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TOWARD ENGINEERING SYSTEMS AS A DISCIPLINE

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The purpose of this note is to work toward a definition of the discipline of engineering systems and is primarily intended to stimulate discussion on this topic.

To work toward this disciplinary definition, we must first establish what we mean by the term "engineering systems". But, even before that, we need to introduce several ideas.

Methods of Analysis

I suggest that there are two kinds of analyses.

a) quantitative analysis is based on *models* which by (this) definition use the language of mathematics. Here we include both representing particular systems mathematically and multivariate statistical analyses of empirical data.

b) qualitative analysis uses *frameworks* -- sets of organizing principles -- and uses natural language to characterize systems and their behaviors.

Both approaches are analytic -- i.e., can be used for *analysis* of specific systems -- and both can lead to designs or recommendations for action. Often quantitative and qualitative analyses are used in tandem to consider particular systems.

Complex, Large, Integrated, Open Systems

Next, I introduce Complex, Large-Scale, Integrated, Open Systems (CLIOS) as a kind of system, with the component terms used as described below.

A system is **complex** when it is composed of a group of related units (subsystems), for which the degree and nature of the relationships is imperfectly known. Its overall emergent behavior is difficult to predict, even when subsystem behavior is readily predictable. The time-scales of various subsystems may be very different (as we can see in transportation -- land-use changes, for example, vs. operating decisions). Behavior in the long-term and short-term may be markedly different and small changes in inputs or parameters may produce large changes in behavior.[1]

CLIOS have **large** impacts. In this definition, "large" has several meanings. Certainly one is impact in a large geographic area -- the planet, a region, for example -- but another interpretation is that such systems have *impacts* that are *large* in magnitude and

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[1] Many alternative definitions of complexity exist. See "Ideas on Complexity in Systems -- Twenty Views", compiled by Joseph M. Sussman, ESD-WP-2000-02, Cambridge, MA, February 2000.

often long-lived. Describing a car as a “large” system will refer more to the large impact of cars collectively than it does to the physical size of the artifact.

Subsystems within CLIOS are **integrated**, closely coupled through feedback loops.

By **open**, we mean that CLIOS explicitly include social, political and economic aspects, which includes marketplace and institutional change issues.

The term “open” provides a broad scope for CLIOS; it is **not** intended to be exclusionary. One can work on CLIOS -- a good example is software -- in which the internal complexities -- making such systems hard to change without introducing bugs -- overwhelm any “open” considerations. Obviously, these CLIOS, in which open issues are not present or can safely be ignored, are of interest. Further, one can work on CLIOS that may be relatively straight-forward internally, but become very challenging when open issues are considered -- a regional water supply system might be a good example. These are also valid systems for us to study. And, of course, a CLIOS with internal complexity **and** difficult open issues as well-- a global supply chain is a good example -- is a valid area of study. There is much of interest to us in all these cases.

Often CLIOS are counterintuitive in their behavior. At the least, developing a model that will predict their performance can be very difficult to do. Often the performance measures for CLIOS are difficult to define and, perhaps even difficult to agree about, depending upon your viewpoint. In CLIOS, there is often human agency involved.

Engineering Systems

Next, I define "Engineering Systems” as simply CLIOS with an important technology component.

Where do engineering systems fit within the family of systems? We have natural systems governed by physical laws at one extreme; we have social systems governed by human behavior at the other. Between those extremes, I claim we have **engineering systems** which often have both physical and social components, which take on different importance depending upon the system of interest. The “artifact” may be software, an urban transportation system, or a system for maintaining aircraft in geographically-dispersed locations.

Engineering systems are almost invariably **complex** in structure, behavior and in the way their performance is judged (usually with a multi-dimensional objective function); indeed such systems are often plagued by sub-optimization. They are often **adaptive** and characterized by **non-linearity** in the interactions of their subsystems. Typically an **interdisciplinary** approach, including quantitative as well as qualitative perspectives, is needed to develop a deep understanding of the system under study. The conversion of resources into outputs reflecting proper consideration of various issues such as costs, customer requirements, and competition in the marketplace, is a daunting **design** task.

