<u>ESD Terms and Definitions</u> (Version 14)

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I. <u>Complexity in Engineering Systems</u>

Arguably the key concept in Engineering Systems is complexity. Thus we discuss it at greater length than the other terms that will follow. There are many definitions of complex systems, but we shall concentrate on just two. A system is *behaviorally complex* if its behavior is difficult to predict, analyze, describe, or manage. In contrast a system is *structurally complex* if the number of parts is large and the interconnections between its parts are intricate or hard to describe briefly. Systems that are structurally complex are usually behaviorally complex. Systems that have complex behavior need not have complex structure, since we know of relatively simple mechanical systems whose behavior are chaotic, and hence complex. On the other hand, most behaviorally complex systems are structurally complex as well.

Complex engineering systems are not simply technical in nature, but rely on people and their organizations for the design, manufacturing and operation of the system, and are influenced by and influence the societal and physical context as well.

II. <u>Basic Terms related to Engineering Systems</u>

Engineering – bringing to reality useful artifacts and algorithms that heretofore did not exist; in English, especially in England, the term is often associated with maintenance and operation, especially of engines, but the French root (ingénieur) is related to ingenious (ingénieux).

System – A set of interacting components having well-defined (although possibly poorly understood) behavior or purpose. Alternately: A system is an instance of a set of elements having relationships with one another sufficiently cohesive to distinguish the system from its environment thereby giving the system an identity. It can then also be said to have a purpose. The concept is subjective in that what is a system to one person may not appear to be a system to another.

System Architecture –

Practical definition:

An architecture is the conceptualization, description, and design of a system, its components, their interfaces and relationships with internal and external entities, as they evolve over time.

Fundamental definitions:

1. The architecture of a complex system is a description of the structure or regularity of the interactions of the elements of that system (inherently the non-random and longer lived aspects of the system relationships).

2. The architecture of a complex system describes the functional character of the elements and the structure of the relationships among the elements.

Intermediate definition:

An architecture declares the modules and defines their functions

It also declares and defines the interfaces, including which modules they relate and what relations are supported

Finally it declares or embraces standards that define common rules of design, structure, interfaces, or behavior not otherwise declared, including performance evaluation

Engineering System – a system designed or evolved by humans having some purpose; large scale and complex engineering systems, which are of most interest to the Engineering Systems Division, will have a management or social dimension as well as a technical one.

System Environment – a set of conditions external to and affecting a system; environments include both natural and man-made conditions

Natural environment – natural surroundings and context (e.g., air, water); the natural environment can sometimes be considered the core of a system, with engineering systems providing interfaces to it

Complex system – a system with components and interconnections, interactions, or interdependencies that are difficult to describe, understand, predict, manage, design, or change. (This implies non-random and non-simple structure.)

> The concept of complexity has several meanings: dynamic (in the sense of complex behavior), and static or structural (in the sense that a complex system is composed of many components interconnected in intricate ways). In addition, while the complexity of a system can be a quantifiable and even an absolute quantity, what makes a system appear complicated to people is subjective (simplicity is in the eye of the beholder); how complicated the system appears depends on the nature of the interface of the system that is presented to its users.

Interdependence – the relationship between entities that cannot exist or operate without each other; independent entities exist and operate without influence from each other; interdependencies may be intended or unintended

Interaction – the property of entities that exchange something material or immaterial that constitutes or contributes to their interdependence

Interconnection – the relationship between entities that are physically or abstractly connected and the connection provides the pathway for the interaction; software connections are often abstract

These three terms are clearly interrelated (pun intended). We distinguish at least three types of interdependence: one is the interdependence that may occur among components or subsystems in a given design of a system, a second is the interdependence created when global constraints (such as weight, volume, cost, or 2^{nd} Law of thermodynamics) force a redesign, and a third is one that occurs as a result of subdivision of tasks or the management of the flow of materiel or information.

