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An Exploration of C2 Effectiveness – A Holistic Approach

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Abstract

This paper discusses effectiveness and its use in the evaluation of Command and Control (C2) systems. The need for a broader definition of effectiveness is advanced and it is suggested that modelling techniques such as Value Networks capture important interaction flows that are critical to C2 effectiveness.

In this rapidly changing world, both of technology and threats to society, inappropriate emphasis on Measures of Effectiveness (MoE) and the optimisation of individual systems risks compromising the agility, adaptability and resilience of future C2 military systems. Disruptive technology provides (and often enforces) an opportunity to rethink how a system can be structured. It is imperative that effectiveness be defined so as not to preclude the introduction of new technology as it becomes available.

A system's effectiveness is often measured in isolation to its broader "eco-system" and the definition of effectiveness needs to encompass external factors. In addition, this paper defines intrinsically valuable properties that are crucial to the achievement of effectiveness.

The relationship between MoE and Measures of Performance (MoP) will be explored and it is recommended that a layered approach to MoEs be used. Effectiveness is defined within the problem-space but measurements can only be made in the solution-space. The mapping between these two spaces is the ultimate challenge.

1 Introduction

Modern defence forces need to contend with a rapidly changing world. Technology is evolving at a significant pace and the security outlook and possible threats to society, that is, the context in which the technology will be used, are also continuing to change. Defence forces must determine their capability development priorities in the light of these changes and in order to achieve the best outcome for the available investment dollar, tradeoffs need to be made. This means that emphasis must be placed on determining the effectiveness of various capability options. While determining the effectiveness of an individual option or system may be straightforward, the comparison between disparate options is not and performing a tradeoff between spending on a Command and Control (C2) system versus spending on a weapon system requires some evaluation of the relative effectiveness of such systems.

This paper will discuss C2 effectiveness and its use in the development and evaluation of C2 systems. The unexpected impact of disruptive technology motivates a discussion on the issues associated with using Measures of Effectiveness (MoE) to measure and guide the design and evaluation processes for C2 systems. The need for a broader definition of effectiveness will be advanced and it will be suggested that descriptive techniques such as Value Networks Analysis capture important interactions that are critical to C2 effectiveness.

This paper will introduce definitions for C2 and MoE. These definitions will be followed by comments on effectiveness and mathematical formulae and plots of surfaces will be used to illustrate and disambiguate the concepts presented.

Having clarified our view of effectiveness the issue of measurement will be discussed where the challenges and limitations will be covered. The paper will conclude with comments on MoE and MoP and their value to C2 assessment and pose some open questions regarding effectiveness and its measurement.

2 Definitions

There is no single agreed definition for either Command and Control (C2) or Measure of Effectiveness (MoE). Various definitions that are still evolving and have minor variations in meaning depending on their context and origin are given below to illustrate the some of the points that are relevant to this paper.

2.1 Command and Control (C2)

One of the simplest definitions of C2 is that provided by the Military Operations Research Society as quoted by Green [7]:

"The exercise of authority and direction by a properly designated commander over assigned forces in the accomplishment of his mission"

The American definition of C2 is:

"the exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission. Also called C2." [3]

This definition provides more detail about how C2 is executed and is very similar to the definition that was used by the Australian Defence Force (ADF)[1].

It captures many of the nuances of other definitions such as the NATO definition quoted by Malerud[11] which defines some components of C2:

C2 concept: *A set of characteristics of a C2 system describing how it reaches its objective.*

[1] The ADF has recently changed its definition of C2 by separating it into its constituent parts i.e. defining command separately from control. Although this allows each aspect to be considered separately, for the purposes of this paper, the combined definition will be used.

C2 structure: *An assembly of personnel, organisation, procedures, equipment and facilities arranged to meet a given objective, and within fixed economical limits.*

C2 system: *An assembly of personnel, organisation, procedures, equipment and facilities organised to accomplish C2 related functions. A C2 system comprises three main components: C2 tasks, C2 functions and a C2 structure.*

Within the framework of this paper, Kirzl's description of C2 systems [9]:

"The current command and control systems can be considered as adaptive control systems, and as such must monitor their environment, develop an understanding of what is happening, develop and assess alternative courses of action to control the environment, predict the consequences of selecting a course of action, decide on a course of action, develop a plan and provide direction to subordinates and then monitor progress."

highlights the "sense-making" aspects of C2. Sense-making and Situational Awareness are important aspects of the commander's role in C2 and this paper will use Endsley's [5] definition of Situational Awareness, namely:

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

This definition is particularly suitable for discussions of MoE as its three component parts are logically distinct and have sequential dependencies.

2.2 Measure of Effectiveness (MoE)

Green and Johnson [7] describe the evolution of MoE concept from the late 1950's definition of Goode and Machol: *"The measure of effectiveness is the criterion by which solutions will be judged – proposed solutions, solutions under test, or solutions in being"* to the 1964 report by the Weapon System Industry Advisory Committee (WSEIAC): *"Systems effectiveness can be defined as a measure of the extent to which a system may be expected to achieve a set of specific mission requirements"*.

Starr [15] describes the mid 1980's Mission Oriented Approach (MOA):

"The MOA revolves around the addressing of four questions:
• What are you trying to achieve operationally?
• How are you trying to achieve the operational mission?
• What technical capability is needed to support the operational mission?
• How is the technical job to be accomplished?
This approach emphasises that it is important to evaluate ***C4ISR*** *systems within the context of the missions that they are to support. The MOA approach is implemented by employing a top-down decomposition linking missions, functions, tasks, and systems"*.

MORS and the NATO Code of Best Practice (COBP) for C2 Assessment process developed hierarchical definitions that assume that measurements at lower levels contribute to assessing the effectiveness at higher levels such as force effectiveness or policy effectiveness. MoE is defined by MORS [15] "*Measure of how the C2 system performs its functions within an operational environment"* or NATO COBP [5] *"A measure of how a C2 system performs one or more of its functions within an operational environment (C2 level). MOE measures a C2 system's effect on other entities on the battlefield and are scenario dependent."* Other hierarchical models have been proposed [13] that are based on a hierarchy of information and decision requirements that are necessary to attain military effects superiority.

