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Toward A Resilience Framework for Sustainable Engineered Systems

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Abstract

We discuss the development of sustainable engineered systems (SES) using emergent features of complex systems: large and diffused information content, non-linear causality, time lags in response to forcing functions, diffused control hierarchy, and uncertainty in end-points. If SES are to maintain their performance indicators over long durations, their success should be defined by the ability to monitor the changing risk profile and take timely actions to prevent the likelihood of failure. Resilience engineering (RE) is a new systems engineering design approach that takes into consideration such likelihoods and provides ways of generating prevention schemas before perturbations turn into system failures. We intend to extend the notions provided by RE into the SES conceptualization.

Keywords: Sustainability; systems engineering; resilience; sustainability

1. Introduction

Ecological resilience *"is the underlying capacity of an ecosystem to maintain desired services in the face of a fluctuating environment and human use"*[1]

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Technologists increasingly trust engineered systems as embodiments of larger natural systems (see for example Arnarson[2] on design-based bio-mimicry). The overarching belief is that to be successful, any effort to design and improve complex systems should be able to deal with system characteristics such as uncertainty, progression, accumulation, and dynamics of interactions with the natural system within which they reside. For example, design of a large eco-industrial park complex does little to assure ecological sustainability when it uses irreplaceable oil and minerals, and/or produces indestructible pollutants into the ecosystem within its long life-cycle. They also look to natural systems as potential models for engineered systems design, placing human activity in the context of larger ecosystem with resources to consume and sinks for wastes – the transformations of material and energy for use by all system components.

Another development that is taking shape is viewing design of engineered systems from a scientific perspective. Recently, advances have been made in attempting to understand the roles of sustainable engineered systems (SES) from a systems science perspective[3,4]. From an engineering perspective, it is argued that sustainability should be viewed as an emergent property of a complex engineered system[5] in contrast to the traditional, static view of engineering design. Some even suggest that SES will tend to be limited in their robustness, if they remain distant from rigorous, quantitative systems-based sciences[6]. In this respect, the fields of systems science and engineering are becoming agents of synthesis for integrating sustainability into large-scale engineered systems. For example, the emergent and dynamic behaviors of ecological systems have been explored using agent-based modeling and simulation techniques[7,8].

We discuss the development of SES using emergent features of complex systems: large and diffused information content, non-linear causality, time lags in response to forcing functions, diffused control hierarchy, and uncertainty in end-points[9]. By definition, SES must maintain their performance over long durations. As such, success in SES is defined by the ability to monitor the changing risk profile and take timely actions to prevent the likelihood of failure[10]. We see in Hollnagel et al[11] a treatise on this subject with the central idea being that failure is not necessarily a consequence of malfunction or poor design. Rather, it is a result of the "web of ongoing interactions and adaptations" that characterizes complex systems behavior in the real world. For a complex system to survive over its entire life-cycle, it must be able to deal with disruptions (events or conditions) that interrupt or impede normal operations by creating discontinuity, confusion, disorder or displacement[12].

And, increasingly, we feel the need to formalize the ability for a SES to survive these events. Among all properties of complex systems, de Weck et al[13] conclude that system requirements for survivability, resilience, and robustness can be made explicit and verifiable. This increases the likelihood that a system can be developed with such properties with a high degree of safety over its life-cycle. Therefore, the notion of resilience engineering has been advanced as formalization to successfully deal with the above-mentioned disruptions[14]. Resilience engineering is concerned with building systems that are able to circumvent adverse events through anticipation, survive disruptions in key processes, recover from negative consequences, and grow through learning and adaptation[10]. Here we discuss extending the notion of resilience engineering to SES. Ultimately, there needs to be a set of heuristics, as a function of the type of disruption, the type of system being designed and managed, and the type of resilience needed to deal with these disruptions.

2. Resilience Engineering

There is a growing recognition that system failures can be traced to a set of complex interactions among factors that are sociotechnical in content. It is also becoming evident that large complex systems development invariably demands both high productivity and high safety levels. It is this recognition that has stimulated the noticeable rise in interest in resilience engineering. In resilience engineering, failures do not imply a breakdown or malfunction of a normal system. Rather, they represent an inability of the system to adequately adapt to perturbations and changes in the real world given finite resources and time available[11,15]. As such, success is defined by the ability of the system to monitor the changing risk profile from disruptions, and take timely action to prevent the likelihood of damage. Failure, in this context, is simply the absence of this ability to deliver itself at the appropriate temporal-spatial conditions.