Components – parts of a system relative to that system; a component can be a system too if it contains other components

Large scale systems – systems that are large in scale and/or scope; such systems have a large number of components; as a result large scale physical systems will be distributed over a region that is large relative to its smallest components;

Designing –an open-ended human process whereby plans for useful artifacts and processes are created

Function(s) –broad: desired behavior(s) of a system or a component; these behaviors are presumably desired because they contribute to a stated purpose; more specifically, fundamental behaviors (not including the ilities – see below) of an engineering system that fulfill its stated purpose. In Computer Science, the function is simply what the system does. How well it is done is generally called performance. Characteristics such as the "ilities" are other properties that a system has. This usage is followed in ESD. 342 as well.

Properties-term used to describe all characteristics of a system that determine its usefulness to a variety of stakeholders and thus includes all functions (and performance), ilities and factors such as size, weight, cost

Requirements – the properties that an engineered system is supposed to achieve, deliver, or exhibit;

Effectiveness –ratio of performance of function(s) achieved to the totality of functions and performance desired

Efficiency – ratio of function(s) achieved to resources used

Life cycle – The sequence of phases that an engineering system undergoes, which can be divided into three major parts: Conceiving, developing, and deploying. Conceiving includes identification of need/opportunity, initiation of requirement elicitation and gathering. Developing includes analysis, design, implementation manufacture or production, and testing. Deploying includes assimilation, use, maintenance, modification or upgrade, repair, retirement, dismantling, recycling, disposal, erasure or remediation, and possible replacement; replacement is a critical element in creating a cycle

Systems changes – multiple dimensions by which systems change, including the rate of change (e.g., evolutionary, moderate, revolutionary), the structural direction of change (e.g., top-down, bottom-up, networked), or the breadth of change (e.g., pilot initiatives, wall-to-wall)

III. Ilities and related system issues

Ilities- desired properties of systems, such as flexibility or maintainability, often ending in 'ility.' These properties of systems are not necessarily part of the fundamental set of requirements on the system's functions or performance

Flexibility – the ability of a system to undergoing changes with relative ease in operation, during design, or during redesign. The basic metric is the degree of change per unit of effort (or cost including engineering, investment etc.)

Agility – ability of a system to be both flexible and undergo change rapidly

Resilience – the property of a system that can quickly return to its original function and performance following a disturbance or shock; a resilient system may use its flexibility to achieve robustness

Robustness – related to resilience, demonstrated or promised ability to perform under a variety of circumstances; ability to deliver desired functions in spite of changes in the environment, uses, or internal variations that are either built-in or emergent (see below)

Adaptability – – the property of a system that can change its structure, processes and behavior to meet changing requirements in its environment; in biology when adaptation is successful the organism will increase the likelihood of its reproduction; the changes under adaptability may be more complex than is available from flexibility

Scalability- the ability of a system to maintain its performance and function, and retain all its desired properties when its scale is increased greatly without having a corresponding increase in the system's complexity

> An increase in scope (that is, an increase in the system's functional capabilities) usually involves an increase in scale, yet scalability does not normally imply ease with increasing the scope of a system without unduly increasing its complexity. Such ease is usually related to the structure of the system's architecture (see below) and its flexibility

Modularity The concept includes two different aspects- at times it means the degree to which a system can be decomposed into subsystems that can be designed and/or manufactured independently of each other; at other times it is taken to mean the degree of direct association of functions with particular elements and their interactions. In biology: repeating patterns of the same or similar structure.