Many of these definitions included the phrase "Measure of Performance (MoP)" which MORS [7] defined as "*Related to inherent parameters (physical and structural) but measure attributes of system behavior*." and NATO COBP [11] defined as "*A measure of the performance of subsystems within the C2 system (technical level). The MOPs are scenario independent.*"

Sproles [14] postulates that MoEs are required to answer the question "Does this meet my need?" and hence defined MoEs as *"standards against which the capability of a solution to meet the needs of a problem may be judged. The standards are specific properties that any potential solution must exhibit to some extent. MOEs are independent of any solution and do not specify performance of criteria*". He distinguishes between MoP and MoE by declaring that MoP measures the internal characteristics of a solution while MoE measure external parameters that are independent of the solution – a measurement of how well the problem has been solved.

The definition we will use for MoE is *"A measure of the ability of a system to meet its specified needs (or requirements) from a particular viewpoint(s). This measure may be quantitative or qualitative and it allows comparable systems to be ranked. These effectiveness measures are defined in the problem-space. Implicit in the meeting of problem requirements is that threshold values must be exceeded."* This definition shares the concern with comparing systems as exists in Dockery's 1986 definition [4] *"A measure of effectiveness is any mutually agreeable parameter of the problem which induces a rank ordering on the perceived set of goals".*

2.3 Problem Space versus Solution Space

This paper draws a distinction between the problem-space and the solution-space where the problem-space denotes the needs (or requirements) of a system and the solution-space is the mechanisms used to achieve those needs. This is the distinction between "what" is required versus the "how" it is achieved. Figure 1 illustrates this distinction. Within the solution-space the "what" question can be asked leading to a further decomposition. For example: a C2 requirement could be "to assist decision-making" which may be achieved using various computer algorithms like Expert Systems or Automatic Neural Networks (ANN). The problem-space for ANN could be the "the ANN will monitor the commander's decisions and correlate scenarios to decisions made".

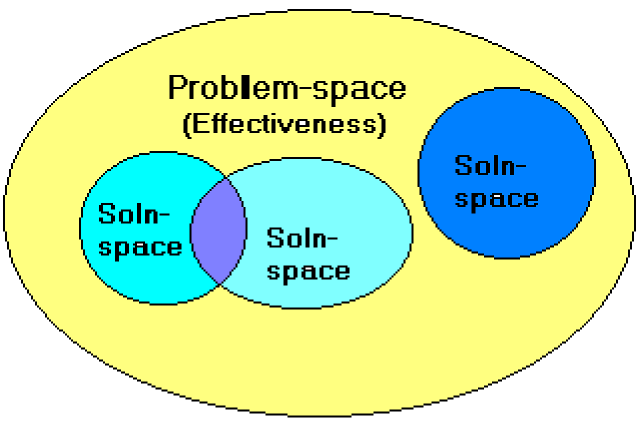

Figure 1. Problem versus Solution Space

Measures within the solution-space are generally agreed to be MoP and these measures can be used to assist in assessing effectiveness. To continue the "to assist decision-making" example, a badly performing ANN (which can be measured on various criteria) which cannot correlate scenarios to decisions will not be effective in assisting the decision maker. These concepts are illustrated in Figure 2 (surrogates measures will be discussed later).

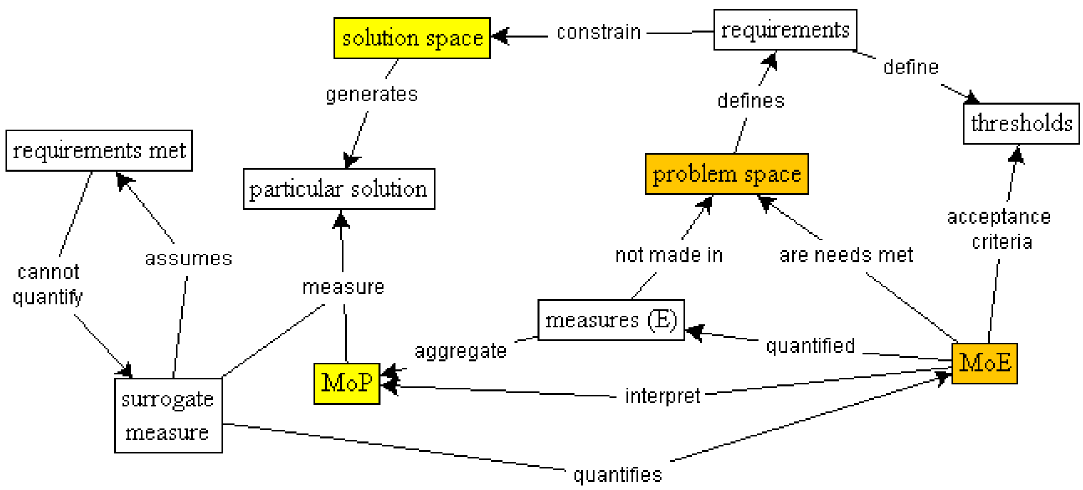

Figure 2. Conceptual Aspects of MoE

2.4 Mathematical Representation of MoE

To a first approximation MoE (for a particular mission) can be represented mathematically as a weighted sum of performance attributes [6], where it is assumed that to be effective all critical requirements must be achieved to at least some threshold value. The weights indicate the relative importance of each performance attribute. Other mathematical representations are discussed in Section 4.5.

The following formula is used as a basis for explanatory purposes throughout this paper.

For critical performance measures "p" and weights "a", we can define constant "K" such that

$$\textbf{MoE} = \begin{cases} \boldsymbol{\Sigma_i a_i p_i + K} & \text{if all } p_i \text{ exceed their individual thresholds} \\ \mathbf{0} & \text{if any } p_i \text{ do not meet their individual threshold} \end{cases}$$

where p_i = Performance of i^{th} attribute

That is, MoE includes the notion of acceptable performance for the whole system; the loss of even one critical requirement makes the whole system ineffective. For brevity, future reference to this equation will leave out the zero outcome.

