools to remove selected processes and data flows from the display may aid the understanding of the model.

As a benefit most engineering tools include inbuilt checking that enable model completion to be verified. This would enable the automatic identification of information flows that go nowhere.

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[62] Due to the briefing being only one week before the completion of the human factor's study they were unable to undertake a full reworking and used the opportunity to use the framework to understand the initial and the real-time understanding problem from the perspective of the individual they had chosen to deploy the algorithm with. They argued that for a demonstration it would be more appropriate to deploy the algorithm to only a single individual.

[63] To the extent that he suggested if I did not intend on taking this work further he was more than willing!

8.5.3 Working within a legacy customer base

One of the biggest challenges to overcome will be to work with the legacy customer base: customers who are used to buying platforms or products rather than capability. By them focusing on purchasing the machine functionality without considering the cognitive system they will continue to purchase legacy equipment that is not designed to support human adaptability. With future systems that contain advanced machine decision technologies, this could lead to unforeseen changes to human knowledge, and change the potential human effectiveness, in ways that have not been investigated. A situation where it would be advisable for the system designer to seek to safeguard themselves against possible future litigation.

The good news is that for more than ten years industry has embraced the challenge of understanding military systems exposed to undefined or changing contexts through the use of Battlespace simulations that focus on exploring military capability and possible system evolution. The MoD and other commercial customers have in the last five years woken up to the benefit of these experiments. If we are honest the "engineering" of the system evolution associated with these experiments has been described as ad hoc and they are desperately looking for tools that will enable them to understand the existing system and the human contribution in those systems. This is the planned first third party deployment of the techniques captured in this thesis.

8.6 Conclusion

This section has revisited the framework and engineering process originally proposed in sections 4.3 and 5.2 updating it with the lessons learnt over the two studies. Importantly it has removed much of the theoretical background material that was included in the earlier sections presenting both the engineering framework and process using a standard engineering format in order to make the outcome of this thesis immediately exploitable by engineers.

To meet the needs of engineering management we have also considered the cost and practicalities of using the technology. We found that the man power cost of using this engineering technology was less than that used to undertake a human factors scoping study into the same problem[64] we have also considered cost as a system attribute associated with system effectiveness and the ability to continue to deliver the system purpose even when faced with an evolving context.

Finally this section has examined the practicalities of use, we have considered the compatibility of the technology with the system engineer's skills, knowledge and experience, the desire for tool support and the challenges associated with a legacy

[64] The human factors study looked to identify the work that the human factors team would do in the later human computer interaction study. It did not develop an HCI. So the HF study was comparable with the HCSE study.

customer base. The early indications are that both systems engineers and human factors engineers can relate to this way of working and that it may well be a useful bridge between the two engineering disciplines. The deployment of the technology into the Battlespace experiments will enable not only engineers to be exposed to the technology captured in this thesis but will also be visible to the customer and if they are convinced that we can understand the human contribution we could yet see them move to a more capability based definition of the systems they require.

9 ASSESSMENT OF THE THESIS AND CONCLUSIONS

This final section summarises this thesis, reflects on how well it has provided answers to the research questions set in section 2 and identifies further research opportunities in this area. Section 9.1 provides a summary of this thesis, providing an overview of the motivations behind each of the preceding sections. Then, in section 9.2 it provides a critical assessment of this work, recognising its contributions and the limitations of what has been undertaken. During the conduct of this work additional research opportunities have been identified which are captured in 9.3 This thesis concludes by revisiting the original aim of this work and considers its contribution to cognitive systems engineering.

9.1 Thesis summary

This thesis captures a journey to find engineering technologies to enable the system engineer to embrace the human cognitive contribution in their system engineering process. Its aim was to insure that with the deployment of advanced machine technologies that system engineering had the tools they would need to engineer the cognitive aspects of a system.

It began by looking at some of the roads that have led us to this new discipline of cognitive systems engineering. We saw how systems thinking has evolved the way we look at systems, understand their emergent properties and grew to recognise the influence of context on some types of system. It then considered social systems, a discipline that provided a view on the structure of systems that contain cognitive elements and enabled us to recognise how and why these systems autopoiesis. The challenge of understanding cognition led us to look at the path of cognitive science, it provided for us but a flavour of the challenge of understanding thinking but sufficient for us to recognise the limitation of machine cognition and why machines are constrained to solving human defined problems.

