Appreciative Methods Applied to the Assessment of Complex Systems

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Abstract. Complex systems have characteristics that challenge traditional systems engineering processes and methods. These characteristics have been defined in various ways. INCOSE has previously identified characteristics of complex systems and potential methods to deal with complexity in system development. The purpose of this paper is to provide definitions and describe distinguishing characteristics of complexity using example systems to illustrate approaches to assessing the extent of complexity. The paper applies Appreciative Inquiry to identify and assess complex system characteristics. The characteristics are used to examine several different examples of systems to illuminate areas of complexity. These examples range from seemingly simple systems to complicated systems to complex systems. Different tiers of complexity are identified as a result of the assessment. The paper also identified and introduces topics on managing complexity and the integrating system perspective that represent new directions for the engineering of complex systems. The Appreciative Inquiry approach provides a method for systems engineering practitioners to more readily identify complexity when they encounter it, and to deal more effectively with this complexity once it has been identified.

Introduction

INCOSE published a *Complexity Primer for Systems Engineers* (McEver, 2015) developed by the Complex Systems Working Group to help systems engineering professionals understand the nature and some implications of complexity. Responses to this Primer from INCOSE members included requests for examples of systems which are complex and non-complex (simple, complicated or complex), and the characteristics which can be used to identify complexity, and to deal with it more effectively. A Complex Systems Exemplars Team was established by the Complex Systems Working Group to discuss examples of complex and non-complex systems. This paper is the result of the efforts of this team.

The focus of the team activity to date has been on engineered systems, but natural systems were also considered when they offered the best examples of some characteristics. In this paper, we first describe and define the distinguishing characteristics which can be used to differentiate between complex and non-complex systems; next we discuss how complexity can be managed in light of these characteristics. The following section discusses the challenges of communicating about complexity, including the use of Appreciative Inquiry. Next five examples of systems are presented and assessed against the distinguishing characteristics to identify whether (or when) they are complex. This assessment shows that complexity is not a binary, yes or no attribute, but systems have many different characteristics which lead to varying degrees of complexity. This section finishes with an introduction to the integrating perspective which can improve the likelihood that a system is understood accurately. Finally, the summary highlights the key points a systems engineer (or other stakeholder) should take away from this paper, and offers topics for possible investigation in the future.

Assessing Complexity

Complexity is challenging to communicate and describe to others and is a poorly understood aspect of contemporary engineering work. Previous bibliographic research has provided evidence of trends and identifiable gaps in existing literature on project complexity over the last 50 years, and documented a variety of focus areas constituting a research front - 'an evolving network of scientific publications cited by researchers'. (Rezende, et al, 2018)

Although this paper leaves a more exhaustive survey of the literature to future work, our preliminary research suggests a serious gap in research on identifying complexity in practice, or organizational solutions to such situations. Existing literature (Chen and Crilly, 2016) pertains to diverse developments and characteristics of complexity in specialized domains but does not consider practices relevant to more generalized engineering work. This issue has been articulated in terms of an emerging field of complexity engineering and methodological gaps have been raised. Past studies have considered how organizations learn - through 'Critical Learning Incidents' - to resolve dynamically complex problems in system dynamics model-based engagements. (Thompson, et al, 2016) Other studies consider methods based in Activity Theory applied to structuring complex problems (White, et al, 2016) These efforts can be seen within a longer tradition of Activity Theory and Action Research which we characterize as a larger field of 'appreciative methods' stemming from the work of Checkland and Holwell. (Checkland and Holwell, 1998)

Table 1: Using Appreciative Inquiry to Leverage Insights into Complexity

Problem-Solving Focus	Appreciative Inquiry Focus
Identification of problems	Identifying what is known and unknown, risks and opportunities
Analysis of possible causes	Assessing distinguishing characteristics of complexity; identifying areas to focus on
Analysis of possible solutions	Identifying strategies which have been useful with comparable complexity in other systems/situations
Implementation	Trying promising strategies
V & V	Noticing effects
Iteration	Refining our understanding of which areas of complexity to focus on
***Basic assumption**: Complexity presents problems to be solved*	***Basic assumption**: Complexity offers a mystery to be explored*

Complexity is not easy to address using the common engineering paradigm of problem-solving. An alternative is using Appreciative Inquiry Methods and Appreciative Inquiry. These two independently developed methodologies (Stowell, 2013) both offer an alternative to the conventional engineering problem-centered approach. Appreciative Inquiry Methods were inspired by Checkland's Soft Systems Methodology (Checkland, 1999). Appreciative Inquiry Methods focus on participants/stakeholders, environment, authority, relationships (including the power relationships between stakeholders) and learning as a way to understand the complexity in a system and its interactions. Appreciative Inquiry (Cooperrider, 2003) is a transformational change methodology which leverages understanding from the disciplines of organizational behavior and the sciences of sociology and psychology (Stratton-Berkessel, 2018). Social and organizational systems are complex, and as such Appreciative Inquiry is based on methods used to understand these complex systems. Thus, Appreciative Inquiry provides an excellent approach to begin a more in depth study of complex systems. Appreciative Inquiry involves the art and practice of asking questions that strengthen the capacity to apprehend, anticipate and heighten positive potential. It seeks to identify and build on the knowledge of what has already been proven to work, when this knowledge is spread across many diverse stakeholders. (Cooperrider and MacQuaid, 2012). Table 1 illustrates the contrast between a problem-solving focus and an Appreciative Inquiry focus.