2.5 Purpose of MoE

MoE is used for at least two purposes – to analyse systems in existence and to predict the effectiveness of future systems. Existing systems allow for direct measurement whilst future systems are measured against models developed with input from subject matter experts.

To assist in discussing MoE, the C2 requirements or needs can be visualised as a landscape where the peaks and valleys represent the relative importance and interaction of the various requirements. Using the same visualisation mechanism, the meeting of the requirements can be represented by an effectiveness landscape. These landscapes will be used to discuss effectiveness and move the discussion away from placing numerical measures on effectiveness. Figure 3 shows such a representation.

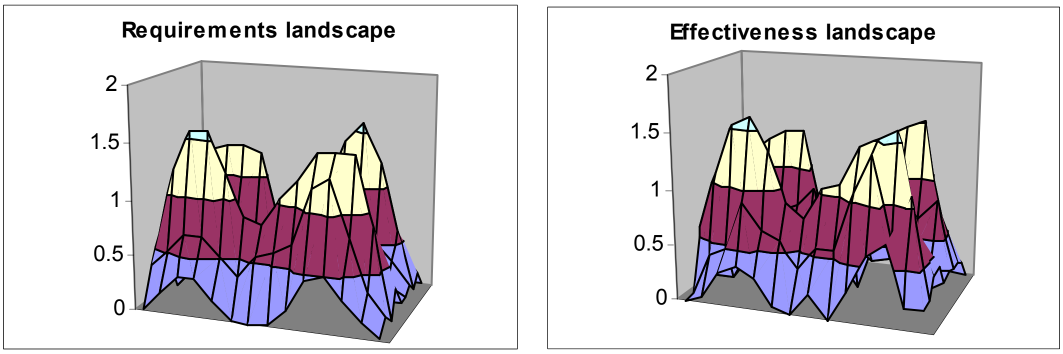

Figure 3. Requirements and Effectiveness Landscapes

These landscapes will be compared in this paper and the phrase "*net effectiveness*" will be defined as the difference between the effectiveness surface and the requirements surface and will thus show a surface where positive values indicate that the requirements have been exceeded, as shown in Figure 4. Based on the threshold definition, to be effective all net values should be positive.

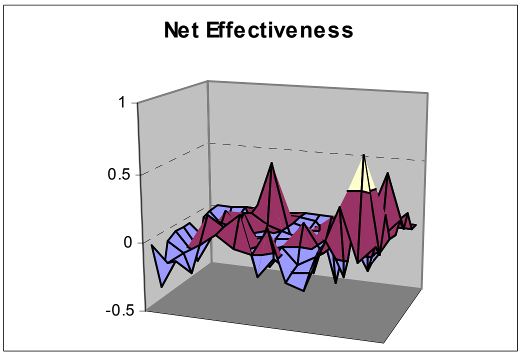

Figure 4. Net Effectiveness Landscape

3 Aspects of Effectiveness

The following discussion is motivated by attempting to answer the questions: "why are systems, which are apparently effective, rendered ineffective over time or changed circumstances?" and "what should be measured to avoid this risk? ". Four major factors will be discussed: the evolution of requirements with time, the impact of external (sometimes unknown) influences, the impact of disruptive technology and intrinsically valuable properties.

3.1 Evolving Characteristics

MoE is often considered an enduring quality of a system but the reality of any complex system (of which C2 systems are good exemplars) is that with experience, usage and changing circumstances the requirements often evolve and consequently the MoE must evolve to reflect these new requirements. Whilst this appears to be an obvious observation, it can have wide ranging ramifications for effectiveness and its measurement. Experience may indicate that some system parameters have been over or under-estimated in importance but more importantly unknown requirements may surface which critically impact effectiveness.

Especially with new technology, usage highlights design or conceptual weaknesses and these may introduce completely unexpected (and unpredictable) requirements. This is particularly so for very successful systems where proliferation and widespread adoption often creates new requirements. For example, widespread adoption of active radar surveillance increases the need for interference abatement; overlapped surveillance increases the criticality of data fusion.

Using the mathematical approximation above, these changes to requirements can be expressed as:

$$\mathbf{MoE} = \Sigma_i a_i p_i + \Sigma_j b_j p_j + K \qquad \text{where } p_i = \text{Perf of } i^{th} \text{ original attribute}$$

$$p_j = \text{Perf of } j^{th} \text{ new or changed attribute}$$

3.2 Externalities

Whilst it is tempting to treat a complex system as a closed system and measure effectiveness accordingly, this ignores those influences outside the system (externalities) that can strongly influence effectiveness. These external factors often constrain system performance and their influence is only recognised when their characteristics move outside the design parameters of the system. There are two externalities that need to be considered – those that are explicitly considered within the design and those that were ignored or not even contemplated at the design stage. The externalities are part of the constraints of the problem-space.

The general concept of effectiveness needs to explicitly include the impact of the external environment within which a system is used. The environment provides the boundary conditions under which a system must operate and operating outside these conditions can greatly impact effectiveness. The environment can dynamically change or subtle environmental conditions can have unforeseen impacts. A C2 system always exists within an operating environment and is made up of various subsystems; all of which contribute to its effectiveness. Until externalities are incorporated into a C2 system, its effectiveness will be less than ideal, as shown in Figure 5.

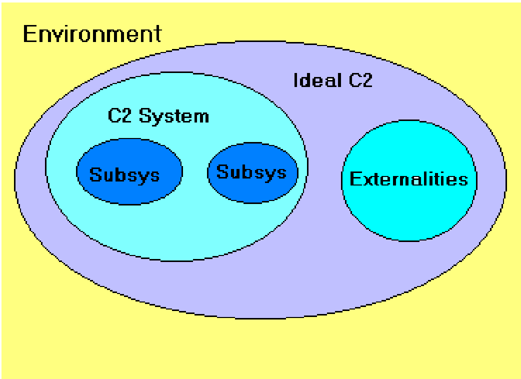

Figure 5. C2 Systems in Context

The externalities can be interpreted in two ways – they either degrade the potential effectiveness (particularly those which were unknown at the design stage) or for environmental impacts they can be incorporated into the requirements increasing the effectiveness thresholds that need to be surpassed to attain an effective system. Either way they decrease the net effectiveness.

