# Synergy and Emergence in Systems Engineering

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## Abstract

Decomposition is the basic tool of tradeoff studies, and is employed in two basic ways: Criteria decomposition is used for evaluation purposes, and architectural decomposition of the system is used to define subsystems and components. This paper develops and illustrates a clear, varied, and comprehensive set of decomposition and allocation examples, as well as methods to account for synergies and emergence among decomposed elements. Complementarity is fundamental in tradeoff studies for the mating of at least two substantially different descriptions of a system, namely, a predominantly qualitative description, and an architectural (often physical) description. Complication enters tradeoff studies when complementary decomposition descriptions, differentiated by type, increase in number and split into branches and levels in different combinations, with independence among decomposition elements being the most important assumption. Complexity enters tradeoff studies when synergy or emergence creates additional holistic properties that must be considered in addition to the properties of individual component elements. Simplification occurs in tradeoff studies when important allocations among complementary elements are emphasized while the remainders of full sets of correspondences are ignored, often unknowingly instead of deliberately.

Key words: Trade, tradeoff studies, criteria, decomposition, independence, complementarity, correspondence, allocation, attribute substitution, combining functions, synergy, emergence, complication, complexity, impedance

## 1, Introduction

### SYSTEMS ENGINEERING PROCESS ELEMENTS

Customers know their preferences in a qualitative way before recording them in more definite Need Statements, Requirements Documents, or Functional Requirements Documents. Criteria derived from these documents are used to decide the fitness of systems that the customer often does not technically design or integrate. The Systems Engineering (SE) Process [Mil-Std-499b, 1993] translates Customer Needs toward an Architectural Synthesis as shown in Figure 1:

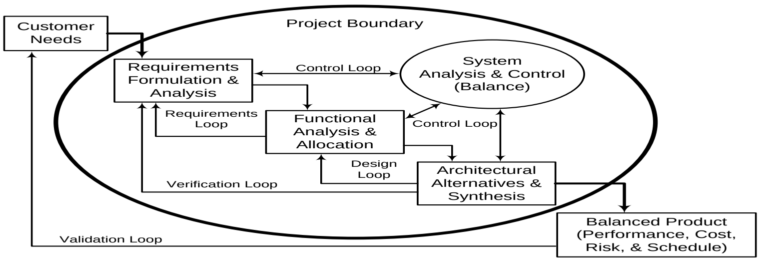

Figure 1: Systems Engineering Process [Mil-Std-499b, 1993]

Needs, Requirements, and Functions as SE Process elements are often talked about as allocated to subsystems and components of an architectural decomposition, but there is often insufficient clarity as to where these SE Process elements are actually allocated. Deficiencies in the differentiation and allocation of these SE Process elements subsequently lead to uncertainty as to where in the architectural decomposition important attributes exist. Without an exact understanding of where SE Process elements are allocated to an architectural synthesis, a subsequent analysis, optimization, or other SE method cannot be employed accurately and effectively.

Tradeoff study criteria and measures -- often qualitative before quantitative -- traditionally arose from requirement-derived criteria, but criteria can also arise from any of the SE Process elements, as the examples below illustrate:
**Need**: Customer needs construction equipment for an Alaskan project.
**Requirement**: System must operate in Prudhoe Bay in January.
**Functional requirement**: System shall dig trenches.
**Architectural Synthesis**: System will be a trencher with a de-icing subsystem.
Examples of decomposition trees based on different SE Process elements appear in Figures 2-5.

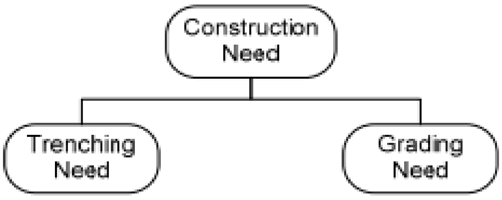

Figure 2: Need tree

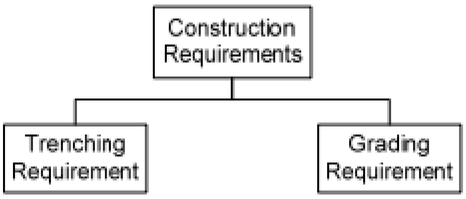

Figure 3: Requirement tree

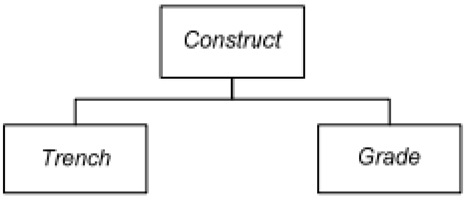

Figure 4: Function tree

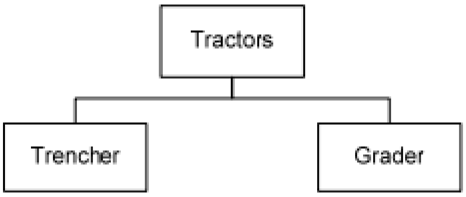

Figure 5: Architectural element tree

Much confusion results from mixing SE Process elements in the formation of a decomposition tree, as illustrated in Figure 6.

