Australian Government
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Defence Science and
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An Exploration of C2 Effectiveness – A Holistic Approach

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Introduction

- Broader definition of effectiveness required
- Fast changing world, both threats and technology
- Disruptive technology often ignored
- External factors need to be part of definition

These concepts are developed and illustrated via simple mathematics and "landscapes".

Given this broader view of effectiveness, approaches to measuring effectiveness are then discussed:

- Hierarchical decomposition in problem space
- Surrogate measures
- Causal chain and Value Network Analysis
- Weighted sums and effectiveness landscapes

MoE Definition

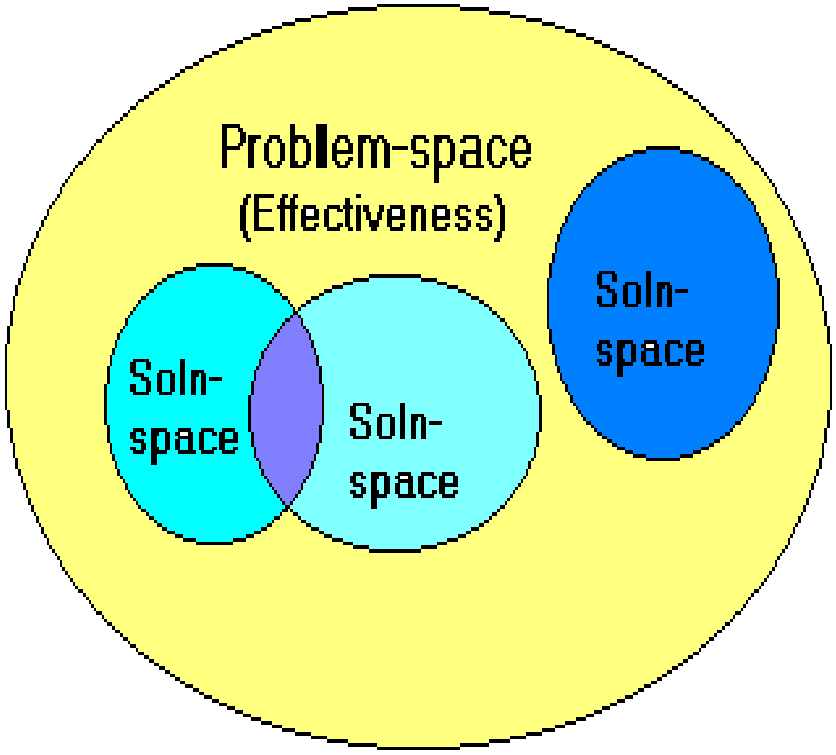
MoE: Smith & Clark *"A **measure** of the ability of a system to meet its **specified needs** (or requirements) from a particular viewpoint(s). This measure may be quantitative or qualitative and it allows comparable systems to be **ranked**. These effectiveness measures are defined in the **problem-space**. Implicit in the meeting of problem requirements is that **threshold values** must be exceeded."*

Problem space vs Solution space

- **Problem Space:** The needs, what is required. Where effectiveness needs to be measured
- **Solution Space:** Mechanisms to satisfy needs, how is it achieved. Where performance is measured

Decomposition possible as the solution space generates needs which are resolved by lower level solutions.

Multiple solutions can satisfy needs (requirements), sometimes sharing solution components.



Mathematical Representation of MoE

To illustrate effectiveness, we will define MoE mathematically as a weighted sum of performance attributes ($\mathbf{p_i}$), thus:

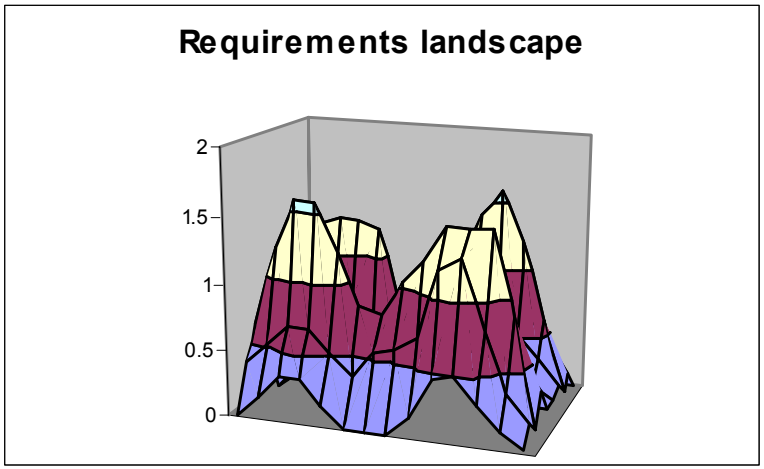
MoE	$= \sum_i \mathbf{a_i}\ \mathbf{p_i} + \mathbf{K}$	if all p_i exceed their individual thresholds
	$= \mathbf{0}$	if any p_i does not meet its individual threshold
		where p_i = Performance of i^{th} attribute