To account for degraded effectiveness due to externalities, MoE can now be described thus:

$$\mathbf{MoE} = \Sigma_i \, a_i \, p_i^{/} - \Sigma_j \, b_j \, p_{je} + K \qquad \text{where } p_i^{/} = (1- e_i)\, p_i \,,$$

, p_i are known requirements

, e_i is environmental impact and

, p_{je} are performance of unknown externalities.

Changed requirements due to externalities can be visualised via the requirements landscape (Figure 6) where the first externalities landscape shows the requirements extending beyond those designed for and the second plot shows the requirements being influenced by the environment:

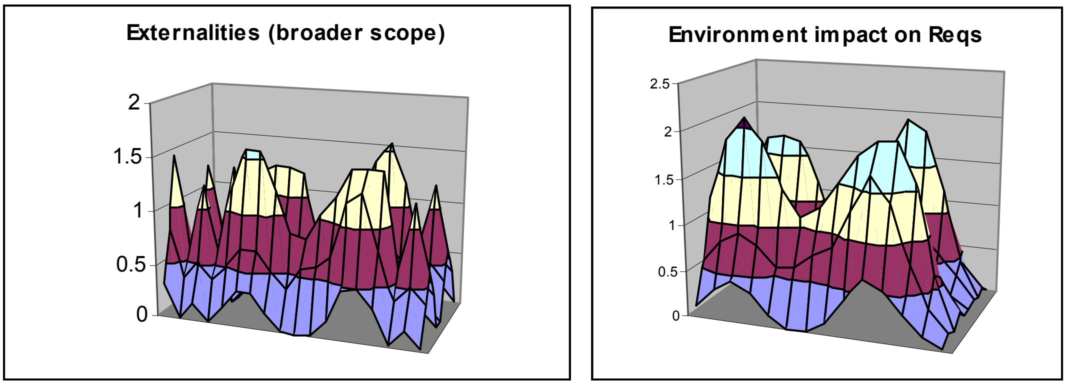

Figure 6. External Impacts on Requirements

Either way the net effectiveness has been reduced by detrimental externalities, as shown in the net effectiveness landscape (Figure 7) where the blue region indicates where requirements are still being met.

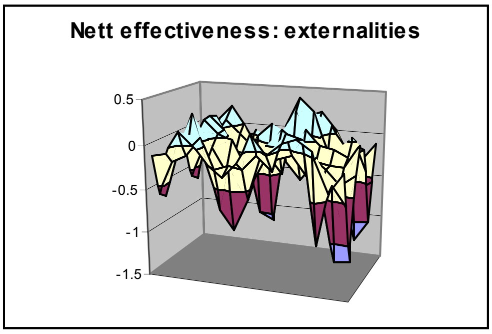

Figure 7. Influence of Externalities

3.3 Disruptive Technology

The term disruptive technology was coined by Clayton Christensen [2] to describe a new, low cost, often simpler technology that displaces an existing sustaining technology. Sustaining technology is usually well-known technology that has a predictable growth curve based on enhancing known technology.

"Disruptive technologies are usually initially inferior to the technology that they displace, but their low cost or convenience creates a market that induces technological and economic network effects that provide the incentive to enhance them to match and

surpass the previous technology" [16]. When describing the effectiveness of disruptive technology Christensen [2] emphasises that the performance attributes of disruptive technology are different to those of a sustaining technology and hence they are often ignored. This difference can be illustrated by the following equations where the disruptive MoE substitutes disruptive technology for some of the sustaining technology:

For performance measures p and weights a and b, we can define constants K_s and K_d such that

$$\mathbf{MoE_{(sustaining\ technology)} = \Sigma_k\, a_k\, p_{sk} + K_s} \qquad \text{where } p_{sk} = Perf_{(sustaining\ technology)k}$$

$$\mathbf{MoE_{(disruptive\ technology)} = \Sigma_i\, a_i\, p_{si} + \Sigma_j\, b_j\, p_{dj} + K_d} \qquad \text{where } p_{dj} = Perf_{(disruptive\ technology)j}$$

Initially $MoE_{(sustaining\ technology)}$ surpasses $MoE_{(disruptive\ technology)}$ as shown in the following effectiveness landscapes (Figure 8) and consequently the disruptive technology is ignored.

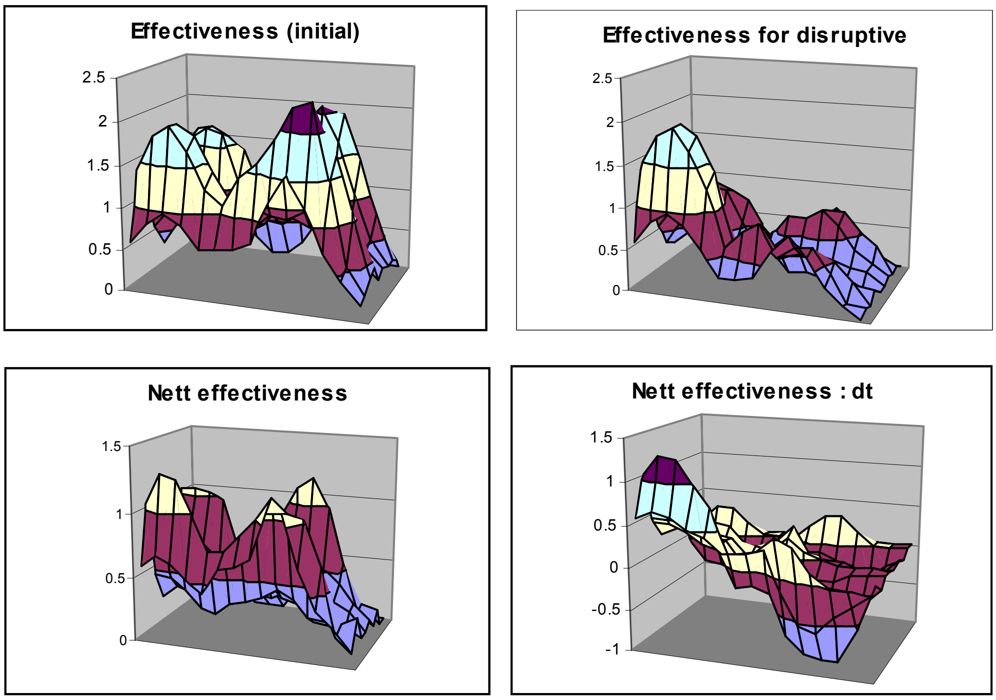

Figure 8. Sustaining versus Disruptive Technology

Christensen argues that the disruptive effects occur because not only does the inferior technology eventually become superior but, more importantly, its superiority is not recognised until it is too late because it is judged by different performance measures. This is shown in the following Venn diagram (Figure 9) where the yellow and green segments are observed within the sustaining technology but the blue segment is ignored, as the effectiveness characteristics are downplayed or ignored within the solution space.