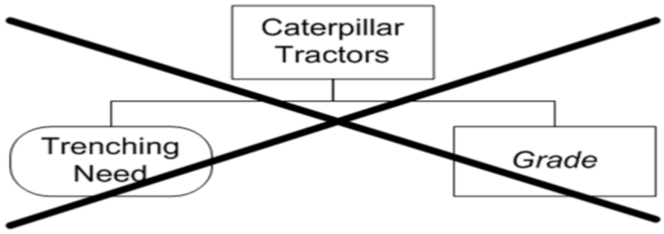

Figure 6: Incorrect mixed-element tree

For clarity, only a decomposition tree of uniform and consistent SE process elements of the first three (3) types – needs, requirements, or functions -- should be allocated to an architectural decomposition tree. In addition, attributes and capabilities are qualitative SE Process elements types that can be mated with an architectural decomposition tree.

## ARCHITECTURAL DECOMPOSITION

In a tradeoff study, SE Process element trees are paired with an architectural decomposition tree of branches and levels, as show in Figure 7.

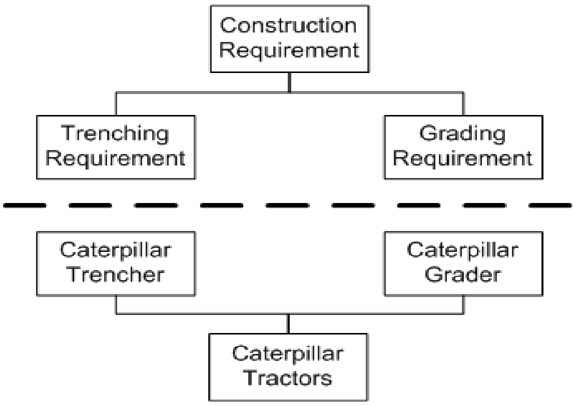

Figure 7: Pairing of a requirement and architectural decomposition tree

Similar pairings can occur between needs and the architecture, or functions and the architecture, among other possibilities. Architectural decomposition trees can also consider interfaces, hardware, software, controls, or data, among other architectural elements.

## COMPLEMENTARITY

Tradeoff studies are a system engineering tool that unifies a customer with a system, as shown in Figure 8:

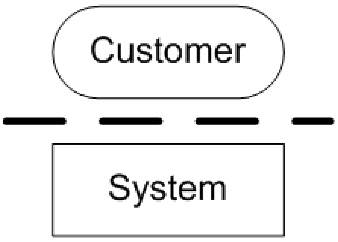

Figure 8: Customer with complementary system

Tradeoff studies can also be seen as mating two complementary descriptions of a system, namely, a conceptually qualitative description with a concretely quantitative description. See Figure 9.

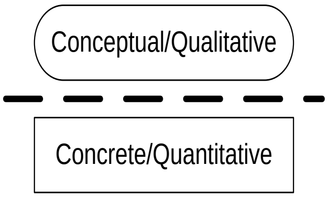

Figure 9: Conceptual/qualitative description with complementary concrete/quantitative description

Starting with the Mil-Std 499b illustration of the SE Process, the separation between the conceptual/qualitative elements and concrete/quantitative elements occurs as shown in Figure 10.

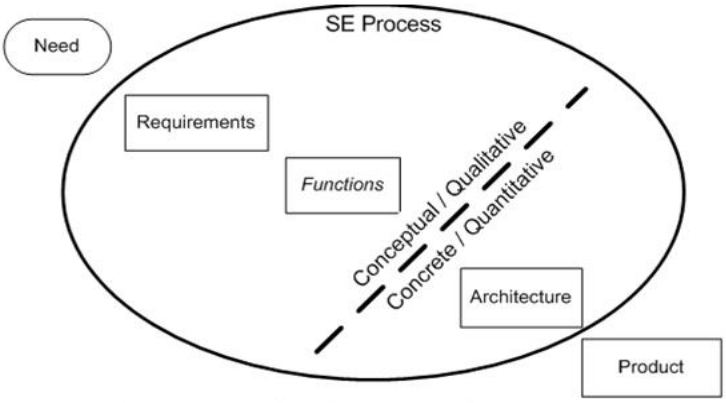

Figure 10: Separation of conceptual and concrete elements in SE Process

## ATTRIBUTES & CAPABILITIES

Other conceptual/qualitative elements that do not appear in the traditional SE Process, but can be used in tradeoff studies, include attributes and capabilities. Attributes are characteristics of value inherent in situations or objects, and have been defined as “complex intangible characteristics that are difficult to capture, but yet are crucial in directing systems engineering activities” [Smith and Bahill, 2010, p. 3]. “Attributes” are global qualities that the customer needs. “Capability” is a required ‘functionality’ composed of one or a set of functions with prescribed performance levels. Wasson defines a capability as “an explicit, inherent feature activated or excited by an external stimulus to perform a function (action) at a specified level of performance until terminated by external commands, timed completion, or resource depletion" [2006, p. 26]. The location of attributes and capabilities therefore lies within the SE Process as shown in Figure 11.