Appreciative Inquiry is typically used to deal with group processes that consider the knowledge (and areas of ignorance) distributed throughout a community or communities of practice. Groups of individuals working on complex physical systems may themselves be considered complex systems, yet to date it appears that attention given to the language of complexity focused on physical and logical systems may be a factor holding groups back from greater effectiveness in managing social risks they face directly and indirectly in their work. A broader understanding of the social complexity involved in the development and application of various systems is an important factor in system complexity. This understanding helps to discern the variations of complexity for a given system and context. The system context (i.e., the social environment) brings in various social aspects including government and organizational policy and law, budgetary constraints, schedule, organizational culture, environmental impact, etc. (Watson, 2018)

Distinguishing Characteristics

In order to assess the complexity of a system, the characteristic which distinguish the system complexity must be identified and understood. The identification is the first step of Appreciative Inquiry as discussed in Table 1. The understanding must come within the context and nature of complexity. Complex systems must be considered in their full context (i.e., mission context or statement of the problem to which the system provides the solution) including both the developmental and operational environments. This includes both the natural environment and the social environment in which the complex system is developed and operated. Boundaries and controls are sometimes employed to contain complex responses and can at times mask some characteristics of complexity within the system. The nature of system complexity can be either subjective (based on the limits of understanding of an individual or social structure) or objective (based on the characteristics of the system itself or its environmental interactions).

Complex systems tend to exhibit variety in their characteristics rather than uniform repetition. After reviewing the discussion of complexity in sources that reviewed the breadth complexity understanding at that time (Sheard 2006, McEver 2015), we identified the following 14 distinguishing characteristics of complexity and developed associated definitions for each. The assessment of the complex system examples provided in tables in the appendix illustrates the application of these characteristics.

Diversity. Diversity is defined by Webster as: quality, state, fact, or instance of being diverse (different; dissimilar; varied); difference; variety. (Webster, 1982) In a complex system context, diversity encompasses the structure of the system, the behavior of the system, and the states of the system. The structure of the system includes the types of nodes, number of nodes, types of interfaces, and number of interfaces.

System behavior involves types of responses and types of functional interfaces. Responses include stochastic (Bayesian, Frequenist) vs. deterministic. Minor system differences can lead to large behavior changes in a complex system. Types of functional interfaces include information, material, and energy flows. States involve structural states (coupled, uncoupled), functional states (moving, stationary), and behavior states (dynamic, static).

Based on these considerations complex system diversity can be defined as:

> <u>Diversity</u> - *The structural, behavior, and system state varieties that characterize a system and/or its environments.*

Connectivity. Connectivity characterizes the systems connections both internally and externally. This connectivity includes the system environment and the interrelationships among the structural components of the system. Dynamic connectivity is more complicated or complex than static connectivity. Dynamic connectivity adds consideration of time, motion, transition and other types of change to the system, potentially increasing the complexity of the system, rendering a simple system complicated or a complicated system complex. Note, complexity of interactions are more characteristic of a complex system than merely the number of interacting elements.

Based on these considerations complex system connectivity can be defined as:

> Connectivity *- The connection of the system between its functions and the environment. This connectivity is characterized by the number of nodes, diversity of node types, number of links, and diversity in link characteristics. Complex systems have multiple layers of connections within the system structure. Discontinuities (breaks in a pattern of connectivity at one or more layers) are often indications of complex system connectivity. Simple and some complicated systems may be characterized by simpler structures such as hierarchies.*

Interactivity**.** Interactivity involves the behavioral reactions of the system both internally and externally. Human interaction greatly increases the system interactivity characteristic. The greater the potential the system has for multiple human stakeholders the greater the likely system complexity.

Based on these considerations complex system interactivity can be defined as:

> Interactivity *- The behavior stimulus and response between different parts of a system and the system with its environment. Complex systems have many diverse sources of stimulus and diverse types of responses. The correlation between stimulus and response can be both direct and indirect (perhaps separated by many layers of system connectivity). The types of stimuli and responses vary greatly. The levels of stimuli and responses can range from very subtle to very pronounced. The timeframe for system responses can vary hugely.*

Adaptability**.** Adaptability involves the system coping with changes from both internal and external sources. This includes both the complex system's environment and usage. Complex systems are generally expected to accommodate future changes in system environment and usage. Complex systems can change their environment. Note that there are differences between a complex system, a complex environment (in which simple systems, complicated systems, and complex systems can all function), and complex interfaces.

Based on these considerations complex system adaptability can be defined as:

> Adaptability *– Complex systems proactively and/or reactively change function, relationships, and behavior to balance changes in environment and application to achieve system goals.*

Multiscale**.** Multiscale is a characteristics that can be applied to systems in general (i.e., simple, complicated, complex). Multiple scales exist in nature from the atomic level to the macroscopic. Thus even simple systems, such as an iron bar, can be viewed as consisting of multiple scales.

Note, there are properties which do not define system complexity but are more general, applying to multiple system types:

> Size is not a discriminating characteristic and size can apply to simple, complicated and complex systems.

Multiple stable states is not a defining characteristic of a complex system. Various system types (complicated or complex) can have multiple stable states. A complex system can have stable states, transient states, and no stable states.

Based on these considerations complex system multiscale can be defined as:

Multiscale - *Behavior, Relationships, and Structure exist on many scales, are ambiguously coupled across multiple scales, and are not reducible to only one level.*

Multi-perspective. Multi-perspective involves the different perspective from which a complex system may be understood. These can include performance, reliability, use, durability, interactions, etc. The different perspectives required to understand a complex system may overlap so that orthogonality in perspectives is present but not required to define a complex system perspective. An orthogonal view is an independent view from other views. Different characteristics may be seen by different views. Some orthogonal views may be oppositional views, views which appear to oppose other views of the system. Oppositional views are a source of paradoxes sometimes understood about complex systems.

Based on these considerations complex system multi-perspective can be defined as:

Multi-perspective - *Multiple perspectives, some of which are orthogonal, are required to comprehend the complex system.*

Behavior. Behavior of a complex system is unpredictable when understood from finite resources. An understanding may be gained with infinite resources. The limited knowledge available about the behavior of a complex system limits the ability to model the system and gain a full understanding of the complex system behaviors. The time and effort to fully model a complex system typically exceeds the schedule and budgetary resources of the project. Behavior is nonlinear which means extrapolation of current conditions lead to errors in understanding.