From a view of thinking about systems this thesis then looked at how we seek to engineer systems. We saw how humans have been included in the system design through a process of defining a task and seeking to provide them with interfaces with which to deliver it, a process that does not embrace the individual's potential cognitive contribution or the wider human team. We saw how cognitive system engineering began by recognising the emergent properties of the human team and that machine technologies would influence human decision making. From a good start the cognitive systems community have returned to focus on techniques to understand and support the individual, leaving an opportunity for this thesis to return to the larger system challenge of embracing the human team.

This thesis set about solving this problem by identifying two questions that needed to be addressed:

1. How could a systems engineer recognise and capture the human cognitive contribution to a system?

2. Can we use this technology to understand how changes in one part of the system could impact the potential cognitive contribution of other parts of that system?

We started by defining a study process that would first seek to provide a better understanding of the cognitive system challenge which would then be used as a basis for developing an engineering framework to capture the human cognitive contribution within a system and a process by which to use that framework. This would then be tested by applying them to real world system challenges.

Our starting point for this work was to seek to understand how, as systems engineers, it may be appropriate to think about the cognitive aspects of systems. By working through an example of a military planning system, this thesis recognised that at each stage in the planning process the human was using three cognitive attributes: awareness, understanding and deliberation.

This thesis then used these three cognitive attributes as the basis to develop a framework to provide a way of thinking about the human contribution in our system. It investigated what each of the cognitive attributes provided and recognised the utility of the information flows between them. It then went on to recognise that a model of the entire human team's cognitive contribution could be achieved by joining together models of the individual human roles, providing an answer to our first research question.

To support engineering's use of this framework section 5.2 presented a initial five stage process that looks at how the framework could be used to capture the individual human cognitive contribution to a system, how those individual models could be joined together to form a rich system model and how this model could be used to understand changes to the system cognition such as the deployment of machine technologies, which would enable us to answer the second question.

To verify this framework and process section 6 presented the first of two studies which applied the engineering technologies to real systems. In the first study the challenge was to see if the use of the framework would lead the engineer to be able to anticipate the emergent change in human cognitive contribution to the system effectiveness as a result of the deployment of machine technologies. It indicated that the framework did provide a view on the potential impact of the deployment of machine technologies on human cognitive contribution.

The second validation exercise applied the framework and process to the evolution of an existing system design. To do this it specifically captured the cognitive contribution of individual humans as data flow diagrams and joined these together to form the team cognitive model. From this model we gained an understanding of the team emergent cognition, what they are able to solve together, that could not have been predicted from their individual models. We then, following the engineering process, introduced the machine technology into the system cognitive model as a single process in a data flow diagram. By considering the relationships between the machine technology's data flows and the information flows in the human team cognitive model we saw how it was possible to investigate an appropriate deployment for the machine technology and to make recommendations for additional machine functionality to support the human cognitive contribution. As part of this investigation this work focused us on the machine technologies use of a look up table as a form of machine knowledge and how that redistribution of knowledge within the system could change the way in which the human's sought to understand the context and made additional recommendations to continue to engage the humans in that knowledge item.

These two studies provide evidence that the framework and process can be used to understand how changes in one part of the system could impact the cognitive contribution of other parts, thus answering our second research question.

The final stage in the journey was to revisit the engineering framework and process updating them from the experience gained through the two studies and presenting them in a simplified form suitable for use by an engineer, complete with guidance. As a result this thesis has provided systems engineering with a new engineering technology, consisting of the framework and process, which enables engineers to capture the cognitive contribution not only of the individual but of the entire human team in delivering the system purpose.

The following section assesses what has been undertaken considering its contribution to systems engineering knowledge and the limitations of this work.

9.2 Lessons and limitations

To understand the extent of the contribution of this work we must first recognise the lessons learnt from undertaking it and more importantly the limitations of the technology it has developed. The goal of this thesis was to develop an engineering technique that enables us to investigate the cognitive aspects of systems, the research questions have provided a focus to progress towards goal. We have seen the development of a framework for understanding the human cognitive contribution in our system and used it through the system process to create a rich system model of the human team's cognitive contribution and investigated the deployment of machine technologies into that system.

We saw in section 4 that the understanding of a system problem is contextual and that the context is continually changing, consequently as engineers we can only predict the system context to a limited extent and uncertainties will always remain. This means that our ability to predict the tasks and to specify the decisions that we need our people to undertake is equally uncertain. By taking an abstract view of the system and cognitive challenges we are able to step away from the specific detail and seek to understand at a more conceptual level. Many systems engineers may find this conceptualisation difficult, especially if they are faced with an existing implementation. The use of the framework should help the system engineer overcome this challenge of abstraction and the guidance provided related to the information flows should focus their information elicitation from subject matter experts to populate the cognitive model of the role. Time and lack of available funding has prevented a third party undertaking an independent study into the practical use of this engineering framework and process.