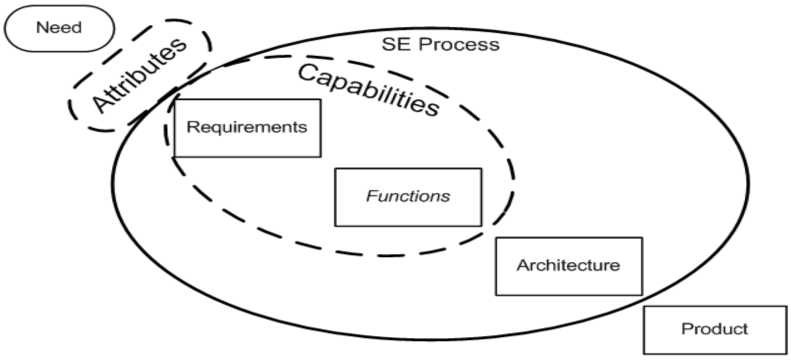

Figure 11: Attributes and Capabilities in the SE Process

## IMPEDANCE MATCHING ACROSS COMPLEMENTARITY INTERFACE

Transitions between high level conceptual/qualitative SE Process elements and low level architectural components should be smooth, providing for good impedance matching. For example, consider that a Customer Need, described in a Mission Statement, is expressed in terms of these four (4) fundamental attributes (assumed independent): Performance, Cost, Schedule and Risk. In a broad sense, these attributes cannot be accurately assessed for evolving architectures, except on a conceptual/qualitative level. More practically, the attributes should be decomposed into capabilities (required functional sets) that will characterize the level of attainment in each attribute. Capabilities will perhaps need to be decomposed into sub-capabilities that will in turn be expressed as sets of functions. Once functions are determined, it is relatively straightforward to determine measures that will directly assess whether a functional action is being performed well. No measure will be available without an analysis (or experimentation) method, which of course must be applied to the systems itself, or a model of the system. A recommended transition hierarchy from SE Process conceptual/qualitative elements to system architecture is shown in Table 1.

| |
|---|
| Need |
| Attributes |
| Capabilities<br>(Required Functionality) |
| Functions |
| Measures |
| Analysis Method |
| System Architecture |

Table 1: Impedance reducing transition hierarchy

Note that additional hierarchies can be contemplated for the system architectural subsystems and components. An example hierarchy is show in Figure 12.

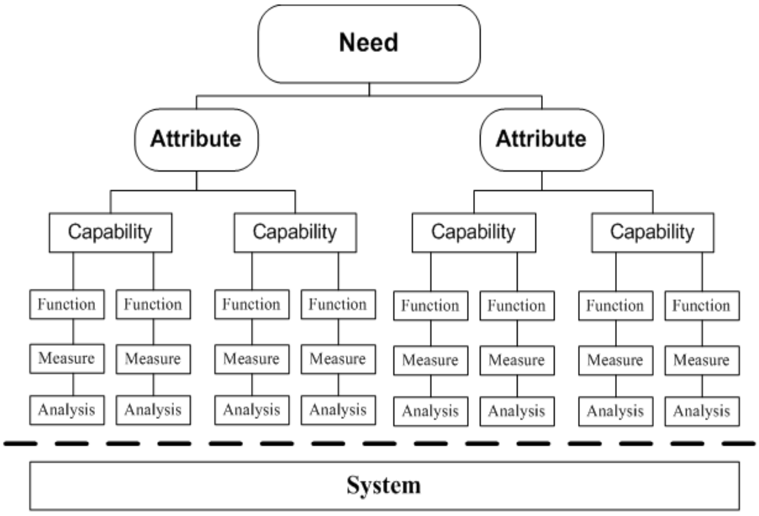

Figure 12: Impedance reducing transition hierarchy

2, COMPLICATION:

Allocations at the complementary boundary. Comparison and matching of a system's conceptual and concrete sides occurs at the complementarity boundary. It is thus very important to precisely identify the matching of qualitative and quantitative elements occurring at all complementarity boundaries. The remainder of this paper will explore matings at the complementarity boundary as the central, primary construction of tradeoff studies, but will not cover other tradeoff study topics. This section assumes that a single type of SE Process element is being used in the tradeoff study, and focuses on the levels of decomposition employed both on the qualitative and quantitative sides. For illustrative purposes, the customer need will play the role of the various conceptual/qualitative SE Process elements that are available.