Based on these considerations complex system behavior can be defined as:

Behavior - *Complex system behavior cannot be described fully as a response system. Complex system behavior includes nonlinearities. Optimizing system behavior cannot often be done focusing on properties solely within the system.*

Dynamics. Complex systems have dynamic states, constantly changing as internal and external conditions change. Complex system states can also be static. They can transition from static to dynamic states unexpectedly and suddenly.

Based on these considerations complex system dynamics can be defined as:

Dynamics – *Complex systems may have equilibrium states or may have no equilibrium state. Complex system dynamics have multiple scales or loops. Complex systems can stay within the dynamical system or generate new system states or state transitions due to internal system changes, external environment changes, or both. Correlation of changes in complex systems to events or conditions in the system dynamics may be ambiguous.*

***Representation*.** Complex system representations are difficult to define or predict. The time to construct and the information needed to define these representations is difficult to compile.

Based on these considerations complex system representation can be defined as:

> Representation – *Representations of complex systems can be difficult to properly construct with any depth. It is often impossible to predict future configurations, structures, or behaviors of a complex system, given finite resources. Causal & influence networks create a challenge in developing 'requisite' conceptual models within these time and information resource constraints.*

***Evolution*.** Complex systems change in structure, behavior, and states over time. These changes occur in response to both internal and external events. The exact stimulus for the change can be difficult to discern and may be the result of the complex interaction of several events.

Cognitive recognition has a time lag with respect to the system change.

Self-Organization is a form of system evolution.

Based on these considerations complex system evolution can be defined as:

> Evolution – *Changes over time in complex system states and structures (physical and behavioral) can result from various causes. Complex system states and structures are likely to change as a result of interactions within the complex system, with the environment, or in application. A complex system can have disequilibrium (i.e., non-steady) states and continue to function. Complex system states and structures can change in an unplanned manner and can be difficult to discern as they occur. The changes in the states and structure of a complex system are a natural function of (is often present in) the complex system dynamics. Changes can occur without centralized control, due to localized responses to external and/or internal influences.*

***System Emergence*.** System emergence has two forms: general and complex. General system emergence result in properties from systems in general, that become apparent over time. Complicated systems may demonstrate some forms of emergence when put in unusual or uncommon environments or circumstances. While not common, these responses are expected.

Emergent behavior is not describable as a response system. Describing the behavior of a system as a response function may require an unobtainable amount of information. System emergence is often described as a novel system response. Novelty is the human subjective response to a change in the system rather than a characteristic of the system. Emergence can be Objective or Subjective. Emergent properties of a system that exist technically (objective) vs. those that are difficult to understand/recognize/identify (subjective). Subjective emergence includes properties where the emergent property is manifest well before the property is discerned by observers.

Based on these considerations general and complex system emergence can be defined as:

> System Emergence *(general) - Features/behavior associated with the holistic system that are more than aggregations of component properties.*

> *<u>Unexpected Emergence</u> (Complex) - Emergent properties of the holistic system unexpected (whether predictable or unpredictable) in the system functionality/response. Unpredictable given finite resources. Behavior not describable as a response system.*

***Disproportionate Effects*.** Complex system responses or changes to events or impulses can be largely disproportionate to the scale of the cause. Small scale modifications can result in radical changes of behavior. Scale can be in terms of magnitude of effect or aggregate amount of change. Weak ties can have disproportionate effects. Note, this characteristic exists over multiple system types. Complex systems appear to demonstrate this as a rule, but having this property does not necessarily indicate the system is complex.

Based on these considerations complex system disproportionate effects can be defined as:

> *<u>Disproportionate Effects</u> - Details seen at the fine scales can influence largescale behavior. Small scale modifications can result in radical changes of behavior. Scale can be in terms of magnitude of effect or aggregate amount of change. Weak ties can have disproportionate effects.*

***Indeterminate Boundaries*.** Complex system boundaries are difficult to define or discern. Complex system boundaries may be more of a transition than a distinct change.

Based on these considerations complex system indeterminate boundaries can be defined as:

> *<u>Indeterminate boundaries</u> - Complex system boundaries are intricately woven with their environment and other interacting systems. Their boundaries can be non-deterministic. The boundary cannot be distinguished based solely on processes inside the system.*

***Contextual Influences*.** System context is the social and physical environments in which a system functions or operates. The social context includes budgetary, schedule, governmental and organizational (i.e., corporate) policy, and governmental law. (Watson, 2018) Within the influences of these context the system application and operation can be complex. These influences tend to confound the system complexity and can increase the system complexity

Based on these considerations complex system indeterminate boundaries can be defined as:

> *<u>Contextual Influences</u> - All systems reside in natural and social environments and relate to these. In the relationship between the system and the natural and social environments there can be complexity. This complex interaction depends on the social application of the system. Social systems often strive to achieve multiple, sometimes incompatible, objectives with the application of the same system.*

How to Manage Complexity

In defining the characteristics of a complex system, some ideas for approaches needed to manage complexity also began to emerge. This corresponds to the analysis of possible solutions as defined by Appreciative Inquiry in Table 1. Managing complexity first requires identifying the complexity of a system. The Multi-perspective of a complex system can make the complexity appear in different ways, and may even mask the complexity. There are various ways a system and its context may appear complex: physical, logical, social interaction, social application, environmental interaction.

Below are some initial ideas about how to deal constructively with complexity. An important aspect of managing complexity is understanding the integrating perspective of the system. This provides a clarifying view of the system as discussed in the section on Integrating Perspectives below.