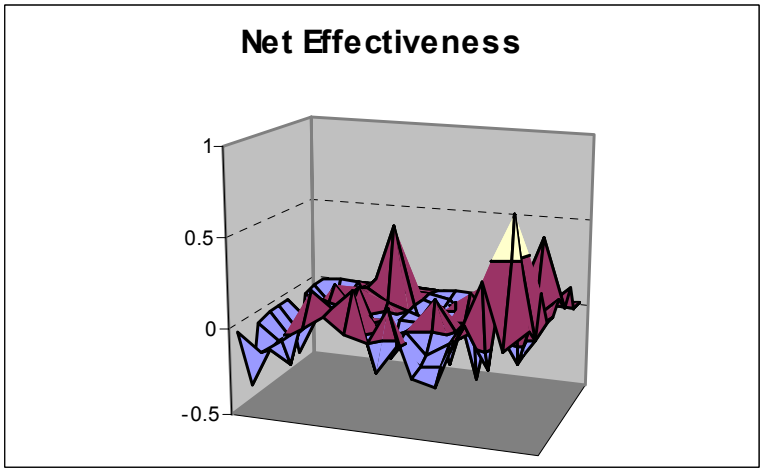
Purpose of MoE

- MoE are used for at least two purposes –
  - to analyse systems in existence (measure directly)
  - to predict the effectiveness of future systems (measure against models)

- We can visualise effectiveness via landscapes (non-numeric representation), thus

Purpose of MoE





Peaks and valleys indicate relative importance of requirements.

Net effectiveness is difference between effectiveness landscape and requirements landscape, positive regions denote satisfaction of requirements (blue region is non-compliant).

Aspects of effectiveness

- **This investigation was motivated by considering the question:**

  "Why are systems, which are apparently effective, rendered ineffective over time or changed circumstances?"

- **Four attributes are discussed:**

  1. **evolution of requirements with time**
  2. **impact of external (sometimes unknown) influences**
  3. **impact of disruptive technology**
  4. **intrinsically valuable properties.**

1. Evolving characteristics

- MoE must evolve to reflect evolving requirements from:
  - experience
  - usage
  - changing circumstances

  which cause
  - under or overestimating importance of attributes
  - unknown requirements to surface

This can be represented as:

$$MoE = \sum_i a_i p_i + \sum_j b_j p_j + K$$

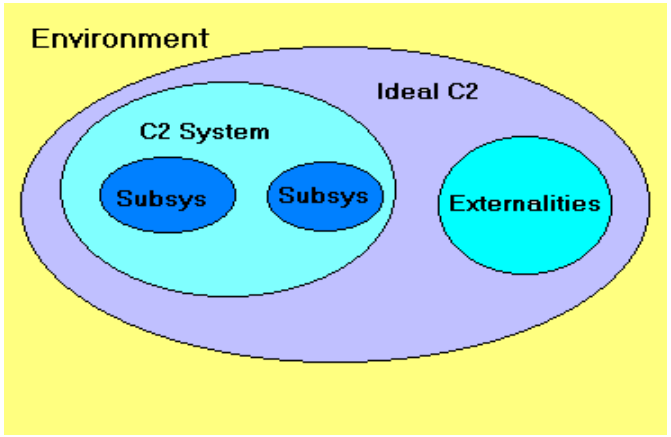
where p_i = Perf of i^{th} original attribute

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

2. Externalities

- It is too simplistic to treat a complex system as a closed system
- Two externalities need to be considered
  - those explicitly considered within the design stage, and
  - those ignored or not even contemplated at the design stage
- Externalities are constraints on the problem space that degrade effectiveness. 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, thus increasing the effectiveness thresholds that need to be surpassed.
- Either way they decrease the net effectiveness.