2.1. Forms of Disruptions

Over the years, four categories of systems have emerged in terms of resilience to disruptions: technological, natural, terrorism, and financial[10]. This paper focuses exclusively on technological and natural systems. With respect to coping with disruptions, it is important to distinguish between two types of resilience: reaction and adaptation. Reaction implies immediate or short-term action while adaptation implies long-term learning. For each disruption, we need to understand root causes, and their implications.

Literature also highlights two types of disruptions: external and systemic. *External disruptions* are most obviated by natural disasters caused by factors (e.g., random phenomena, input transients) outside the system. In this type, the principle of cross-scale interaction[11] is the predominant resilience strategy. In this strategy, the engineered system attempts to achieve a well-integrated and multi-layered communication and collaboration among all the elements of the civil infrastructure system entrusted with responding to natural disasters. These elements include power, water, law enforcement, medical and transportation. Also, predictive sensing and graceful degradation increase resilience, by allowing time for corrective actions. The primary learning implication of external disruptions is that systems need to be built with adequate safety margins to account for uncertainty. *Systemic disruptions*, on the other hand, relate to system function, capability or capacity[16]. It manifests itself in technological systems when, for example, a component fails, (e.g., Challenger space shuttle disaster). Similarly, a software error that results in an erroneous signal being sent to other system modules is an example of a loss of function disruption. Another example of a systemic disruption is the Nagoya air disaster, in which the pilot inadvertently provided an incorrect command to the flight control software causing the human element to be in conflict with the software capability. What is important is that the entire system, pilot and aircraft, were not capable of adapting even though there are many ways to increase the adaptability of the pilot-aircraft system (e.g., notify pilot of mismatch with flight control system, give the pilot more options, and let the flight control system adjust to the newly formed situation). Increasingly, patterns of systemic causality point toward organizational system design as a way of preventing this type of accidents[17]. Systemic sources of disruptions include humans, automated systems, and various combinations of the two, often referred to as "agents." Each agent, by virtue of its inherent capabilities and limitations, can be potentially both a source of disruption as well as a means to contain and recover from disruptions[18]. These sources of disruptions are discussed below:

- *Human Agent Disruption:* On the one hand, they can act unpredictably (e.g., the pilot in the Nagoya accident was central to the events leading up to the accident). On the other hand, they are capable of dealing with complex error correction behavior, making them the most adaptable and capable of responding to disruptions. In many cases, the human agent uses the resilience principle of "flexibility" to prevent system state from moving to unstable (from stable). From a system perspective, it is reasonable to conclude that the reason that most complex systems are not totally automated is that human agents are viewed as more capable of detecting and handling unpredicted situations than their machine counterparts. In this respect the human agent can be viewed as a net asset despite human limitations in cognitive and physical functioning.
- *Automated Agent Disruption:* This disruption is rooted in software, hardware, or in their interactions. Given today's state-of-the practice, software performance is highly dependent on the ability of software designers to envision the possible circumstances in which the software is expected to operate. Hardware is also not immune from disruptions as was the case with the vibrating struts in the Mars Polar Lander. However, hardware failures are generally governed by the laws of physics and, therefore, predictable to a large extent.
- *Multi-agent Disruption:* Disruptions can also occur at the intersectional conflicts among hardware, software and human agents. An example of a dual agent disruption is the Mars Climate Orbiter failure, where the flight control computer sent a signal to the thrusters in English units rather than metric units.
- *Predictable versus Unpredictable Disruptions:* Disruptions in modern technological systems are often predictable due to the ability to statistically/stochastically model the behavior of such systems. In its simplest form, adherence to standards such as MIL-STD-882 can increase system safety significantly. Unpredictable disturbances can occur, either because a phenomenon was unknown to modern science, or because it was unanticipated/unknown to systems designers. Again, the variability of human agents could be viewed as a source of unpredictability, and ultimately disruptions. The quality of engineering does come into play in determining

whether or not the system is able to survive such disruptive events. This is also where resilience engineering comes into play.

In what follows, we discuss the relationship between engineering resilience and sustainable systems engineering.

3. Resilience in Ecological Systems

Engineered systems are built, maintained and eventually recycled within its larger embodied ecological systems (ecosystems). We first define the notion of resilience for all forms of ecosystems. A high-level strategy to represent resilience in a system is to identify circumstances under which various kinds of subsystem influences are mutually supportive (progressive) or mutually non-supportive (regressive)[19]. In both forms, the system components may fail with an initially identifiable negative forcing function. However, in the first case, the failure and its impact on the overall system performance is minor, because the system can rapidly restore/regenerate itself into its previous state. It is through effective mobilization of subsystem regenerative resources that higher levels of adaptability, resilience, and longer-term sustainability can be achieved[20].