A, Need ←→ System

Customers usually do not think in terms of tradeoff study decompositions, and often merely note whether the system's architectural synthesis as a whole satisfies their need, as illustrated in Figure 13.

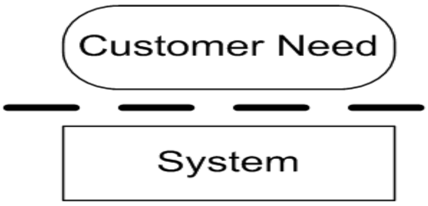

Figure 13: Customer ←→ Need Entire system

B, Need decomposition ←→ System

A clear decomposition of independent SE process need elements, and mating with a whole system. See Figure 14.

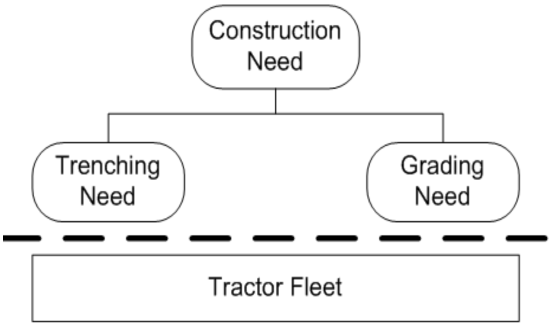

Figure 14: Need decomposition ←→ System

C, Need ←→ System decomposition

Contrariwise, a whole customer need can be mated with a specific architectural decomposition, as shown in Figure 15.

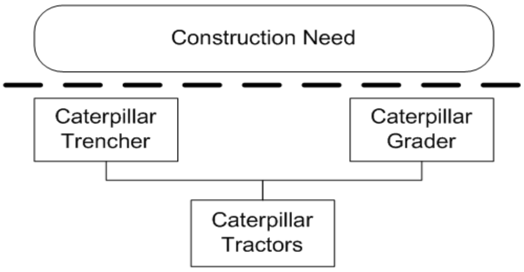

Figure 15: Need ←→System decomposition

D, Need decomposition ←→ System decomposition

Clear decompositions and allocations of independent SE process elements greatly simplify mating across the complementarity boundary, as shown in Figure 16.

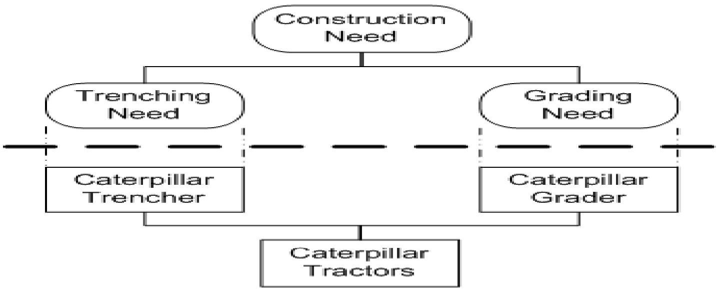

Figure 16: Need decomposition ←→ System decomposition; with allocations

However, it is not always easy or even possible to allocate qualitative SE Process elements precisely with corresponding architectural elements. Without such a clear allocation of qualitative SE Process elements, the matching with architectural elements can become quite complicated. Recall that we are still assuming that the qualitative decomposition can be accomplished successfully into independent decomposition components. An example in Figure 17 shows seven (7) independent attributes with no clear allocation to nine (9) system components of a Space Segment. Space Segment architectural decomposition is adapted from Fortescue, Stark and Swinerd [2003, p. 7].