We need to recognise that this engineering activity is a distinctly different challenge than would be normally undertaken by a human factors engineer who is eliciting information from these subject matter experts in order to understand the existing human task data requirements, so that they can develop an HCI. The systems engineer is undertaking this capture of the cognitive system model in order to define additional requirements to place on the human factor's HCI development; as such it is an additional systems engineering activity that needs to precede the actual HCI design.

We must also recognise industry's desire to "knock up" demonstrators as cheaply and quickly as possible early in the system lifecycle, often as part of a bid phase to engage the customer. We, as engineers, often fail to recognise the limitations of such demonstrators and their HCI is mistakenly seen as the starting solution to the full system HCI solution. If we look back at why this way of working came about we find that it was due to systems analysis not recognising that the act of design changes the problem space. Rapid prototyping was supposed to enable the exploration of the impact of design on the problem space and hence should be an input to system analysis. But the scope of this rapid prototyping like human factors is seeking to understand the individual's interaction with the system, not the team's interaction i.e. the complexity of the interactions.

In the second study where the individual human role models were combined into the rich system model the amount of information flowing and the level of influence of one role on another was more complex than one may have expected. This was reflected in the fact that the totality of the information flows was not apparent until all of the models were combined. This then begs the question how much detail should the system engineer seek to populate these model with? Too much detail will mean that the engineer is in danger of capturing existing implementation details that are context specific, too little should be identified through gaps in the model when it is joined up. As with all engineering modelling it is difficult to define the correct level of detail, it is something that is learnt through experience.

The system examples captured in this thesis are military systems, but the engineering technology should be equally applicable to civilian application for systems in which the human cognition provides a contribution in delivering the system purpose, such as air traffic control. In civilian systems where the problem is too complex for the human to understand, such as power distribution and management, the framework and process could help with understanding the existing processes and potential deployment of machine technologies.

The use of the engineering framework and the process contained within this thesis has been conducted by the author alone. Whilst the response from the human factors team and systems engineers who have been briefed in the technology has been very positive and indicates that third party use of the framework should be successful, they have not yet been applied by a third party.

Whilst systems engineering has its roots in systems science engineering is not a linear process, the individual engineer's experience, knowledge, the way they go about understanding and solving a system problem means that two engineers[65] are highly unlikely to generate the same solution to the same system problem. We could say that there is no single correct solution to any system problem, but through the use of the framework and process contained in this thesis they should however be able to better meet the needs of the humans in the system.

9.3 Future work

Cognitive Systems Engineering is a young discipline and the work contained in this thesis is but one way in which we could go about understanding the cognitive aspects of a system. During the journey captured in these pages we have identified additional research requirements that need to be filled to make the techniques presented in this thesis applicable to a greater variety of systems and opportunities to use these techniques to reshape existing systems.

There is the possibility that rich system model developed by combining the individual human roles could be used to investigate changes to role responsibilities, to redistributing workload or to change the knowledge requirements of the individuals undertaking those roles. As such the techniques may have possible application to better understand the human training[66] requirements for the system.

The FTEWA study touched on two larger systems challenges that should be investigated in the future. The first challenge is to understand the system of system problems where individual human are concurrently contributing to multiple systems and changes in one system may have knock on effects in another system. It may be possible to address this by creating rich system models for the multiple systems and then investigating the concurrent responsibilities of the individual.

The second system challenge identified is that of understanding the applicability of the framework to understand distributed team cognitive contribution challenge. When we consider the distributed system problem, what we are talking about is analogous to a multi agent system and the further development of the techniques in this thesis may

[65] Or even the same engineer, at different times, because their knowledge and perspective will have moved on.

[66] Training is one of the 8 defence lines of development (DLOD). It is highly likely that the engineering technology captured in this thesis would support the other DLODs aspects that could be investigated as the use of these tools is expanded.

provide the means to define the human interaction requirements for such multi-agent systems.

As a result of using the engineering framework and process, additional systems engineering information and understanding has been generated. The next challenge will be to understand how these can be used during the system design process. The relatively easier challenge will be to investigate how human factors could use both the rich system model and human cognitive support requirements as part of their HCI design and verification process. More thought will be required to understand how systems engineering could make use of the rich system view, it maybe that, like the use of the architectural frameworks, the specific techniques used will depend on the intent of the engineer.