2. Externalities (cont)



MoE reduction (against ideal):

$$\mathbf{MoE_{(ideal)} = \Sigma_i\, a_i\, p_i' - \Sigma_j\, b_j\, p_{je} + K}$$

where $p_i' = (1 - e_i)\, p_i$,

p_i are performance of known requirements,

e_i is environmental impact and

p_{je} are performance of unknown externalities.

3. Disruptive Technology

- Disruptive technology (Clayton Christensen) describes a new, low cost, often simpler technology that displaces an existing sustaining (predictable) technology.
- Performance attributes of disruptive technology are usually different to those of a sustaining technology.

Their effectiveness can be represented as:

$$MoE_{(\text{sustaining technology})} = \sum_k a_k p_{sk} + K_s$$

$$\text{where } p_{sk} = Perf_{(\text{sustaining technology})k}$$

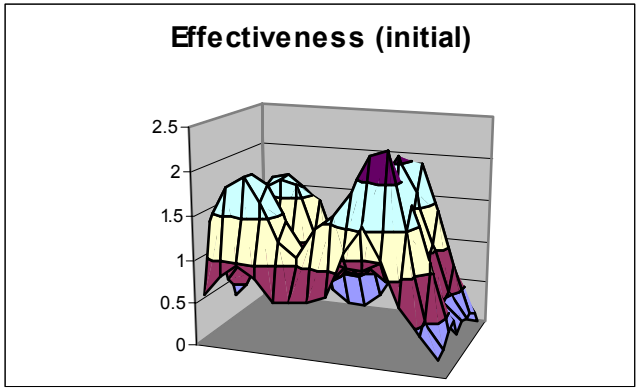
$$MoE_{(\text{disruptive technology})} = \sum_i a_i p_{si} + \sum_j b_j p_{dj} + K_d \quad \text{(mixed)}$$

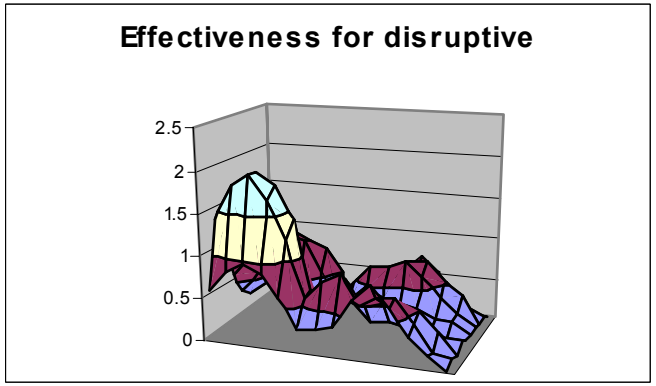
$$\text{where } p_{dj} = Perf_{(\text{disruptive technology})j}$$

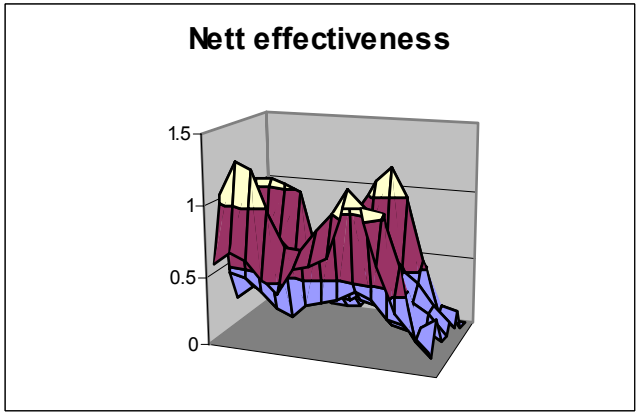
$$p_{si} = Perf_{(\text{sustaining technology})i}$$

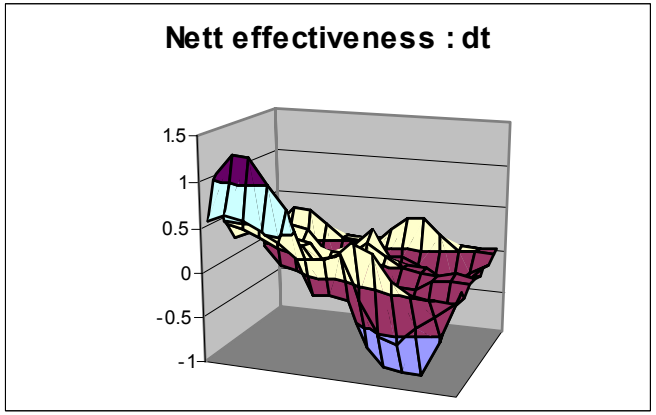
3. Disruptive technology (cont)