Performance measures can only be measured within the solution space and the impact of disruptive technology on performance parameters highlights the need to analyse effectiveness within the problem-space. That is, within the problem-space all technologies need to be observed and tracked for effectiveness. For example: within the C2 problem space, a surveillance need is to track asset movements and various mechanisms can be used to achieve this, for example enhanced data fusion algorithms or new types of radars. For any particular radar system, radar detection cross-section is an indicator of performance (in the solution space) but emphasis on this measure ignores that multiple mechanisms (possibly combined) can effectively achieve the surveillance goal. Alternative technologies may have poor attributes on this measure but still provide effective surveillance through other mechanisms.

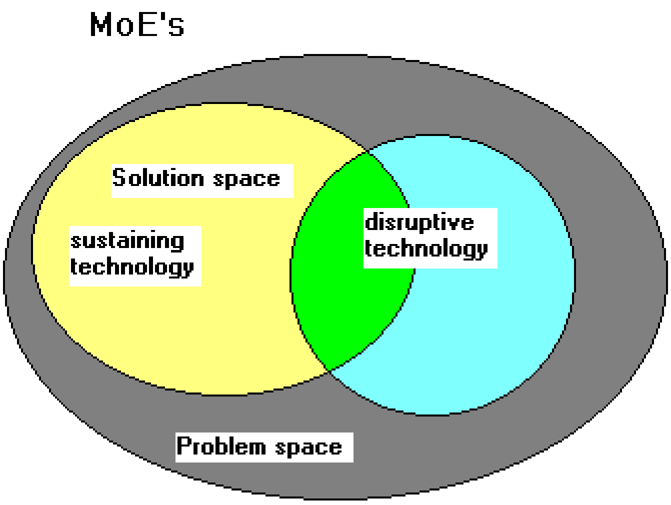

Figure 9. Alternate Solutions

3.4 Intrinsically Valuable Attributes

It is our view that effectiveness is also partially dependent on intrinsically valuable properties. The term intrinsically valuable is used to describe internal properties of solutions that determine whether a system will work and which, when enhanced, always improve the system's effectiveness. Within physical systems an example would be friction, where its reduction always improves effectiveness; within a C2 system it could be argued that enhanced Situational Awareness or reduced message latency [12] are intrinsically valuable.

To produce effective systems, one goal of system development should be the discovery and validation of these intrinsically valuable properties. It is postulated that discovering the intrinsically valuable properties leads to more agile and effective designs as, while these properties may be derived from considering possible solutions, they usually address broad issues that have applicability across the whole problem domain rather being specific to any particular solution. They also usually have the characteristic of being orthogonal to each other and hence improving them does not detrimentally impact other characteristics – improving their effectiveness improves system effectiveness.

In addition to those identified above, candidates for intrinsically valuable properties for C2 systems are security (and resistance to tampering), low detectability, intelligent and/or creative behaviour (by the system), extended communications capacity (range and throughput) and trust (between people and between system and people). Some of these attributes are difficult to measure absolutely but their direction of improvement can often be measured.

To illustrate intrinsically valuable properties, MoE is now:

MoE = $\Sigma\, a_i\, p_i + \Sigma\, b_j\, p_j + K$ where p_i = Performance of i^{th} attribute,

p_j = Performance of j^{th} intrinsically valuable property

This can be visualised via the net effectiveness landscape where improvements in some intrinsic characteristics improved overall effectiveness as shown in Figure 10.

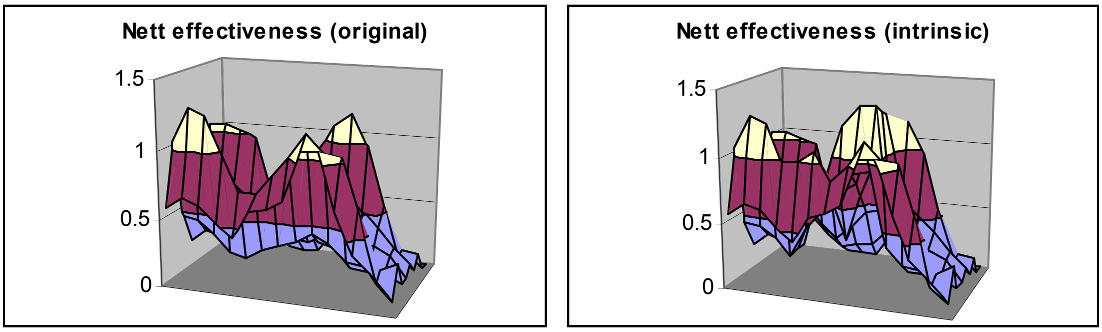

Figure 10. Enhancement of Intrinsic Properties

4 Approaches to Measurement

4.1 Hierarchical Definition MoP and MoE

Since the components can themselves be systems the MoE formulae can be applied recursively from system to subsystem to sub-subsystem as shown in Figure 11. This figure indicates that a system's (or subsystem's) effectiveness is dependent on the performance of its subsystems and that at any particular level a system's performance may be dependent on the effectiveness of other systems at that level. For example, a radar's performance is dependent on a power supply, signal generator and signal receiver (amongst other things) but the signal generator is only effective if the power supply is effective. The power supply's effectiveness is dependent on its generation subsystem and battery subsystem, etc.