Some key points to consider in managing complexity are:

- *Complex systems need balance rather than optimization. The whole is often sub-optimized when a part is optimized, or an optimized system can become rigid and cannot cope with changing circumstances and needs.*

- *Tension is common in complex systems. Tension between large and small, distributed and central, agile and planned, calls for perpetual seeking of balance.*

- *Complexity can be bounded within a simpler structure. E.g., biological cells are internally complex and yet a single cell is a simple structure externally.*

- *Architecture is defined in the INCOSE Systems Engineering Handbook as "the fundamental concept or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution." (INCOSE 2010) The characterization of a system architecture in terms of some coordinated collection of subsidiary design elements (e.g., responsible 'trades' for specific design elements) can be a major step toward organizing and managing complexity. Implicit in successfully navigating this task is mutual appreciation between responsible trades regarding their respective contributions and interactions to the evolving system(s).*
- *Social-Political Complexity. All systems reside in natural and social environments and inherently relate to these. In the relationship between the engineered system and the natural and social environments there can be complex interactions inducing pressures on socio-political and governance structures. This level of interaction often depends on specific and potential applications (uses) of the given system. Social systems often strive to achieve multiple, sometimes incompatible, objectives engendering risks and opportunities for the coevolution of systems services and value to society. Better understanding these co-evolutionary processes may prove useful to engineering organizations.*

Complex System Examples

We have chosen five example systems to characterize using the distinguishing characteristics described above to analyze the possible causes of complexity as defined by Appreciative Inquiry in Table 1. These five systems, with a short summary description of each, are:

- Army Pot Helmet: The Army Steel Pot Helmet (Figure 1) is a simple steel helmet that included a shell, liner, strap, and cover. In application, the helmet had many more uses that were valuable to the soldier than just protecting from bullets and explosive fragments. Functions included head protection, identification, seating, fluid and solid containment, and heating (when used to prepare meals). The helmet could be used as a seat, a shovel, a wash and shave basin, a pot for cooking, and anything else the innovative soldier could image. (New York Times 1982, Webster, 2017)

Figure 1: Army Steel Pot Helmet

- Launch Vehicle: Launch vehicles are very large physical systems whose development requires very large and geographically distributed efforts (operations teams, manufacturing, engineering organizations). Launch Vehicles are a complicated assemblies of physical parts in a static state as illustrated in Figure 2. In operation, they are a complex interaction of thermodynamic fluids, software, and electrical systems. Launch vehicles are not complex adaptive systems in the current state of the art. The addition of artificial intelligence responses to in-flight conditions would transform them into complex adaptive systems.

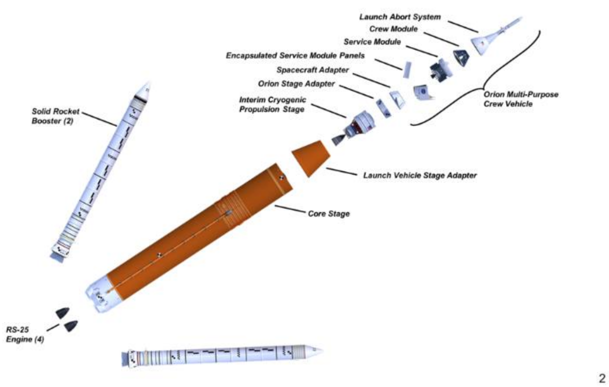

Figure 2: NASA Space Launch System Launch Vehicle

- Bullet Train (Shinkansen). This is a nationwide transportation system in Japan and international catalyst interacting at many levels of hierarchy with multiple business, technical, social, cultural, political groups and organizations. (Straszak, 1981; Okada, 1994; Endo, 2003; Okamura, 2005; Tomii, 2010; Smith, R. A., 2014; Yokoshima, 2017; Asano, 2017) It has a robust and resilient architecture for reliable inter-city passenger transport. (Endo, 2003; Shimamura and Yamamura, 2006; Uda, 2010; Kato and Shinohara, 2013; Smith, R. A., 2014) It is heavily

Figure 3 Shinkasen Train Engine Configurations

dependent upon minute to minute managerial competence due to its one-track paradigm. (Shimuzu, 2002; Kawasaki, 2011; Mochizuki, 2011; Tomii, 2010) The individual cars of the Shinkansen are complicated systems, yet the whole aggregated train is complex. Figure 3 shows various engine configurations used for the train. The Shinkansen system illustrates how aggregation of subsystems and confounding factors can both elevate the complexity of the system.

- Radar: A system which bounces radio waves off of targets to determine various characteristics of the target, usually including position, size and velocity. Analysis of radar echoes can use many techniques, including fractal analysis, which classifies shapes seen by the complexity of their geometrical form (Azzaz, 2017 and Cherouat, 2008) as shown in Figure 4. Practitioners of radar design, and developers of tools to support simulation and modeling of radar components and environments perceive radar design to be complex. For example, the MathWorks website says: “Radar system design, simulation, and analysis is complex because the design space spans the digital, analog, and RF domains. These domains extend across the complete signal chain, from the antenna array, to radar signal processing algorithms, to data processing and control. The resulting system level complexity drives the need for modeling and simulation at all stages of the development cycle.” (Mathworks, 2018)

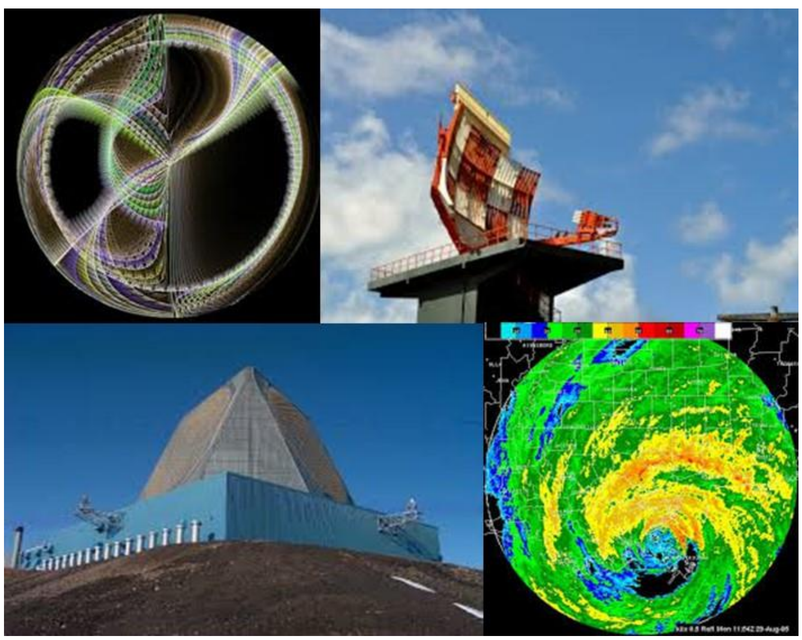

Figure 4: Radar Images. (a) Top Left, Fractal Radar Image (b) Top Right, Air Traffic Control Radar (c) Bottom Left, Air Defense Radar (d) Hurricane Katrina Radar Image