Another consideration is that the science of sustainability requires a deep understanding of ecological complexity. Levine[21] considers ecological systems to be the prototypical complex adaptive systems (CAS) with emergent behaviors and feedback that influences subsequent interactions. Interestingly, a new extension rooted in hierarchy theory[22] finds that the highest levels of complexity occur at intermediate degrees of integration and low levels of perturbation. Ecosystem complexity, being directly influenced by the levels of perturbation, may require special attention from complex systems theorists. To measure the degree of complexity in an ecosystem, some have suggested a new use of Shannon's information-theoretic measure for the web (network) of complexity[23]. There is also a need to further explore the features of ecological systems that make them distinct (diversity, memory, cross-scale interactions, sensitivity to environmental variability)[24]. The challenge for ecologists, however, is finding generalities in system patterns and dynamics to improve understanding and prediction.

In terms of resilience in ecosystems, we face similar challenges to define, understand and predict system behavior. Several of these are highlighted here to stimulate discussion (adapted from Levin and Clark[25]). These highlights are intended to help view resilience as a property of SES.

- *Early warning indicators of impending disaster.* New theories are needed to address ecosystem structures and organization from a sociotechnical systems perspective. They should merge deterministic (mechanistic) and stochastic; holistic and reductionist; physical sciences, social sciences and biological sciences; and must scale from the micro to the macro levels. Changes in any one level may have profound effects on the others. For example, loss of biodiversity has implications for climate change at a much longer time scale. Compositional models make these changes on faster time scales.
- *Sustaining the system throughout its life-cycle.* Integration of ecosystems from biotic activities to processes or the organization level must sustain system resilience. Tools such as life-cycle modeling and analysis could be used in this effort. From a macro system's view, the ecosystem serves global humanity; therefore these services must be viewed as connections between biodiversity and ecosystem services.
- *Proper level optimization.* Systems engineers routinely face the option of optimizing at the micro level, which ill serves the good of the entire system. Nevertheless, what distinguishes complex adaptive systems from designed systems is that the macroscopic properties of complex systems emerge from lower-level interactions, rather than being optimized according to some performance criteria. We need to explain apparent similarities in such properties (e.g., resilience, robustness, quality) across systems (e.g., watershed versus eco-industrial park), from designed to self-organized, even when the levels of selection that have led to those patterns are vastly different. We may see similar sinks in a watershed versus an eco-industrial park, but mechanisms that give rise to them are fundamentally different among these diverse examples. This does not imply that there is no value in examining whether and under what circumstances self-organized, complex adaptive systems may optimize system-level properties (e.g., resilience), subject to specific constraints.
- *Ecosystem resilience depends on multiple time-variability scales.* Ecosystems have the potential for multiple stable states, system flips and path dependencies before they fail. One important recent approach offers

methods for identifying indicators (such as critical slowing down, or high variability) of impending transitions to instability[26]. It is shown that complex dynamical ecosystems can have tipping points at which a sudden shift to a contrasting dynamical regime may occur. There exists a set of generic early-warning signals that may indicate for a wide class of systems if a critical threshold is approaching. Using the statistical relationship between critical slowing down, increased autocorrelation and increased variance, they show that close to the critical point, the system's return speed to equilibrium decreases. Unfortunately, for many large and critical ecosystems (e.g., climate, oceans), we do not have the opportunity to observe such a phenomenon on a statistical autocorrelation basis. More generally, recognition of the nature of systems as operating on multiple time scales (with or without the above-mentioned slowing down) emphasizes the need to understand changes in slow variables that might destabilize systems. Research is needed to gain deeper understanding of how the topology of interconnections in a system influences resilience, and whether self-organizing ecosystems tend toward greater resilience or not.

- *Characterize the interconnectedness of the system components and speed of disturbance.* Complex systems in general and complex adaptive ecosystems in particular, are often characterized by the potential for contagious spread of disturbances. One may start with the classical approaches to modeling the spread of forest fires and epidemics (e.g., see the model presented by Keeling and Eames[27]) for such a characterization. The distinction with the spread of disturbance in ecosystem is that the early epidemiological models were based on population wide random-mixing, but in practice, ecosystems may exhibit a differential and finite set of contacts with the next neighbors (subsystem). Again, network theory and graph theory can help characterize the interconnectedness of systems, and provide measures of system resilience and keys to resilient management.