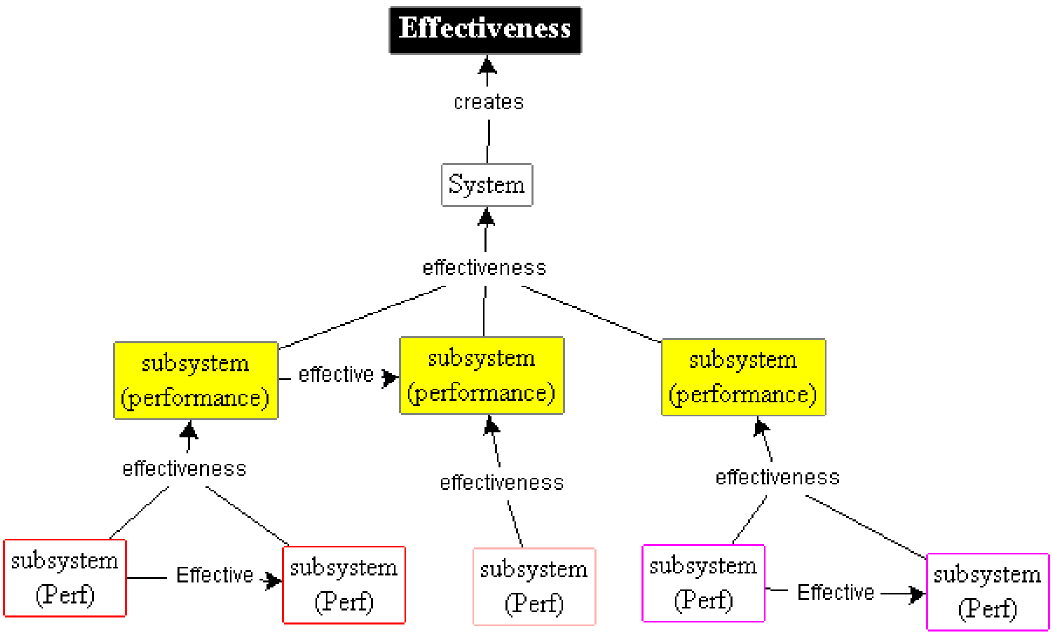

Figure 11. Hierarchical Decomposition of Effectiveness

4.2 Emphasis on Problem Space

Figure 11 encapsulates the view that the effectiveness that a system delivers (the meeting of its requirements) is dependent on the effectiveness of the subsystems (whose performance may be measurable). If this decomposition continues then the same approach can be applied, namely the effectiveness of a subsystem is dependent on the performance of its subsystems. Effectiveness requires that all required characteristics must exceed their thresholds before the whole system is effective. The effectiveness decomposition needs to occur in the problem-space and if the system breakdown does not match the solution breakdown then performance measures need to be allocated across systems to allow aggregation.

To make effective measures there are three measurement issues which need to be addressed: (1) aggregating the measures, (2) ensuring that the measurements have consistent units and a "direction of improvement", that is, measurements need to be formulated so improvements add to the overall improvement of the system; and (3) being able to combine quantitative and qualitative measures [6]. For instance, increasing bandwidth could not be combined with decreasing latency (these both potentially lead to improvements) as they have opposing directions of improvement. Qualitative measures can be allocated to some arbitrary scale to allow their combination with quantitative measures. Measurements ideally should be unit-free and this can be achieved by normalising the measurements [12]. The weighting factors introduced earlier can compensate for inconsistent scales and units.

Performance measures provide measures derived from the solution space but effectiveness needs to be based on the problem space. Solution-space measures need to be mapped back to problem-space effectiveness attributes. For example, within a C2 system measures like bandwidth are not really important in the problem space where the issue is throughput. Throughput is dependent on bandwidth and message size, that is, very large messages can quickly negate any bandwidth improvements. By focussing on the problem space, effectiveness parameters can be more clearly articulated.

4.3 Causal Chains and Value Network Analysis

Another approach to measuring effectiveness is to recognise the dependency between system components and use these dependencies to guide the assessment process. Ittner [8] argues that (within the business world) effectiveness of an organisation can be determined by creating a causal chain from the required objective backwards. Effectiveness is then achieved by determining the drivers of the nodes in the causal chain and improving them. Implicit in this, is the assumption that improving the drivers improves the effectiveness of the node. Improving this node increases the effectiveness of the next node in the causal chain. Ittner's paper, based on case studies, supports this premise. The process of measurement then reduces to measuring improvements to the drivers.

Within a C2 context a causal chain could be the OODA loop as shown in Figure 12, where the drivers for the *orient* node are given as (historical) context, fused data (to minimise ambiguity) and presentation to the commander.

The discovery of these causal chains can be assisted by using a process called Value Network Analysis [1], which analyses how value is added to a system. This process explicitly represents the transactional interchange of (1) products and services, (2) knowledge and (3) intangibles such as trust and loyalty. Value networks are defined as *" a web of relationships that generate tangible and intangible value through complex dynamic exchanges between two or more individuals, groups, or organisations"*. This definition obviously applies to C2 systems (including the people involved) and within a C2 context these three areas of interchange are critical to overall system effectiveness. The loss of any one will significantly reduce overall system effectiveness.

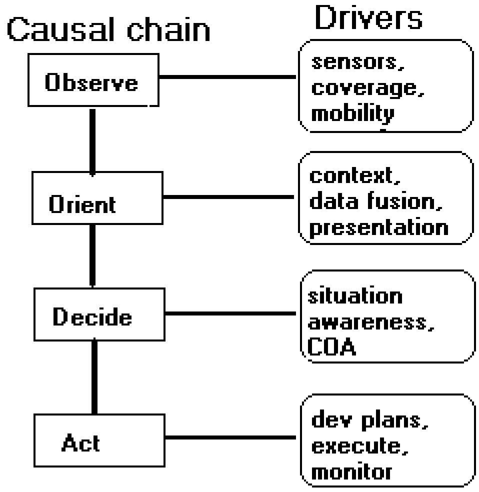

Figure 12. OODA Loop Causal Chain

The extension of C2 to broadly based coalitions (whether with other government agencies or other countries) significantly increases the importance of the transfer of both knowledge and the intangibles, and hence the importance of explicitly representing these transfers and incorporating them into effectiveness models. Figure 13 illustrates a value network for an incomplete C4ISR system and shows the various elements exchanged between the participating systems and people involved.