The environment that radar has to contend with also can be complex, since rain, fog, plant matter and electromagnetic energy generated by other radars can interfere with a given radar’s ability to detect signals; also noise comes from sources ranging from the radar’s own transmitter, to energy from the earth’s atmosphere and the earth itself, to galactic noise from the cosmos. There are many choices, with associated trade-offs, in radar design. Examples of choices include: (1) power level (higher power can yield higher signal-to-noise ratios, and thus better performance, but also create more interference for other systems, and be more detectable (for systems in which the user does not want an enemy to know they are using radar); (2) wavelength (a higher frequency – shorter wavelength -- yields better tracking performance, but a lower frequency means less power needs to be used, and the receiver can be smaller); and (3) receiving aperture size (a bigger aperture means better performance for a surveillance radar).

Radar is starting to use adaptive approaches, such as a "cognitive radar system" based on the fully adaptive radar framework for cognition (Smith, et al, 2016) For example, pulse repetition frequency and number of pulses can be adjusted dynamically to maintain radar tracking performance (Butterfield, et al, 2016). The key concept is that radar system performance can be enhanced through a continuous and coordinated feedback between the transmitter and receiver that implies a dynamic adaptation of the sensor's algorithms to the operational context and environmental replies.

- **Artificial Intelligence Image Collection Manager** – A collection manager is a software system that assists experienced human operators in effective use of image collection assets through the generation of collection plans and tasking commands for a constellation of imaging devices that usually include satellites and may include airborne assets. Some constellations may include a range of earth based assets as well. The collection planning capability includes complexity in a number of dimensions including environment, social context and the interplay among elements of an evolving System of Systems.

  Recently, scientists and engineers have begun to apply Artificial Intelligence and Machine Learning (AI/ML) to realize complex adaptive software systems that identify the best opportunities to collect requested imagery for unique mission needs within the confines of policy and law, environmental conditions and the capabilities of the vehicles and instruments available. Berger (Berger, 2016) describes the problem addressed by this system as "the process of converting intelligence-related information requirements into collection requirements, establishing priorities, tasking or coordination with appropriate collection sources or agencies, monitoring results, and re-tasking, as required".

  In most current deployed systems, this process is managed by a human, augmented by rules based automation. In the case of an AI/ML version of this capability, the system learns based on collection success over time and develops additional rules and algorithms to develop more effective collection schedules. More traditional implementations of collection management systems may be considered complicated or complex systems while AI driven implementations are complex adaptive systems.

Integrating perspective. The integrating perspective of any system allows the system to be more clearly understood. If the integrating relationship is known, then the system can be understood, and may even appear to be less complex from this perspective. The integrating perspective of a complex system is not intuitively obvious to the casual observer.

Intentionally engineered complex systems are constructed in such a way as to provide a direct view of the integrating nature of the system sometime presenting a more informative view of the system. This perspective enhances our understanding of the system and how to deal with this complexity.

The integrating perspective enables the construction of models to aid in the understanding of the system and its complexity. Integrating perspectives reduce resource demand to be able to predict system behavior. Malleability is a property that allows the complex system to be deconstructed and/or reconstituted around the integrating perspective. Complex systems are malleable around their integration perspectives. Complex system variables can be opaque. These complex system variables are difficult to identify and predict apart from the system integrating perspective.

Confounding Factors. The tables in the appendix compare the different examples on each of the distinguishing characteristics of complexity described above. In doing this comparison, we use Appreciative Inquiry to examine both the complexity of the system itself, and, when applicable, complexity caused by what we call "confounding factors". Even with a very simple system, there can be complexity in the environment, in the interactions between stakeholders, and/or other factors. These confounding factors can introduce complexity even when the system under consideration is not, in and of itself, complex. We have rated each example system characteristic on a scale of **1 to 10**, where **1** = simple, **5** is complicated, and **10** is highly complex. When a confounding factor is present, we have also rated the level of complexity it introduces. The purpose of these ratings is to highlight the distinguishing characteristics of each system which are most complex. In dealing with complexity, it is helpful to identify the specific characteristics, and/or confounding factors, which are the major sources of complexity. Once these are understood, discussions with stakeholders and specific techniques and tools to deal with the complexity can be chosen to better address the complexity and the challenges it introduces into a system development, operation or modification effort.

As an example, the pot helmet as a structural system is simple, with very few components (i.e., attachments) and only static properties. Yet in application the pot helmet had many uses: as a stove, a personal hygiene basin, a shovel, a bucket, seat, and many other uses that the innovative soldier could define. The social complexity supported by these applications was tremendous. Without the steel helmet, the soldiers would need to carry a stove, a basin, a shovel, a seat or do without these in the field. The psychological comfort afforded by these applications can substantially boost the morale of the organization (i.e., Army) and affect numerous social level results affecting troop morale, perseverance and longevity in the field, mission effectiveness, and so on. Thus, while a simple structure, the pot helmet had a very complex effect on the army at large.

Complexity Assessment. The assessment of these various systems produced some unexpected results. The initial expectation was the pot helmet was simple, only the Artificial Intelligence Scheduler was complex, and the other systems were complicated. The results of the assessment, however, showed the Launch Vehicle and Bullet Train are complex systems in dynamic operation and social interaction. These systems, much as the radar system, can be viewed as complicated when only considering the assembly (aggregation) of components yet are very much complex in their dynamic operation. This is an aspect of the multi-perspective characteristic and shows complexity can sometimes be hidden from the normally perceived view of the system.