Extensibility – the degree to which sets of components of a system can be extended to a higher level of abstraction

Fail-safe - ability to be guided to a safe state, if the system cannot deliver the full desired function due to failure(s)

Safety- the property of being free from accidents (see below) or unacceptable losses

Durability – ability to deliver a specified level of function for a specified length of time

Sustainability – broad: maintaining economic growth and viability while meeting concerns for environmental protection, quality of life, and social equity; narrow: a property of an engineering system having optimal resource preservation and environmental management over time

Quality- ability to deliver requirements at a "high" level, as perceived by people relative to other alternatives that deliver the same requirements

Reliability – the probability that a system or component will satisfy its functional and performance requirements over a given period of time and under given conditions (acknowledges that no system can meet its functional and performance requirements under all possible conditions)

Repairability –the ability to be returned to the original state of function when some function is lost

Maintainability - the ability of a system to be kept in an appropriate operating condition; the system should also possess the property of repairability

III Design/manufacturing concepts and approaches

Manufacturing – The processes by which materials are made, parts or components are fabricated from materials, and products are assembled from parts; software is implemented rather than manufactured

Manufacturing Systems – The equipment, processes, people, organization and knowledge, as well as the interactions of these that are involved in the manufacturing of a given end product

Lean Manufacturing – A pull based and flexible manufacturing system that is responsive to customer demand, where skilled workers, just-in-time manufacturing processes, and continuous improvement are combined to produce perfect first-time-quality output

Systems architecting - The process by which standards, rules, system structures and interfaces are created in order to achieve the requirements of a system; trade-off studies may precede the determination of system requirements

Systems engineering –a process for designing systems that begins with requirements, that uses and/or modifies an architecture, accomplishes functional and/or physical decomposition, and accounts for the achievement of the requirements by assigning them to entities and maintaining oversight on the design and integration of these entities; systems engineering originally arose in the context of aerospace projects in the 1950's, but has been applied more broadly since then.

> Systems architecting creates a system design at a high, abstract level, whereas systems engineering is often associated with refining such a design; by blending the two processes one accomplishes the assignment of functions to physical or abstract entities, and the definition of interactions and interfaces between the entities

Optimization – a process or methodology for maximizing the function of a system

Multi-criteria optimization – the simultaneous optimization of several criteria

Functional decomposition - the division of functions into sub-functions while retaining all inputs to and outputs from the level above; the decomposed elements perform all the functions of their parents in the decomposition

Logical decomposition – the division of information system components into their logical constituent parts

Physical decomposition –the division of physical systems into simpler subsystems and components

Integration –the act of anticipating or executing a combination of components of a system with the expectation that all system requirements will be achieved.

System structures – abstractions useful within systems in order to understand, control and facilitate the complex interactions – current possibilities include platforms, modules, networks, teams, and hierarchies, and subsets and combinations thereof

Hierarchy – Hierarchies create a ranking of elements in a system. In a layered hierarchy one of any pair of elements is above, below or at the same level as the other. In a tree-structured hierarchy one adds the possibility that a pair of elements have no hierarchical relationship.

Reuse –In the design of systems, repeated use or application in different places of the design of parts, manufacturing tools and processes, analysis, and particularly knowledge gained from experience; using the same object in different systems or at different times in the same system

Module – A part of a system that is constructed to have minimal, standardized interactions with the rest of the system (and is thus often reusable). Alternately, a part of a system that is intended to be the main or only actor in providing a given function or subfunction of the system.

Platform –a module or set of components that splits a system into two parts so that changes can, in principle, be made on either side of the platform interface without affecting the other side as long as appropriate standards are followed; platform implementation: all parts or components on the side of the platform interface farther from the end user, namely the parts or components needed to achieve the desired abstract interface.

Integral architecture – an architecture in which the number of functions or behaviors is significantly larger than the number of designed entities or components, implying that some components are involved in multiple functions

Modular architecture – an architecture in which the number of functions is roughly comparable to the number of designed entities or components; an architecture in which the interactions and interfaces between the components are relatively simple

Interfaces – a boundary or interconnection between systems or their components that define or support interrelationships; interfaces may be intended or unintended

IV Risk/uncertainty/safety in design/manufacturing and operation

Ambiguity – open to having several possible meanings; may also be uncertain

Uncertainty A lack of knowledge about the inputs to a model or process, the model or process itself, or future events that will influence the outcome

Accident – an undesired and unplanned (but not necessarily unexpected) event that results in (at least) a specified level of loss (called a loss event); losses can be economic losses, losses of human lives, losses of function, losses of time, etc.