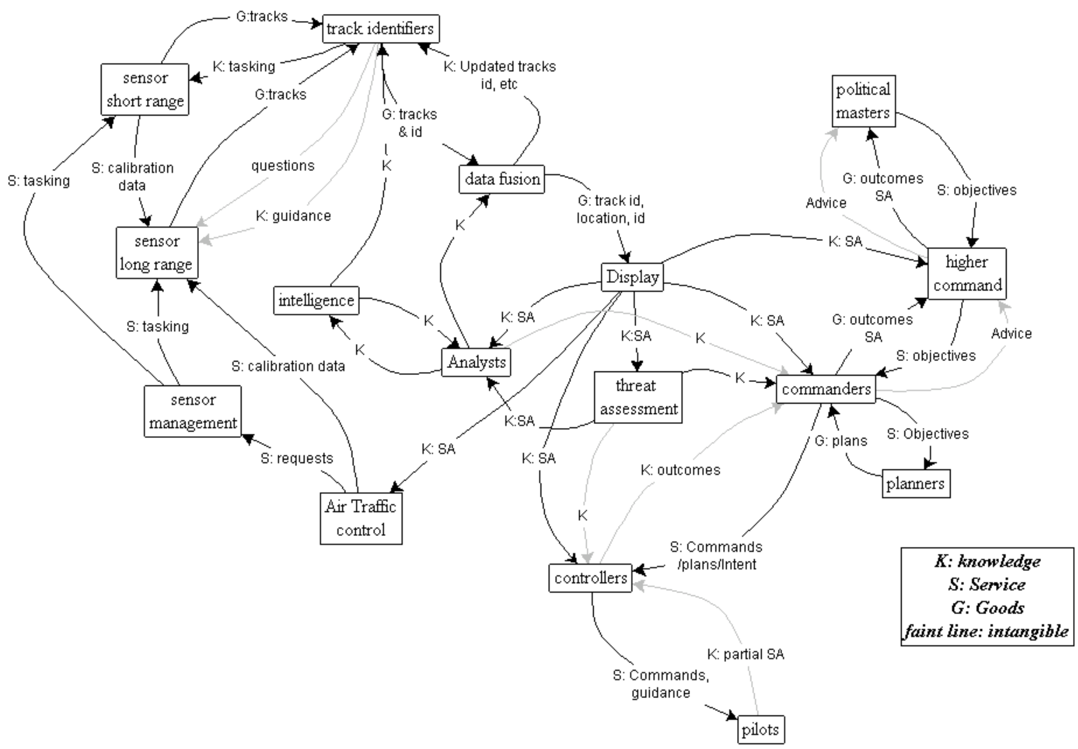

Figure 13. C4ISR Value Network

This form of model is particularly important, as effectiveness of any complex system involving human interactions needs to deal explicitly with both tangible and intangible exchanges. The complex feedback loops shown in Figure 13 indicate the difficulty in formulating a linear causal chain for the whole system but offer guidance in evaluating components. For example: the commander requires an objective (from some higher command) and develops Situational Awareness from displays based on fused sensor data and threat assessment reports. The commander provides his objectives to planners who create plans that are forwarded to controllers, etc. This type of analysis can be extended using Value Network Analysis techniques [1] to look at how value is added by each exchange and at what cost.

This more complete form of analysis complicates the measurement process, particularly with respect to intangible exchanges but it provides a vehicle for analysing the weaknesses of a system and where enhancements can add value. If the model correctly matches the problem-space then, taking the causal view, value-adding enhancements increase the overall effectiveness.

4.4 Surrogate Measures

Both the system decomposition and causal chain approach to assessing effectiveness rely on being able to decompose a system into component parts and knowing their interrelationships. Another approach to measuring effectiveness is to use surrogate measures that indirectly indicate effectiveness.

These measures directly correlate with the needs of a system but the surrogate is assumed to aggregate the effects of the complex interrelationships within the system. Sproles [14] uses the example of platypus population as a measure of river water quality. The platypus life cycle is known to be sensitive to river water quality.

The use of surrogates accepts that the linkage between requirements and system characteristics cannot be elucidated, but that outcomes can be measured which indicate an effective system. The discovery of these surrogate measures is non-trivial and often they initially seem counter-intuitive. If they exist they have the characteristic of being easy to measure.

Such approaches need to be used with caution as they can easily be abused – other extraneous factors may influence the surrogate, or malicious intent may distort the measure. Recent audit and accounting scandals have highlighted the risk of treating a company's share price as a surrogate effectiveness measure. For systems with complex or unknown interactions, surrogate measures are good as long as they are continually cross-validated against other measures and inconsistencies are not ignored. For example, an increasing platypus population in conjunction with obvious measures of water quality deterioration would indicate the measure was wrong or that the platypus population was being manipulated.

4.5 Weighted Sums and Effectiveness Landscapes

Green [7] argues that a probabilistic framework should be used to measure effectiveness and that viewing a system as a network of processes allows probabilistic rules to be used to combine measures. So for sequential processes the total effectiveness is just the product of the individual processes

$$P_t = P_a P_b P_c$$

and for parallel processes the total effectiveness is the sum of their effectiveness minus their product

$$P_t = P_a + P_b - P_a P_b.$$

The application of these formulae is dependent on meeting the probabilistic requirements of independence between processes, which will often not be true in C2 systems. In addition, it does not capture the generally agreed notion that effectiveness is derived from a weighted contribution of system attributes.

Filar et al [6] describe the problem of aggregating measures as being equivalent to Multi-Criteria Decision-Making and that various approaches can be used to produce these aggregate measures. Simple additive weighting has been used earlier in this paper (for illustrative purposes), but there is no universally accepted mechanism to combine the performance or effectiveness measures particularly in complex domains like C2.