Initially MoE of sustaining technology surpasses MoE of disruptive technology as shown

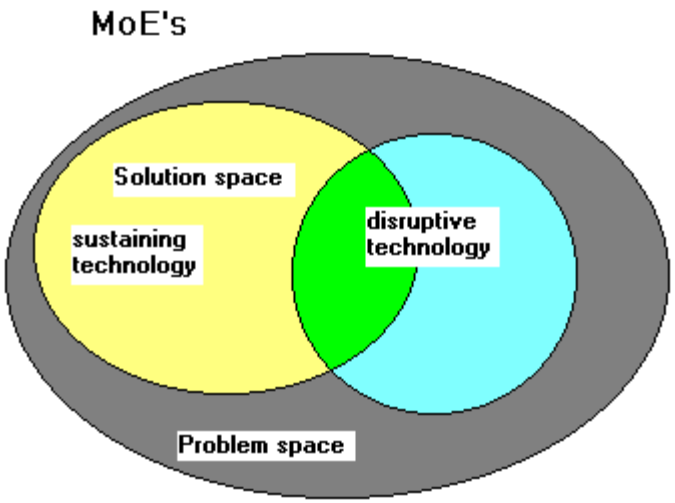








3. Disruptive technology (cont)



Disruptive effects occur because inferior technology eventually become superior and its superiority is not recognised until it is too late because it is judged by different performance measures.

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.**

4. Intrinsically valuable attributes

- Effectiveness is also partially dependent on intrinsically valuable properties which are defined to be internal properties of systems that determine whether a system will work and which, when enhanced, always improve the system's effectiveness.

- Usually have the characteristic of being orthogonal to each other, so improving one is not detrimental to another characteristic.

- One goal of system development should be the discovery and validation of these intrinsically valuable properties. They usually address broad issues that have applicability across the whole problem domain.

4. Intrinsically valuable attributes (cont)

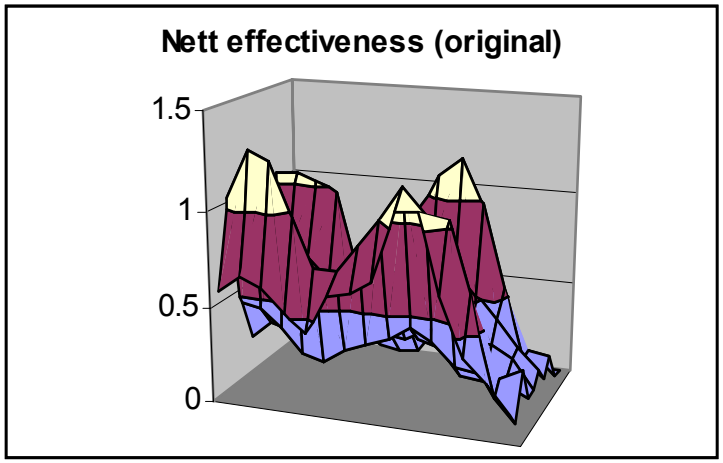
This can be represented as:

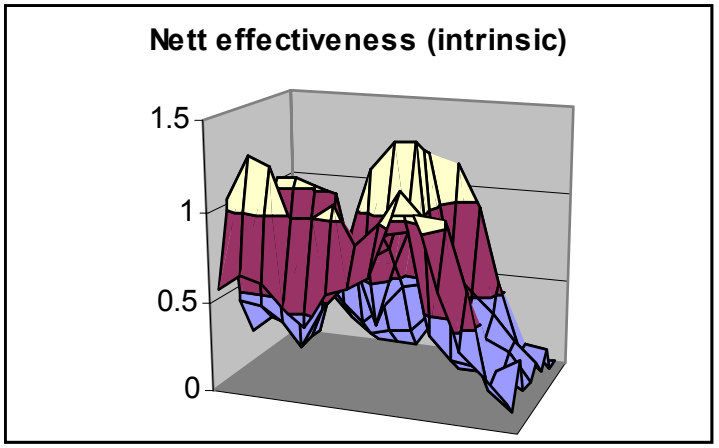
MoE = $\Sigma\, a_i\, p_i + \Sigma\, b_j\, p_j + K$ (mixed attribution)