Complex systems are not complex in all of their characteristics. The assessment in the tables in the appendix show that even complicated systems (i.e., radar systems) can have complex characteristics and that not all characteristics of a complex system may be complex. Thus complexity is not a simple yes or no attribute. Complexity is based on multiple characteristics not all of which are likely to be complex for most systems. Even a Complex Adaptive system only shows complexity in some of the characteristics (i.e., Artificial Intelligence Scheduler) of the system indicating the other characteristics have more of an effect on a systems complexity than the adaptability functions.

Confounding factors are significant aspects in the complexity of a system. These factors can elevate a system from complicated to complex in the systems application. This elevation can be seen for the pot helmet where the application of a simple structural system is complicated and can lead to very complex results in the organizational system that utilizes it. In addition, there are many other subdivisions of complexity that can emerge including managed/constrained complexity (where the complexity is hidden by physical control boundaries and hence “managed or constrained” to not be apparent), expected and unexpected emergence, aggregation, and physical environment interaction.

The assessment of these systems indicates that there are tiers of system complexity. Systems can be a complicated assembly in a static sense, and a complex interaction of parts and physical phenomena in a dynamic sense. A distinction can also be made between complex systems and complex adaptive systems as discussed above. Complex adaptive systems encompass capabilities to respond to their contexts in unexpected manners. Artificial Intelligence can transform a complicated or complex system into a complex adaptive system by imbuing the system with adaptive responses to their social and physical environments. Thus, a tier of complexity can be envisioned for a system as shown in Table 2.

Table 2: System Complexity Tiers

System Complexity Tier	Characterized by
Complicated	Assembly of static parts
Complex	Interactions of dynamic operations
Complex Adaptive	Application of Artificial Intelligence determining system responses

The potentially infinite diversity of complex system examples precludes a 'one-size-fits-all' mentality when it comes to responsible and responsive Systems Engineering approaches to working with complexity. Much has been written on the nature of complexity in engineered systems though there is little consensus on what precisely generates complexity let alone what to do about it - and that can be seen as the general nature of it. Often, the path to a viable engineered response and a successful design lies in a diverse organization; a 'society of mind' as Marvin Minsky (Minsky, 1986) put it. Interestingly, this suggests that complexity exists in the response to complexity and that solutions can emerge unexpectedly. This can be seen in the complex organizations necessary to build complex systems today. (Watson, 2018) Consider that this is the nature of novel invention (as distinct from rational, parameterized design), and that once rational solutions are identified, a system may no longer be considered 'complex' in and of itself.

While outside the scope of this paper, we would be remiss to suggest that complexity and engineering are completely antithetical concepts. On the contrary, it is important to recognize that complexity can (and demonstrably does) spawn novel engineering communities that coevolve with their work products and also that it is essential that engineering organizations avoid fixating on singular methods or approaches to complex design problems by failing to appreciate the multiplicity of considerations that may be salient to problems at hand. Complexity can offer exercise to the imagination, to say the least. Future efforts toward discovering useful guidance may benefit from considering the 'appreciative tendencies' of organizations responsible for and responsive to successful complex system design and implementation.

Summary

This paper has described characteristics which can be used to identify complexity in a system, and the additional confounding factors (i.e., social and physical environmental interactions) which can elevate complexity of complicated systems. Systems can have various tiers of complexity ranging from static to dynamic to adaptive complexity. The evaluations of system complexity show that complexity is not a simple yes or no assessment, but there are several different characteristics of a system which may be complex. Not all of these distinguishing characteristics of the system need to be complex in order for the system to be complex.

This paper offers an attempt to develop a more explicit recognition of and familiarity with important dimensions of complexity that SE's may encounter and to provide a practical scaffolding for dialog on engineering innovation. It is essential to notice that engineered systems and engineering organizations (including directly/indirectly interested and disinterested agents) constitute complete systems operating 'far from equilibrium' and that complexity, managed appreciatively, need not be an insurmountable barrier to the effective realization of engineering value.

"Complexity engineering has still not been established as a proper engineering domain. Research remains scattered and focused on specific examples, which is the reason why most methodologies are not generally applicable. We would like to encourage other researchers to make efforts in complexity engineering, and to coordinate their research with peers. A general framework for complexity engineering should be created, linking existing and new methods with each other, giving receipts for how to approach which type of problem. Complexity engineering requires particular attention concerning the following issues: theory, universal principles, implementation substrates, designing, programming and controlling methodologies as well as collecting and sharing of experience." (Frei and Di Marzo, 2011)

This paper indicates several topics of future research. The concept of Complexity Tiers observed in the assessment of the examples is a fruitful concept that may help explain the sometimes divergent opinions on what is or is not complex. In addition, there are subcategories of complexity indicated in the assessment of the systems in the paper which should be further defined, including ideas such as managed complexity, constrained complexity, expected or unexpected emergence, social application complexity, operational complexity, etc. Some of these topics may be related and research is needed to define these subcategories more clearly and what constitutes a complicated or complex system when there is a large mix of complicated and complex system characteristics. Also, research into the benefits which have been obtained from different systems engineering techniques when faced with complexity of a system or its confounding factors on each individual characteristic may yield useful guidance for dealing with complexity.

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Appendix

Assessment of the Complexity of Example Systems

In the tables below, each example system characteristic is rated on a scale of **1 to 10**, where **1** = simple, **5** is complicated, and **10** is highly complex. When a confounding factor is present, it is described briefly, and the same scale is used to rate the level of complexity it introduces.