Rather than solve the aggregation problem, it is the authors' view that the use of effectiveness landscapes provides another method to analyse and visualise effectiveness. These landscapes suggest that the quest for a number representing effectiveness may be too simplistic and that some higher dimensional approach should be explored [12]. Ignoring the mechanics of creating these landscapes, a major premise of this paper is that effectiveness is related to problem needs (requirements) and that effectiveness needs to be judged against these requirements. This was visualised in Figure 3 via landscapes that show regions of the problem space having different levels of importance. The notion of net effectiveness (as defined earlier and shown in Figure 4) provides a mechanism and visualisation to compare systems for effectiveness to answer the question "which system is more effective?".

The comparison between alternatives can be done by comparing the net effectiveness surfaces. When all critical requirements are met (all thresholds exceeded) then this comparison can take many forms: the volume enclosed is one measure of net effectiveness or some weighting could be applied to allow for the relative importance of the requirements. In the simplest case, a surface that fully encloses another surface is obviously more effective and this measure can be done by subtracting the net effectiveness landscapes. Figure 14 compares disruptive to sustaining technology (from Figure 8) showing the extra effectiveness afforded by the sustaining technology.

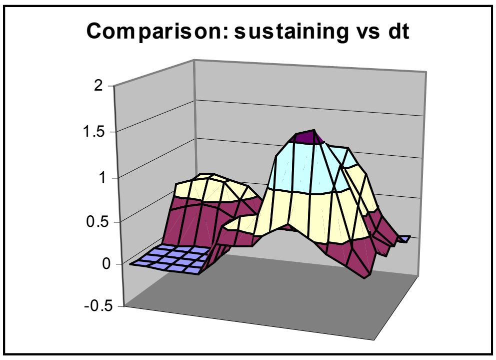

Figure 14. Net Effectiveness: Sustaining minus Disruptive

5 Conclusions

This paper has argued that the definition of effectiveness needs to be broadened include the impact of externalities on effectiveness and to identify intrinsically valuable properties which facilitate effective systems. The general impact of these extensions has been illustrated through simple mathematical formulae and effectiveness landscapes. The use of these extensions and the focus on defining effectiveness within the problem space (instead of the solution space) maximises the likelihood of new technology (particularly disruptive technology) being considered and incorporated into evolving C2 systems.

This is particularly important for disruptive technology, as, by its very nature, it is initially inferior to existing technologies. It is postulated that the discovery of intrinsically valuable properties, which apply to the problem space and hence have a more enduring quality, will lead to more agile architectures that can be varied to meet changing requirements.

Landscapes have been used to illustrate issues associated with effectiveness as this approach highlights the complexities involved. The comparison of landscapes varies from being straightforward (one encloses another) to very complex and dependent on value judgement. These landscapes reinforce the view that requirement thresholds must be met before a system can be considered effective.

The causal chain view of effectiveness was also discussed and within the context of improving an existing system this approach has merit, particularly if it is accepted that improving the drivers to the causal nodes increases overall effectiveness. The analysis of complex systems, such as C2, requires modelling tools that capture the full range of interactions observed and the Value Network Analysis approach meets many of these requirements as it models the dependencies of a system plus the flow of both tangible and intangible exchanges.

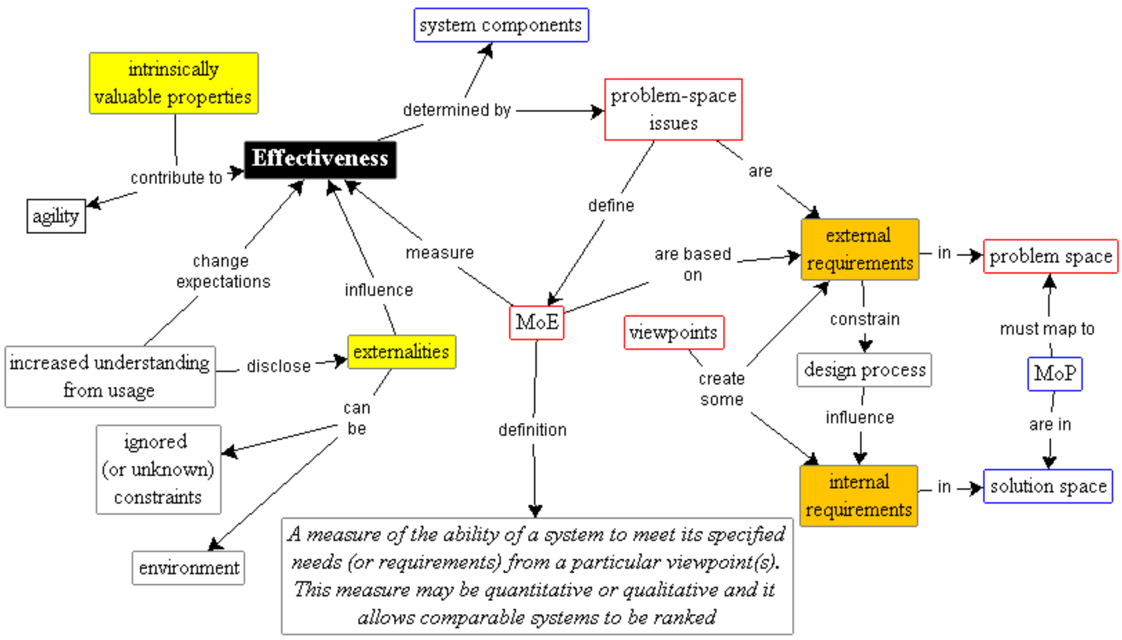

Figure 15. Effectiveness Relationships

Figure 15 shows effectiveness and its relationship to various concepts and approaches to its definition. This paper sees effectiveness as being a problem-space issue that needs to be assessed from measures that can only be made in the solution-space. The mapping between these two spaces is the ultimate challenge.

Whilst this paper has covered some new ground in the discussion of effectiveness and tried to broaden its scope, further questions are yet to be addressed. These include:

- What is the relationship between effectiveness and efficiency?
- What is the relationship between time and effectiveness? (that is, what is the impact of system life on effectiveness?)
- Does it make sense to try to measure emergent properties (particularly of future systems)?

- Weighted sums of performance makes sense, can the same be said for sums of MoE?
- Can systems be partially effective and if so, can they be compared? (how is non-compliance compared?)

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