where p_i = performance of i^{th} attribute,

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

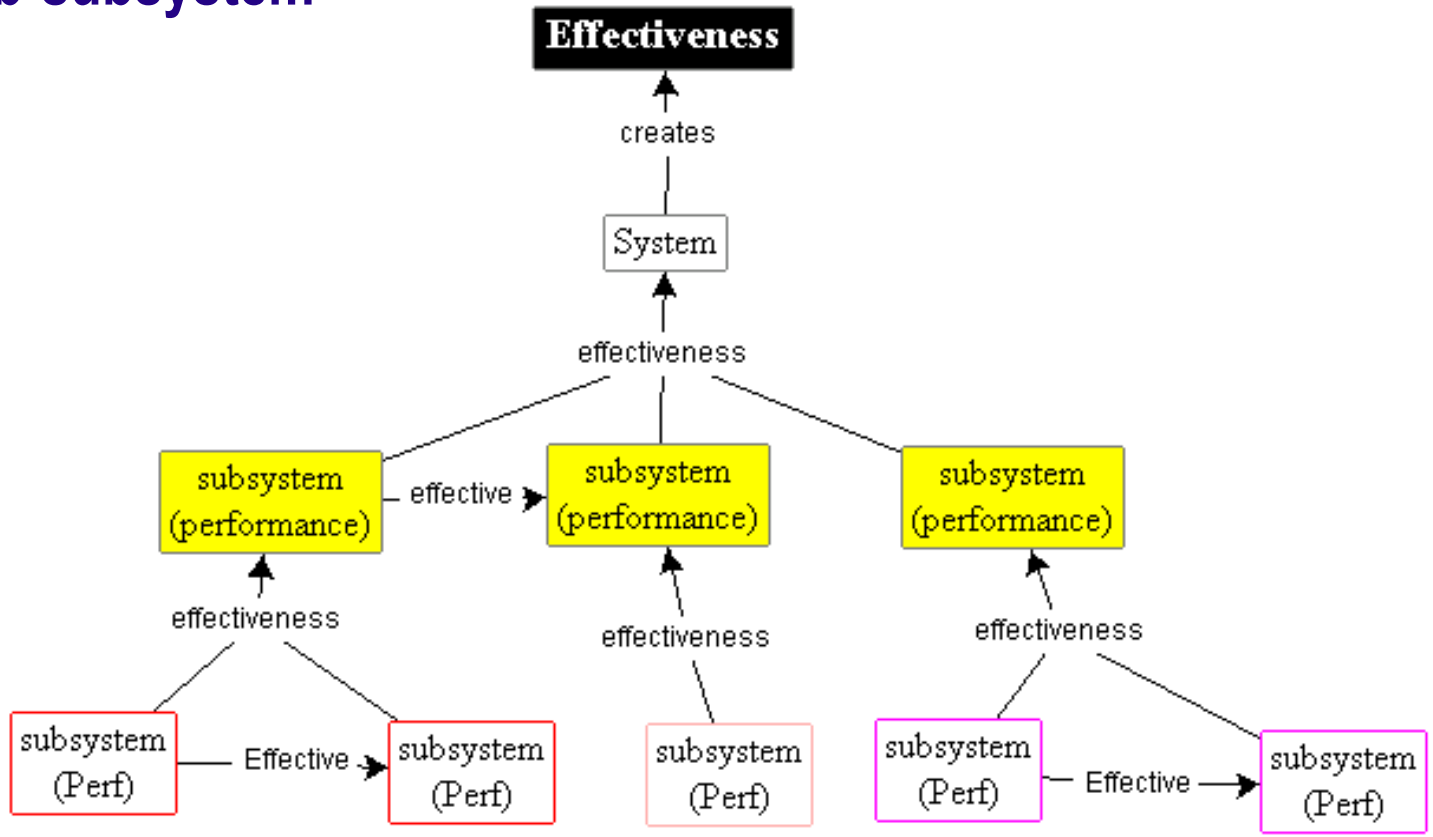
Landscape visualization (improved intrinsics):





Approaches to Measurement

Since the components can themselves be systems, the MoE formulae can be applied recursively from system to subsystem to sub-subsystem