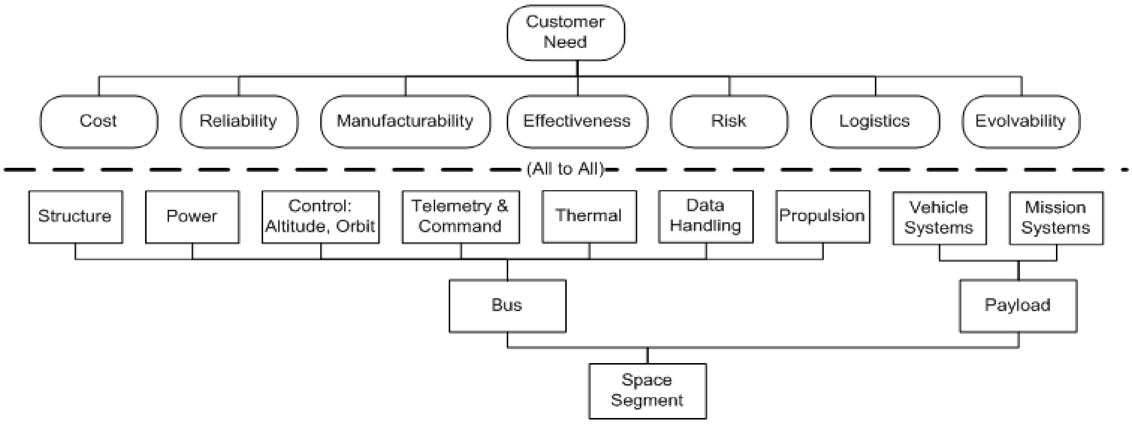

Figure 17: Implied all-to-all allocation of SE Process elements

Because the allocation is not determined, the matching must be all-to-all; that is, nine (9) architectural components assessed by seven (7) independent attributes creates 63 needed assessments and measures. Such an expansive set of assessments may be impractical, despite the usefulness.

Multi-Level Allocation:

Complicated (numerous) complimentary matches can be simplified by considering simplifying matches at multiple levels. In this approach, any decomposition level can serve as the bottom level, and the choice of level effectively sets the bottom level. Figure 18 shows a definite, exclusive, and simplifying allocation match between Evolvability and Payload, which is a higher-level subsystem compared to its now-ignored components.

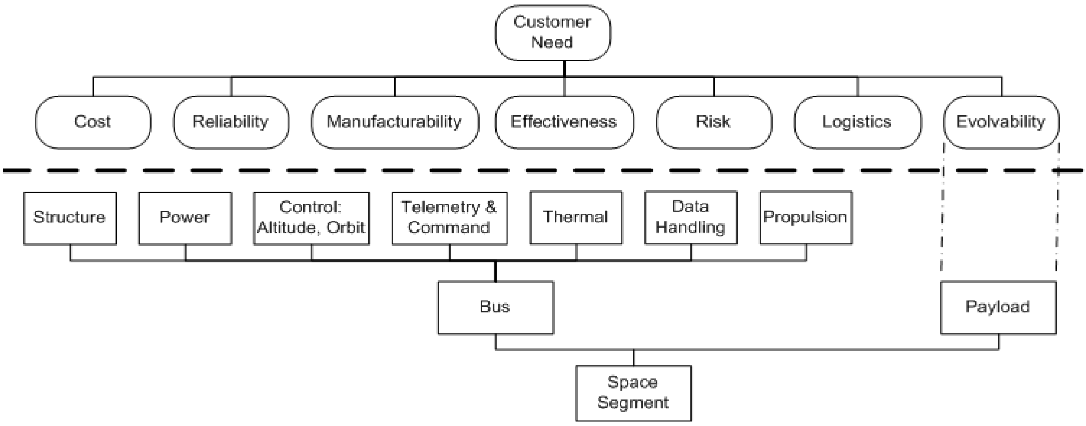

Figure 18: Simplifying allocation at a higher architectural decomposition level

Instead of 63 assessments and measures, now only 43 are needed. This is a result of six (6) attributes assessing seven (7) Bus components, and Evolvability assessing Payload; thus, 6(7) + 1 = 43.

ATTRIBUTE SUBSTITUTION, and SIMPLIFICATION

In reality, most tradeoff studies unknowingly employ allocations at multiple levels, in an unexposed simplification strategy that has its roots in the mental operation of the human brain. “Attribute substitution” occurs when a question at a high attribute level is answered by first substituting a lowerlevel attribute as the framing criteria [Kahneman and Frederick, 2002]. Because of its general relation to deductive reasoning, attribute substitution is rather ubiquitous in engineering [Smith and Bahill, 2010]. This simplifying approach often works well as a time and effort saving heuristic, but it fails to take into consideration the whole system – the touchstone goal of systems engineering. As an example, note how easy it is to simplify the currently considered tradeoff study by employing attribute substitution and creating the allocation illustrated in Figure 19.