The final process captured in section 8.2.2 includes guidance for the engineer. This is based on the author's personal engineering knowledge, intuition[67] and the experience gained during the conduct of the specific studies chosen. We can recognise that the application of the engineering technology to different systems in the future is likely to identify new guidance or to refine that which has already been captured, as well as developing reasoning mechanisms to support the engineer undertaking this type of analysis.

The applicability of the framework and process to support the development of a totally new system, something that has never been tried before or that a human team does not exist, still needs to be investigated. We can recognise that for this type of green field system challenge, it is normal for an engineer to use analogies with systems that they have experience with to both understand the system and how the problem space may be solved. In this type of problem they will normally start with seeking to understand what it is that the system is trying to do, then to identify the options for achieving it, the system decisions and the information that supports those decisions. In doing this we could consider that they seek to form the top level cognitive system model. It would seem appropriate to seek to capture this top level system understanding as such a model as a basis for the engineer develop a lower level rich system view with which to investigate the appropriateness of the analogy they have chosen.

Whilst the study examples presented in this thesis have been defence applications, the engineering technology presented should be equally applicable to civilian systems. If we consider the characteristics of the military they are trained to think in a certain way, in the main civilians are not and in many civilian systems role definitions are not as formal. But there are civilian systems associated with the Chemical industry, emergency services, Health, Police, Power management, etc. which are complex systems which rely on human cognition, which have formal structure and defined roles, that adapt to context. The application of the engineering technology to these systems may form a stepping stone to being able to capture the aspects of less formal civilian systems.

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[67] Resulting from over 20 years experience developing real-time defence systems.

At the time of completing this work the SEAS DTC is proposing to fund the follow on research item looking at extending the work captured in this Thesis to investigate the distributed system challenge.

An important item of future work will be the third party application of both the engineering framework and the process to their understanding of the cognitive aspects of systems.

9.4 A stepping stone on the journey

The aim of this research was to develop an engineering technology that would enable systems engineers to ***engineer the cognitive aspects of a system such that we, at least maintain human effectiveness***. The journey has taken us from theorising about the challenge of thinking about cognitive systems, to developing a framework to aid the capture of the cognitive aspects and its associated engineering process. We have seen their application to two studies and how our understanding of their potential use has matured. As a result this thesis has provided the following contributions to our understanding of the challenges of human centric systems engineering:

- It has developed a framework that enables an engineer to reflect on and capture the cognitive focus of individual human roles in a system and to recognise the information they require.

- By joining together these individual models, it has provided the engineer with the ability to create a rich model of the system that captures the human team's cognitive contribution to delivering the system purpose.

- The rich system model provides the necessary human team information model into which the deployment of machine decision technology can be considered. The model enables the engineer to move beyond being restricted to considering one machine technology deployed to one human role, to recognising the team wide implications of any such machine technology deployment.

- As a result of using this model it is now possible to identify additional human support requirements to support the entire team that would otherwise not have been recognised.

When we set out on this journey, we did so with an expectation of achievement based on our past experience, but a journey extends our experience, with it comes new information, new knowledge and from them we create new understanding that enables us to identify new challenges, new questions to be answered.

The journey never ends.

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11 ABBREVIATIONS AND ACRONYMS

AAWC	Anti air Warfare Commander
AAWO	Anti air Warfare Officer
ACO	Air Co-ordinator
AI	Artificial Intelligence
C2	Command and Control
CAP	Combat Air Patrol
CAS	Complex Adaptive System
CECA	Critique-Explore-Compare-Adapt
CPO OPS(s)	Chief Petty Officer (Sonar)
CO	Commanding Officer
CONOPS	Concept of Operations
Dstl	Defence Science and Technology Labs
FC	Fighter Controller
FTEAA	Force Threat Evaluation and Asset Assignment
FTEWA	Force Threat Evaluation and Weapons Assignment
FM	Force Marshal
FSM	Finite State Machine
GOMS	Goals, Operators, Methods and Selection Rules
HCSE	Human Centric System Engineering
JDL	Joint Defence Laboratories
NATO	North Atlantic Treaty Organisation
OFM	Operator Function Model
OODA	Observe-Orient-Decide-Act

PTEWA	Platform Threat Evaluation and Weapons Assignment
PWO	Principal Warfare Officer
RTO	Research and Technology Organisation.
SA	Situation awareness
SEAS DTC	Systems Engineering for Autonomous Systems Defence Technology Centre.
SLAM	Simultaneous Localisation and Mapping
SoS	System of Systems
STRIPS	Stanford Research Institute Problem Solver
TASI	Torpedo and Anti-Submarine Instructor (Latterly known as a Anti-Submarine Warfare Instructor ASWI)
TMA	Target Motion Analysis
TTCP	The Technical Cooperation Program
UVA	Unmanned Air Vehicles
WTEWA	Weapon Threat Evaluation and Weapon Assignment