Emphasis on Problem Space

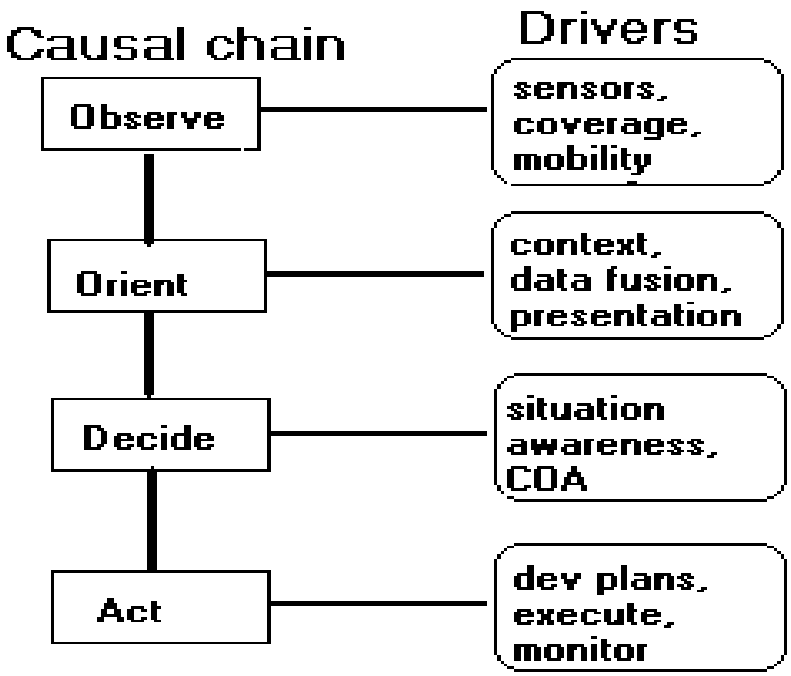
- The effectiveness decomposition needs to occur in the problem-space and if the system breakdown does not match the solution breakdown then performance measures need to be allocated across systems to allow aggregation.

- Three measurement issues which need to be addressed:
  - aggregating the measures,
  - ensuring that the measurements have consistent units and a "direction of improvement",
  - being able to combine quantitative and qualitative measures

- By focusing on the problem space, effectiveness parameters can be more clearly articulated.

Causal Chains and Value Network Analysis

Dependency between system components can guide the effectiveness assessment process. These dependencies form a causal chain that is influenced by their drivers. Ittner argues that improving the drivers leads to more effective systems. For C2, we have:

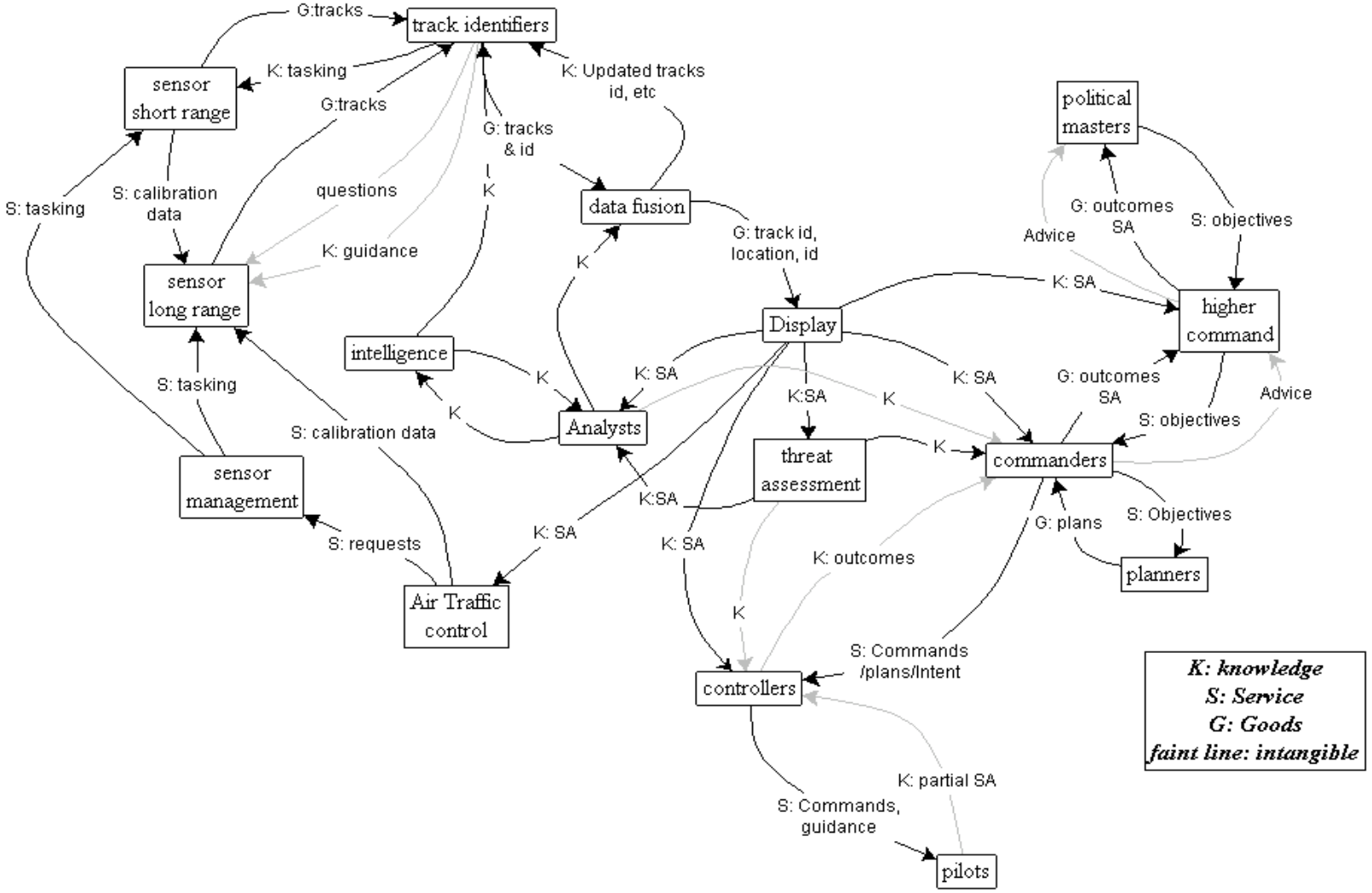


Causal Chains and Value Network Analysis

- Value Network Analysis provides a mechanism to discover these causal chains. It explicitly represents the transactional interchange of
  - products and services,
  - knowledge and
  - intangibles such as trust and loyalty.

- These models highlight the complexity of evaluating effectiveness (mainly due to feedback loops), but small segments can be analyzed. For example: the commander's needs.

Causal Chains and Value Network Analysis

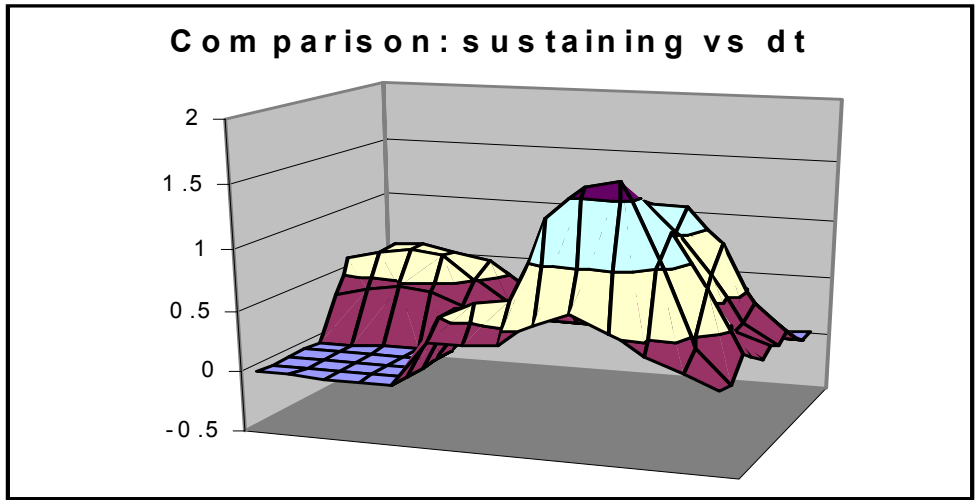


Surrogate measures

- If a system is too complex or cannot be successfully decomposed then surrogate measures of effectiveness can be used.
- These measures directly correlate with the needs of a system and the surrogate is assumed to aggregate the effects of the complex interrelationships within the system.
- They can easily be abused:
  - extraneous factors may influence the surrogate
  - malicious intent may distort the measure
- Hence, they require cross-validation against other measures.