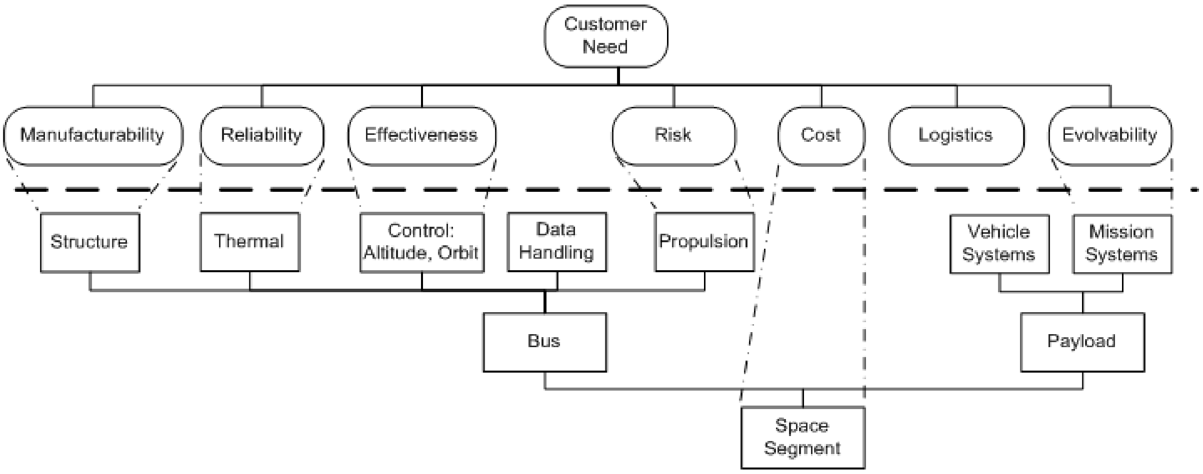

Figure 19: Attribute substitution simplifying a tradeoff study

Instead of the full set of 63 assessment and measures, now only six (6) assessments are necessary, by matching Manufacturability to Structure, Reliability to Thermal, Effectiveness to “Control, Altitude, Orbit,” Risk to Propulsion, Cost to Space Segment, and Evolvability to Mission Systems. Note that some attributes and architectural components have been totally ignored – as people using attributes substitution are prone to do.

Although the human brain greatly favors this drastic reduction in complication by accepting ignorance of the complete set of assessments, there are significant problems in the example. How can such important attributes as Reliability, Effectiveness and Risk be focused to assess only lower-level architectural components? How can Cost assess Space Segment if cost assessment is not applied to the architectural components of Space Segment in a bottom-up accounting? How can Evolvability assess Mission Systems if Evolvability will be affected by the ability of Vehicle Systems to support Evolvability? If there is any hope of accurately assessing systems with the method of tradeoff studies, synergy and emergence must be considered as products of the non-independence of decomposition elements.

## 3, COMPLEXITY SYNERGY

Synergy is here defined as a holistic coupling of SE Process elements or architectural components at the same decomposition level. Synergistic coupling of decomposition elements is often not considered or assessed, and mathematical formalisms have not been sufficiently developed. A simple example of synergy is components that together have increase reliability, such as multiple rollers synergizing on a conveyer belt; of course, a negative synergy may also occur if the reliability of individual components is reduced because of unexpected interactions among components. A second example of synergy involves the beneficial interaction and support among different drive subsystems in a hybrid car. Figure 20 illustrates synergy among functions of a military ship.

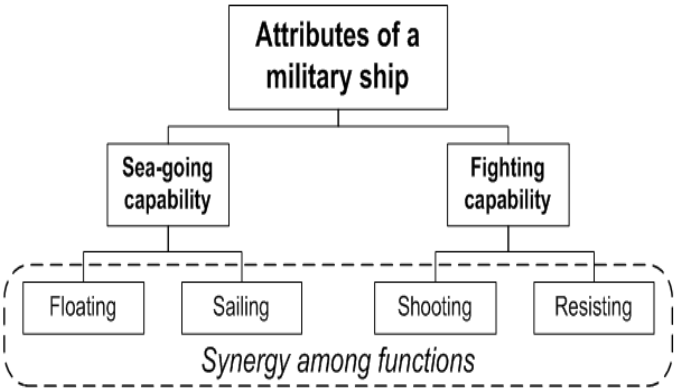

Figure 20: Synergistic union at a bottom functional level

The military sailing ship in this example is aided by the synergy among its functions. For example, Floating is facilitated because the performance of Sailing allows improvements in the Floating function, and, Shooting is aided by above average performance of the Resisting function. Synergistic union among elements still allows for the independent consideration of the constituent components. Figure 21 illustrates.

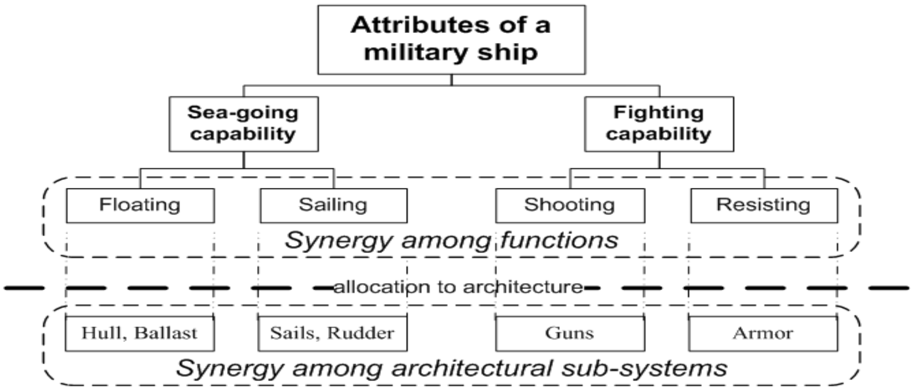

Figure 21: Synergistic union (at one level) and independence simultaneously

Mathematically, synergies among SE process elements need to be considered in equations such as: $z = F(x, y) = x + y + xy$, where the synergy between $x$ and $y$ is accounted for in the term $xy$.