12 GLOSSARY

One of the fundamental problems in any new area of technology is that we have a tendency to use terminology that we are all familiar with without explicitly defining our meaning in the new area. This can result in a lack of common understanding. To foster a common understanding in this thesis we are using the following terms and definitions:

Term	Definition	Source of Definition
Adaptation	The ability to change processes and organisation in order to take advantage of characteristics of a situation	
Agent	A system element capable of independent decision making at the deliberative level, elements include artificial autonomous agents (machines) as well as natural autonomous agents (humans and animals).	
Automatic	Performed from force of habit or without conscious thought	Oxford English Dictionary
Autonomy	The ability to initiate or modify actions in the light of ongoing events. The freedom to determine one's own actions or behaviour. Self-governing.	Oxford English Dictionary
Awareness	An agent is aware if they not only observe, but also draw inferences and establish relations from those observations. Those inferences and relationships are formed by the agent using its knowledge but they can themselves be considered to be a type of knowledge and can be used to evaluate potential effects arising from decision choices.	
Capability	The ability to generate an operational outcome or effect in the context of defence planning, Capability is the enduring ability to generate a desired effect.	UK MoD AOF
Cognition	The mental act or process by which decision making is achieved.	
Complex	Something that is woven together, the opposite is simple	
Complicated	Something that is folded together, the opposite is	

	independent.	
Data	A measurement that has a value, which has been given a label by which to define what it is a measurement of.	
Decision making	The ability to choose between different alternative outcomes.	
Deliberation	The ability of an individual agent to undertake decision making taking into account the potential effects of those decisions in order to seek to promote desired outcomes, taking into account that agent's value system.	
Flexibility	Ability to identify multiple ways to achieve the goal and to be able to plan to move between them.	
Goal	A symbolic representation of an outcome.	
Information	Is data complete with contextual reference. Is data that has relevance to the consumer of that data, it enables awareness, and shapes understanding, so ultimately	
Innovation	The ability to do new things and the ability to do old things in new ways.	
Knowledge	Knowledge comprises all cognitive expectances that an individual agent uses to interpret situations and to generate activities. This knowledge includes that built up by acquiring information through personal experiences, as a result of which the knowledge evidential to each agent may be unique.	
Linearity	Resembling a line, for a system these are systems that can be described using linear differential equations. Their output can be determined from their input.	
Mission	A clear, concise statement of the task of the command and its purpose.	
Mission	Real-time system management and planning	

Management		
MPDM	Mission Planning and Decision Making	
Non-Linearity	A system whose structure or fixed elements are inherently non-linear, their output responses and stability depend on the initial condition values and the input values.	
Planning	The act of creating a detailed scheme or proposal for achieving something.	
Procedural Knowledge	Knowledge of how to achieve a goal using agents and objects.	
Resilience	The ability to recover from deviations in the anticipated operational context.	
Responsiveness	The ability to react in response to changes in the context in a timely manner.	
Robustness	Effective across different contexts.	
Sensemaking	Putting the available data into context and identifying the relevant patterns that exist	
Situation Awareness	This is a specific term that is used in human factors to refer to human "perception of elements in the environment within a volume of time and space, the comprehension of meaning and the projection of their status in the near future"	
Technology	Tools or machines that can be used to solve problems. Or: Knowledge of how to combine resources to produce desired products, to solve problems, to fulfil needs or to satisfy wants. Or: A cultural activity which seeks to understand the complexities of combining technologies to recognise the unintended or unforeseen consequences or problems that may arise from their	Wikipedia

	use.	
Understanding	Understanding is process of comprehension of relationships in the operational context and the recognition of their significance or affordance in light of the system mission or purpose.	

吾言甚易知甚易行天下莫能知莫能行
言有宗事有君夫唯無知是以不我知
知我者希則我者貴是以聖人被褐懷玉

[Lao Tsu 600BC][68]

[68] My words are easy to understand and easy to perform.
Yet no man under heaven knows them or practises them.

My words have ancient beginnings, my actions are disciplined.
Because men do not understand, they have no knowledge of me.

Those who know me are few, those that abuse me are honoured.
Therefore the sage wears rough clothes but holds the jewel in his heart.