Weighted Sums and Effectiveness Landscapes

- Any attempt to derive a simple numeric MoE needs to solve the aggregation problem, that is: how are MoE's, MoP's combined.
- This is still an open problem.
- Effectiveness landscapes provide another method to analyse and visualise effectiveness. The comparison between alternatives (which can take many forms) can be done by comparing the net effectiveness surfaces



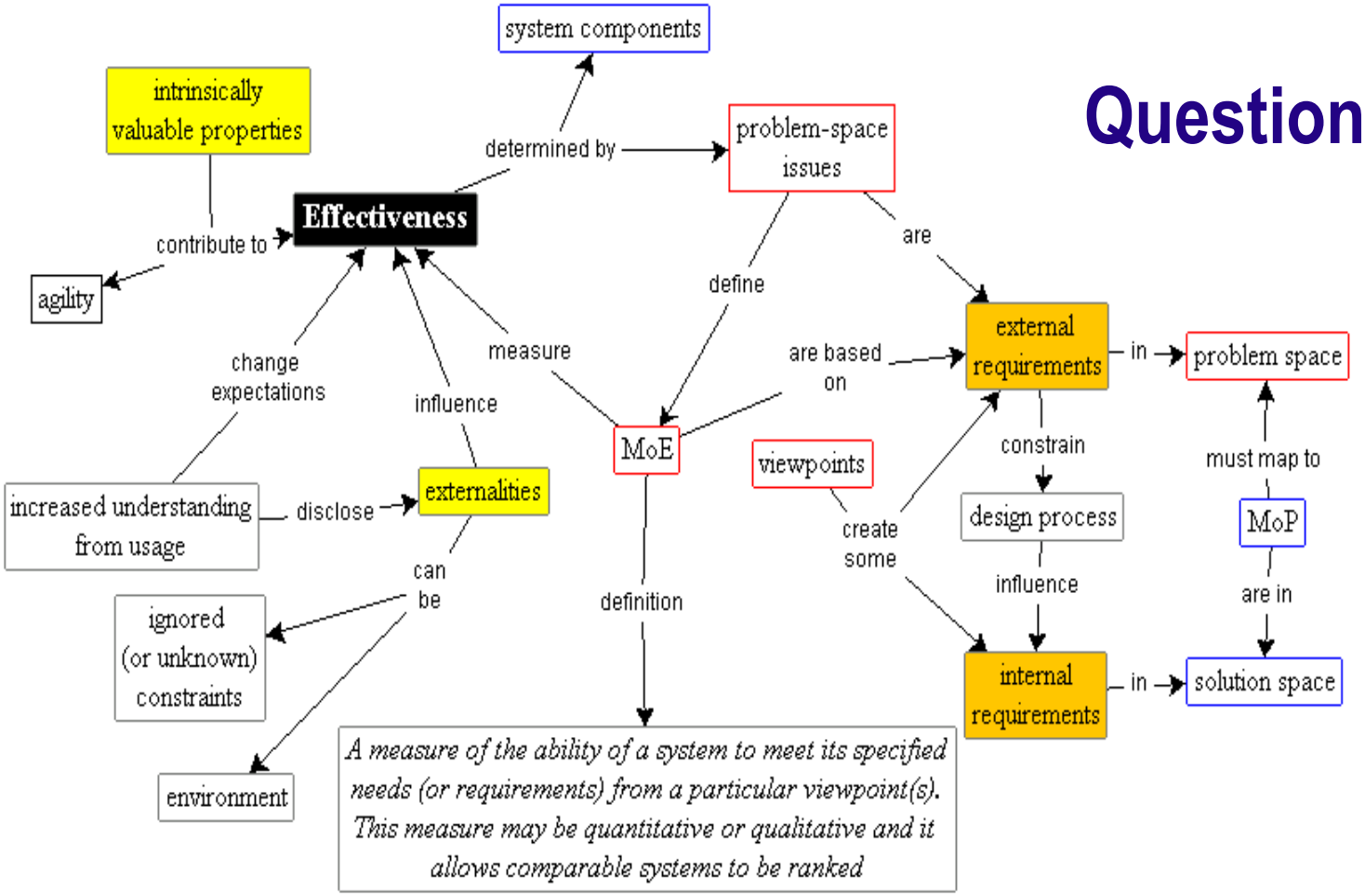
Conclusions

- This paper sees effectiveness as being a problem-space issue that needs to be evaluated from performance measures that can only be made in the solution-space. The mapping between these two spaces is the ultimate challenge.

- Effectiveness was discussed from four perspectives and the issues involved were illustrated by simple equations and effectiveness landscapes.

- Issues associated with measurement were also considered and Value Network Analysis was proposed to model the complexity of C2 systems. These models assist in determining the causal relationship between system components.

MoE Concept Map



Questions?