## EMERGENCE

Emergence occurs when properties that are not present at a lower level arise at a higher level. In other words, the whole at a higher level is fundamentally different that any predictable consequence of combination of elements or properties at a lower level. Historically, “Cartesian Reductionism could not explain why some wholes possess capabilities, have properties, and behave in ways that were not evident from examination of their parts in isolation. This observation was labeled ‘emergence’ and some wholes were observed to possess or exhibit properties, capabilities and behaviors not exclusively attributable to any of their rationally separable parts” [Hitchins, 2007, p. 7]. Figure 22 illustrates a tradeoff study where the assessment of all allocated lower-level functions will not fully characterize the complementary mating -- because of the presence of emergent properties at the capability and function levels.

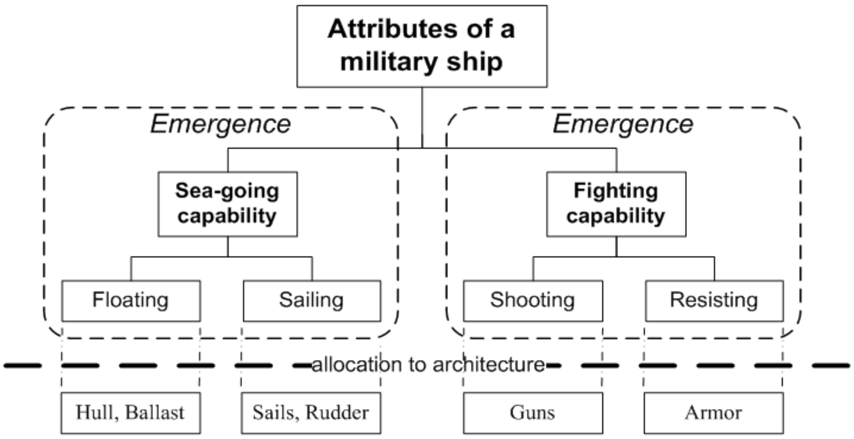

Figure 22: Emergence across levels with simultaneous independence

It may be possible to match emergent wholes with corresponding subsystems across the complementarity boundary, as Figure 23 illustrates; Note that the synergy among sub-systems will have to be considered.

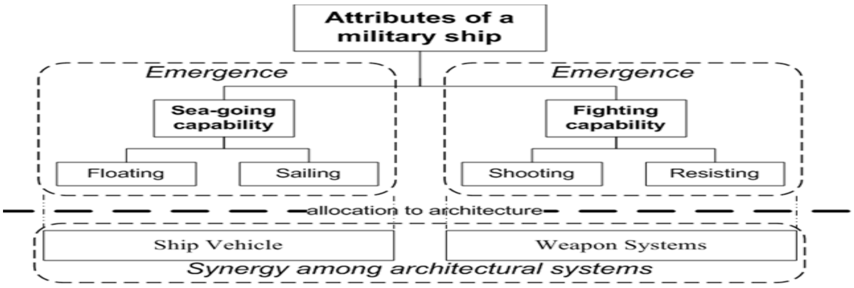

Figure 23: Emergence across functional and capability levels, and synergy among sub-systems

ATTRIBUTE SUBSTITUTION and SIMPLIFICATION
Attribute substitution can again provide for a reduction in the number of allocations and needed assessments by selecting connections, perhaps among synergistic components and emergent wholes, as shown in Figure 24. Note that a limited number of SE Process elements are used; namely, capabilities, functions, and system parts.