Hazard – a state or sets of conditions that, together with worst-case external conditions, can lead to an accident

Risk – the level of hazard combined with the likelihood of the hazard leading to an accident, and the duration or exposure of the hazard; a combination of the likelihood, severity and lack of detectability of an accident or loss event

Opportunity – likelihood and possible beneficial impact of uncertainty

V Management and related Social Science Issues

Organization – the structure of roles and responsibilities of people who are engaged in some common purpose

Enterprise – a defined scope of economic organization or activity, which will return value to the participants through their interaction and contribution

Lean enterprise – an enterprise that delivers value to its stakeholders, while minimizing waste (waste can be in terms of materials, human lives, capital, time, physical plant, equipment, information, and energy)

Learning Organization - an organization that systematically reviews its experience with its internal and external environment and acquires knowledge in order to improve its functioning

Negotiation – an interactive process aimed at communication and agreement among multiple stakeholders who have both common and competing interests

Socio-technical systems – broad: systems in which both human and non-human elements interact, where the social or management dimensions tend to dominate

Socio-technical systems design – the design of work systems that attempts to optimize human psychological and physiological dimensions along with the technical aspects

Policy studies – studies of courses of action, chosen from alternatives, that guide present and future decisions by, for example, governmental bodies

Interdisciplinary – involving two or more academic disciplines or professional practices

VI General Concepts and Approaches related to Systems

System point of view – a conviction that system behaviors are qualitatively different from the behaviors of a system's components, that system design requires doing more than designing the components, and that special effort is required to understand systems and their behavior over and above what is required to understand any individual component

System thinking – includes holism, an ability to think about the system as a whole; focus, an ability to address the important system level issues; emergence (see below), recognition that there are latent properties in systems; and trade-offs, judgment and balance, which enable one to juggle all the various considerations and make a proper choice

System theories –theories that attempt to explain the interacting and combining behavior of a system as well as how the interaction of its components contribute to the behavior of the system

General Systems Theory – Originated by Bartanlaffy in the 1950's; an approach to modeling systems using sets of differential equations

Cybernetics – Originated by Norbert Wiener; models systems using feedback processes

System Dynamics – Originated by Jay Forrester; used to model systems in the social sciences and management; uses networks of nodes and feedback relationships amongst them

Complexity theory (in the sense of the Santa Fe Institute) – a set of approaches to understanding systems that encompasses chaos theory and related theories; used to understand biological systems as well as physics-based ones.

Complexity theory (as used in computer science) – approaches to the analysis of the computing time and effort required by various algorithms; usually relies on techniques in combinatorics and logic

Operations Research – a scientific approach to executive decision-making, including problem formulation, mathematical modeling, and system optimization.

System Modeling – vocabularies, symbols, rules, and representations (behavioral, structural) that make use of the vocabularies, symbols, and rules for the purpose of displaying and predicting the structure and behavior of systems, or which represent in symbolic form or operational ways one or more aspects of the system under study

Network models of systems – models of systems at relatively high abstraction, emphasizing elements and their interactions, typically using the symbols and methods of graph theory

Emergent properties – properties or behaviors of a system that are discovered (i.e., properties that were there but latent), those that emerge spontaneously over time or space, and those that arise in response to behavior of other systems and environments**;** in a hierarchical view of systems, emergent properties show up at one level of the hierarchy, but not at lower levels

Synergy –mutually advantageous behaviors or properties that exist only because distinct elements are joined or can interact

Multi-agent models – models of systems that emphasize independent actions of individual elements that obey rules based on their internal states and knowledge (perhaps limited) of the states of other elements