Work in engineering systems focuses on understanding system structure and behavior and developing trade-offs among strategic options in that domain. Implicit in the study of engineering systems is that optimal "solutions" to CLIOS are hard to come by.

Both models for *quantitative* analysis and frameworks for *qualitative* analysis are used. Methodology development in engineering systems focuses on representing systems and their characteristics in coherent ways, structuring useful questions about their performance, and discerning important characteristics of their behavior. There is little explicit methodological focus on the efficiency of the methods for searching the solution space, because the goal of the study of an engineering system is often not a "solution", but rather understanding.

Contrasting Systems Engineering and Engineering Systems

Because of unfortunate terminology, based in history, engineering systems and systems engineering are often confused with each other. We now try to explain the differences.

Systems engineering was well-defined by Earll Murman as follows:

"The application of structured processes to guide the definition and implementation of producible products (systems) containing a group of elements which interact and function together as a whole to satisfy stakeholder needs."

"Engineering" in this context is an *active verb*. In "systems engineering" we are "engineering" the system of interest. On the other hand, an engineering system is a *kind* of system as defined earlier; "engineering" in this context is an adjective.

The study of engineering systems and the field of *systems engineering* are *similar* in that they both are concerned with *complex* systems; further, they both take a broad, interdisciplinary approach to the understanding of systems, and try to effectively represent the interactions among apparently disparate parts of those *integrated* systems.

They are *different* in that while engineering systems focuses on the large-scale, systems engineering focuses on both the large- and small-scale (e.g., an airplane or a part of an airplane wing). A further and more important difference between the two concerns the boundaries of study. The study of engineering systems deals with CLIOS with an important technological component, which, since they are open, concern social, economic and political factors as *part* of the system and subject to (qualitative or quantitative) analysis. The idea is to consider those social, economic and political factors as design variables to the extent possible.

Systems engineering tends to focus on the engineering of "closed" systems, often without explicit consideration of social, political and economic factors; if they are considered, they are treated as constraints rather than design variables for the system in question. As noted above, there are certainly CLIOS in which internal complexity dominates, and for these a closed system perspective is certainly appropriate.

These ideas are summarized in the following table.

	SYSTEM SIZE	**SYSTEM BOUNDARIES**	**METHODOLOGIES**
Engineering Systems	Large	Open	Quantitative Qualitative
Systems Engineering	Small or Large	Closed	Quantitative

Critical Contemporary Issues

Let me introduce another idea that I view as central to the field of engineering systems: *critical contemporary issues*. Such issues include productivity; competitiveness; economic development; sustainability, including energy / environment / air quality / global warming; urban form (e.g., the mega-cities of the developing world and sprawl in the developed world); social equity; environmental justice; quality of life; congestion / mobility / accessibility; technology development and deployment; and doubtless others.

Critical contemporary issues share the characteristic of *first* requiring **interdisciplinary** approaches -- approaches that do not come neatly boxed in traditional disciplines (engineering or non-engineering) -- and *second* are characterized by substantial **complexity**. This complexity may be internal, as in a complex technological project. Or the complexity can be external, stemming from interactions with social, political and economic factors. And some systems may exhibit both kinds of complexity.

I argue that addressing these critical contemporary issues is an important component of the engineering systems field, as I define it (I recognize this is controversial!). The **interdisciplinary** and **complex** nature of these issues make them of special interest to engineering systems professionals; further, these professionals are collectively uniquely equipped to deal with these issues and have an obligation to address them, given their importance to humankind.

The Discipline of Engineering Systems

Finally, I suggest a definition of the discipline of engineering systems.

This discipline is the development of a structured set of **models and frameworks**, together with appropriate methods of **qualitative and quantitative analyses**, and their application to a broad set of **CLIOS** with important **technology** components. It includes a coherent, **interdisciplinary** approach to engineering system **design** (or more humbly, discernment) and a broad-based context for studying **critical contemporary issues** as described above.

I hope this note is helpful as a starting point for discussion of engineering systems as a new discipline. As always, comments are welcome.