Table A-1: Simple and Confounding Complexity Examples

Example System => **Characteristic:**	Army Pot Helmet	Bullet Train	Radar
Bottom line: Simple, Complicated or Complex?	Simple	Complex	Complicated (with dynamic artificial intelligence algorithms, may be complex adaptive)
Diversity	**3** Minimal	**8** Stable goals for system wide performance are difficult to attain and maintain due to constant pressures for increased speed, ridership, social embrace, and profitability. Over years of operation the system accumulates an increasing variety of rolling stock, component inventory, operating procedures, and levels of regional capacity.	**7** Moderate (many different engineering disciplines needed, leading to high subjective complexity)
Connectivity	**2** Minimal (head interface)	**8** Ultimately, system connectivity is defined by inter-nodal relationships (e.g., riders moving from one place to another). These relationships are mediated by rider trust and the 'weighting' afforded by trusting populations. These populations are further coupled with events e.g. business schedules, seasonal activities, weather, economic cycles, etc.	**6** Moderate (may connect to other systems)

Example System => **Characteristic:**	Army Pot Helmet	Bullet Train	Radar
Interactivity	**2** Minimal (adapt, don/doff, secure /release) **6** **Confounding factor:** Uses for other purposes (such as cooking)	**9** Numerous interactions between the system and its environment: various experiential dimensions (e.g., cost, punctuality, comfort, quiet) and social embrace/ridership/profitability; various technical dimensions (e.g., aerodynamics and vibration, earthquakes and safety, weather and punctuality, rolling stock and performance, etc.)	**6** Moderate (often interacts with other systems)
Adaptability	**2** Minimal (size, shell on/off, cover on/off)	**8** In order to achieve overriding goals for system punctuality, the technical system must be extremely adaptable in responding to variability in weather conditions across geographical regions as well as multilevel (across temporal and spatial scales) scheduling logistics, anticipated ridership, etc.	**6** Moderate
Multiscale	**1** No	**9** The technical system is a composite of elements that can be described at various scales: materials, components, unit assemblies (cars, engines, couplings, stations, tracks, region/prefecture, whole system, etc.). In addition the operating organization can be described at various levels of hierarchy (e.g., departments, lines, company, etc.)	**8** Yes: particulate level affects performance, while higher-level choices such as waveforms and frequency have different dynamics; coverage is at a large scale.

Example System => **Characteristic:**	Army Pot Helmet	Bullet Train	Radar
Multi-perspective	**1** No	**9** Technical system states and events are routinely represented, referenced, and interpreted from multiple perspectives by different facets of the operating organization (mechanics, schedulers, service personnel, management, etc.), stakeholders (riders, residents, business, towns, cities, prefectures, regulators, journalists, countries, etc.), and others (disinterested humans and non-humans). Such perspectives routinely and generatively feed back into system states and events.	**5** No (though may be used in a system -of-systems which is multi-perspective)
Behavior (not describable as a response system)	**1** No	**9** At lower levels of assembly hierarchies (bogies, pantographs), behaviors can be well characterized. But given the diversity and unpredictability of the system at higher levels of aggregation, system control becomes increasingly subject to human intervention and certain inputs (e.g., energy flows, line loads) or outputs (e.g., trackside noise, sparking) may exhibit challenging or problematic behavior; such side effects can effectively limit important dimensions of system performance (profitability, market share) prompting system evolution (research and development).	**3** No **10** If artificial-intelligence algorithms are used to dynamically alter characteristic of waveforms sent and receiving processing

Example System => **Characteristic:**	Army Pot Helmet	Bullet Train	Radar
Dynamics complex	**1** No	**5** While selected dynamics of the technical system may be reproducible in test facilities, in the field such simple results may not be conclusive. Consider, for example human response to noise, vibration, pitch, and yaw under variable track conditions. To the extent that changing conditions can be anticipated, adaptive responses can be designed and deployed.	**4** Moderately
Representation difficult	**1** No	**8** Considering the variety of operational states achieved and/or maintained far from equilibrium by the technical system relative to e.g., specific environment, component operating and life-cycles, physical, technical, or economic conditions, a discrete enumeration of system states could prove un-representable. However, managerial and technical systems exhibit numerous representational features contributing to robustness and resilience of long term development: e.g. active tracking of commitments to physical infrastructure, research and development capability and performance measures considering large-scale/long-term effects, such as long term profitability and growth, technical performance competitive with air travel.	**8** Representation complicated; interference and noise make response description less accurate

Example System => **Characteristic:**	Army Pot Helmet	Bullet Train	Radar
Evolution	**1** No	**5** Day to day and year to year operational system evolves with experience and technology, through techno-social and organizational learning processes. Day to day and year to year operational system continuously generates novelty - although it is usually hidden or ignored/tolerated to a degree (e.g., within bounds of system-wide punctuality). Also see the entry on Representation.	**3** No **10** (except when dynamic AI-based algorithms are used)
System Emergence not predictable behavior	**1** No	**8** Stable goals for system wide performance are difficult to attain and maintain due to constant pressures for increased speed, ridership, social embrace, and profitability. Over years of operation the system accumulates an increasing variety of rolling stock, component inventory, operating procedures, and levels of regional capacity.	**5** No **10** (unless dynamic AI-based algorithms are used)
Disproportionate Effects	**1** No	**10** Local events or state changes at distant station pairs can produce system-wide effects. Also see above re small scale modifications. Due particularly to one-track logistics, small changes on the scale of minutes can produce extensive change in system configurations and system wide effects taking place over days and longer. Also see the entry on Unexpected Emergence	**4** No **Confounding factors: 9** Environmental changes, especially ones which are very rapid, can cause unanticipated performance problems

Example System => **Characteristic:**	Army Pot Helmet	Bullet Train	Radar
Indeterminate Boundaries	**1** Distinct Boundaries	**10** Physical track corridors are determinate however the boundaries of interactions between the technical system and surrounding environment are fuzzy. Noise envelopes, ridership catchment, and line capacity are soft and always evolving. for example. Also, maximum speeds are opaque in the absence of extensive testing, standard development, and public feedback. This only partially accounts for other variables such as management and energy costs associated with schedule maintenance which are effectively unknown until they happen.	**3** The boundaries between a radar system and the context in which it is operating are typically very clear.
Contextual Influences	**5** In Application	**10** Nationwide system (Japan) and international catalyst interacting at many levels of hierarchy with multiple business, technical, social, cultural, political groups and organizations. Managerial system exhibits numerous strategic features contributing to robustness and resilience of socio-political interactions: e.g. participation in regional, national, and international transportation standards and policy development.	