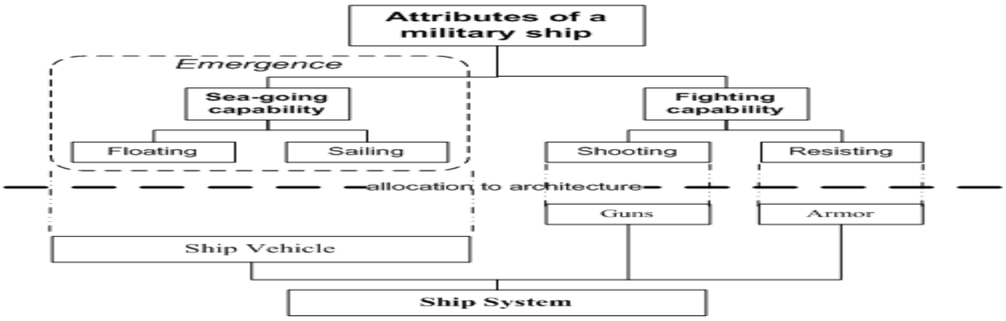

Figure 24: Selective or prioritized allocation by attribute substitution

In a strategy that saves time and effort, but increases the possibility of blindness errors, full allocation sets are often not considered because of the implicit use of attribute substitution in selecting decomposition components for allocation. SYNERGIES AND EMERGENCE AMONG DIFFERENT SE PROCESS ELMENTS A refinement of good systems engineering and architecting practice may be to consider synergies and emergences among different SE Process elements. For example, do certain requirements enhance functions at the same level? Or, do functions at a lower level create emergence in capabilities or attributes at higher levels? Consideration of such interactions among different SE process elements may be important for good architecting practice, which is not yet sufficiently understood. ATTRIBUTE SUBSTITUTION as a source of errors: A common but incorrect form for a tradeoff study results from the use of mixed SE Process elements and their selective allocation to architectural subsystems or components as important correspondences come more the mind of the designer. Deficient formulations of tradeoff studies result from unconsciously employing attribute substitution in supposedly ‘efficiently representing the most relevant factors.’ Figure 25 illustrates a tradeoff formulation that may seem intelligent while in mind, but is obfuscated and uncertain when laid bare on paper.

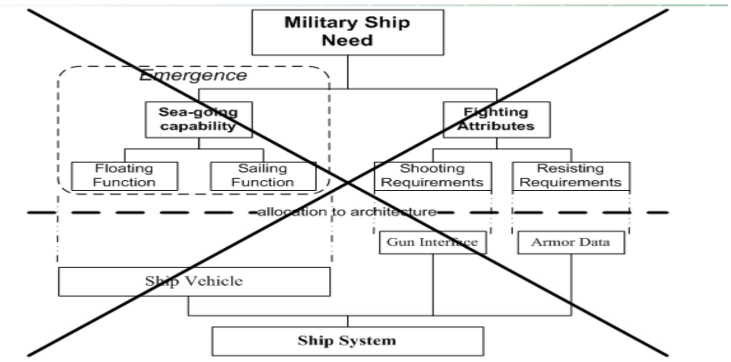

Figure 25: Mixed SE Process elements with selective allocation to mixed architectural elements

Clear awareness of what SE Process elements correspond strongly to particular architectural components, without summarily discarding secondarily important correspondences, is imperative.

## 4, Value of Information

Value of information has been to examine situations in which information is available and to show how decisions can be made systematically regarding the source of information to select and how much an expert’s information might be worth.

Value of information plays an elegant and subtle role in structuring for decisions and in the entire process of developing a framework to view a complex situation from different perspectives.

Decision-centric valuation of the benefit of new information that would reduce uncertainty. Information A can make Information B more or less valuable. The lack of information is to reduce uncertainties in the decomposition tree.

Engineers can make better decisions whether to obtain information or which information source to consult. The decomposition trees can be used as a framework for calculating the expected outcome and can be used to provide uncertainty in information.

## 5, CONCLUSION

Clarity in tradeoff studies comes only with classifications that clearly differentiate:

1,Complementary conceptual/qualitative and concrete/quantitative sides
2, SE Process element(s) to be employed
3, Levels and branches of decomposition trees
4, Allocations between qualitative and quantitative components that constitute the interfacing of decomposition trees
5, Synergies and Emergences Many issues of clarity, variety and formulation of tradeoff studies have not previously been well illustrated. The fundamental nature of tradeoff studies is complementarity, involving the allocation of corresponding SE Process conceptual/qualitative elements to concrete/quantitative architectural elements across the complementarity boundary. As the number of allocations increases, tradeoff studies become more complicated. However, only the phenomena of synergy and emergence bring true complexity to tradeoff studies.
Why have tradeoff studies previously not seem so multidim ional? Humans are very good at mentally focusing only on important complementary pairings, and ignoring secondary pairings, as part of the general mental operational method of attribute substitution. Attribute Substitution has traditionally simplified tradeoff studies when mental matches across the conceptual/qualitative and concrete/quantitative complementarity boundary are intuitively found, with disregard for the complete multidimensional nature of tradeoff spaces. Attribute substitution is very efficient, but it can also cause myopia and premature decision making along lines of personal and closely-held biases.

A clearer understanding of complementary tradeoff spaces should lead to better qualitative characterization of systems, better engineering decisions, and higher customer satisfaction.

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