Table A-2: Complex and Complex Adaptive System Examples

Example System => **Characteristic:**	Launch Vehicle / Rocket	Artificial Intelligence Scheduler
Bottom line: Simple, Complicated or Complex?	Complex	Complex Adaptive
Diversity	**8** Constrained Diversity - The system design accounts for diversity in operation	**5** The learning function of the scheduler is very diverse. Specific intent to make everything but the learning function as deterministic as possible. The majority of the system has constrained diversity typical of a software system that controls hardware in space.
Connectivity	**7** Intricate and Diverse Connectivity	**6** The learning function of the scheduler has complex connectivity. The system has structural complexity typical of a software system that controls hardware in space.
Interactivity	**8** Controlled Boundaries, not well predicted.	**6** The scheduler is instructed to propose the most likely collection opportunities based on historical performance, which it assesses using learning algorithms The majority of the system has stimulus/response complexity typical of a software system that controls hardware in space.
Adaptability	**6** Limited: Vehicles are designed to withstand changes and operations to stay within limited ranges. Advanced GN&C software is emerging that is adaptive and will increase the vehicle adaptability to trajectory and environmental perturbations.	**8** Open adaptability within loose constraints. This system is designed and encouraged to adapt.
Multiscale	**10** Yes: The system has several scales: rocket, stages, and engines. Each can be viewed as a separate system or a component system part of the larger whole.	**7** Possible multiscale. The schedulers learning decisions may be based on conditions at multiple scales, but the precise rationale for the decisions is opaque.

Example System => **Characteristic:**	Launch Vehicle / Rocket	Artificial Intelligence Scheduler
Multi-perspective	**9** Yes: There are several perspectives needed to understand the system as a whole: Physics (thermodynamic, mechanical, electrical, optical, atmospheric, etc.) Value (Economic), Policy, Law, multiple stakeholder classes with different values of the system.	**7** The leaning scheduler itself has a single perspective, but its options are constrained by rules made from multiple perspectives.
Behavior (not describable as a response system)	**9** Yes: The amount of information needed to understand system response through all flight phases is not currently obtainable. The models of things such as atmospheric conditions, space radiation environments, and thermal vacuum interactions are not accurate enough to fully describe the system behavior.	**7** Difficult to describe. Scheduler learned decisions are opaque.
Dynamics complex	**7** Yes: Monte Carlo is state of the art analysis for many aspects. Nonlinear response regimes are particularly not simple averages. **Confounding factors:** Natural / Induced Environments can induce highly dynamic behavior	**7** Somewhat dynamic. Scheduler is intended to learn to deal with the interaction of multiple environmental constraints.
Representation	**10** Yes: Disaggregated There is a great deal of unpredictability in the component systems, and their interactions. Most accidents stem from not understanding or predicting the system level response from some "simple" changes in a system or environmental parameter.	**7** The learning algorithms are difficult to represent beyond fundamental equations and logic structures.
Evolution	**5** Somewhat: Rocket designs to evolve with time and technology. Shuttle was stated as a 30 year flying experiment. The shuttle never flew the same system configuration twice. There were always changes and upgrades. **Confounding factors: 10** Artificial Intelligence could lead to evolutionary characteristics in future systems.	**8** Designed Evolution. The system changes its rules but not its functions.
System Emergence not predictable behavior	**9** Somewhat: Novelty comes from the flight patterns and payloads placed in orbit. The space program continuously generates novelty. The rocket is part of	**8** System is designed to learn based on results and emergent behavior in

Example System => Characteristic:	Launch Vehicle / Rocket	Artificial Intelligence Scheduler
	this larger system and enables the novelty.	some fashion is expected. Unexpected Emergence in collection requests over time.
Disproportionate Effects	**10** Yes: This is seen everyday in rocketry. A few temperature degrees change can cause < mm change in dimensions and cause the system to lose functionality. Small pressure changes can have large effects on propulsion efficiency. Rockets have very subtle relationships. Soft foam moving at Mach speeds can break strong reinforced carbon panels. There is no direct tie, yet the interaction is catastrophic.	**8** Highly Disproportionate Effects. Learning decisions may create large shifts in behavior based on small changes in input.
Indeterminate Boundaries	**8** Environments are highly indeterminate. Flow fields are indeterminate. Mechanical boundaries are well defined in nominal operation. **Confounding factors:** **9** Atmospheric environments are complex and difficult to predict for a given launch site and day of launch.	**8** Environments and requests are highly indeterminate. Environmental boundaries are indeterminate and vary with local conditions. Requests vary widely.
Contextual Influences	**10** The natural environment relationship is highly variable and difficult to predict. The social interactions between the large design teams (1000's) and the rocket design are large. There is significantly complexity in the social interactions of the design organization leading to vary different designs for similar problems. The designs are difficult to compare without the integrating context. The social value of the rocket is also subtle and difficult to measure. Value for commercial telecommunications satellites vs. intergalactic astronomy platforms is very different in both near term value and long term value. The value of these different applications (payloads) is not currently possible to quantify.	**8** High impact. Law and policy of multiple nations and many mission requirements interact to constrain the system.

Biography

Michael D. Watson is the co-chair of the INCOSE Complex Systems Working Group and chair of the Systems Engineering Principles Action Team. He is in the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center (MSFC) System Engineering Office. He is leading the NASA Systems Engineering Research Consortium responsible for definition of elegant product focused systems engineering. He graduated with a BSEE from the University of Kentucky in 1987 and obtained his MSE in Electrical and Computer Engineering (1996) and Ph.D. in Electrical and Computer Engineering (2005) from the University of Alabama in Huntsville.

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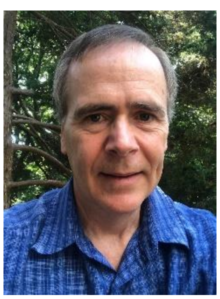

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