- *Trade-off between resilience and other ecosystem properties.* A number of investigators have explored the relationships and semantic sets amongst system properties (sometimes referred to as "ilities" such as scalability or extensibility). Systems may exhibit preference for one set of "abilities" versus another, when they are assessed independently. Yet, sometimes, we see system requirements that demand two seemingly opposing properties such as "robust, yet fragile." For example, Mortiz et al[28] used the concept of highly optimized tolerances (HOT) to model wildfires and found resilience is traded-off with robustness in different fire-prone ecosystems. This means that adaptation to particular sets of conditions trade off against the ability to respond to changing sets of conditions. There same tradeoffs may exist between vulnerability and adaptability. We have learned that optimizing for one set of criteria may leave the system suppressed in fluctuations in another, which may prove costly when the system is on the brink of "total collapse."

4. Resilience and Adaptation

4.1. Quantification of Resilience

As noted earlier, ecological systems are both complex and evolving. As this is the case, a system may flip from one metastable state to another. A classic example is provided by Scheffer and his colleagues in describing alternative equilibria in shallow lakes[29]. Generally speaking, shallow lakes are spatially heterogeneous and fluctuations in environmental conditions affect their stability. The critical nutrient level for lakes to become turbid is higher for smaller lakes, and seems likely to be affected by climatic change. It is shown that shallow lakes could exhibit a bi-stable behavior. If low in nutrients (e.g., droughts), the water is generally clear and vice versa. However, the transition from one state to another is not gradual, once the bifurcation point is crossed. Some nutrient conditions favor the algae feeders that reduce turbidity, while some favor bottom feeders that increase it. The turbidity and especially the unanticipated flip from one state to another, results both from the general conditions of the system (e.g., temperature, water depth) and from particular types and number of organisms that comprise it and whose populations evolve with it. The shift between a clear and a turbid state remains one of the more dramatic examples, but is surely not the only discontinuity that can be observed in the response of these ecosystems to environmental change.

Another feature of meta-stable ecological systems can be described by the notion of "adaptive cycle."[30] The transitional behavior of a system is plotted against four system functions. An early-stage system in the exploitation phase gradually increases connectedness, which increases its stability. At a certain level of connectedness, the new opportunities for exploitation decrease and the system becomes stable (begins conserving its resources). A major disturbance is then needed to release the system. In this new phase, the potential and connectedness are rapidly transformed. In the final phase called reorganization, the system undergoes its resiliency test. Certain degree of unpredictability is introduced, which could lead to a regeneration of the original system, probably with variations, or an escape to another type of system. This reorganization is often referred to as state shifts involving "fold bifurcations" with hysteresis, and are well known in geological history of Earth[31]. In reliance engineering, we quantify the degree to which fold bifurcation exists in between the system and its environment. In mathematical terms, fold bifurcation is a local bifurcation in which two fixed points (or equilibria) of a dynamical system collide and annihilate each other. If the phase space is one-dimensional, one of the equilibrium points is unstable (the saddle), while the other is stable (the node). The normal form of a saddle-node bifurcation is:

$$\frac{dx}{dt} = r + x^2$$

Here x is the state variable and r is the bifurcation parameter.

- If $r<0$ there are two equilibrium points, a stable equilibrium point at $-\sqrt{-r}$ and an unstable one at $+\sqrt{-r}$.
- At $r=0$ (the bifurcation point) there is exactly one equilibrium point. At this point the fixed point is no longer hyperbolic. In this case the fixed point is called a saddle-node fixed point.
- If $r>0$ there are no equilibrium points.

4.2. Adaptive Management and Holarchies

SES inherently comprises of complex socio-technical agents. One way of capturing complexity in SES is the use of adaptive holarchies[32]. A holon is simultaneously a whole and a part. The concept originates from the ideas that complex systems will evolve from simple systems much more rapidly if there are stable intermediate forms present in that evolutionary process than if they are not present. And this is true for both ecological and socio-technical systems. Although it is easy to identify sub-wholes or parts, the locus of control in wholes and parts in an absolute sense do not exist in a location; and if one were to define some, they would shift over time from one level of holarchy to another. Holons are also autonomous, self-reliant units that possess a degree of independence and handle contingencies without asking higher authorities for instructions. Continuous formation of new subsystems could shift the locus of control from the social to technical aspect of the SES. The first property ensures that holons are stable forms that are able to withstand disturbances, while the latter property signifies that they are intermediate forms, providing a context for the proper functionality of the larger whole, under influences from their local environment. The multi-agent autonomous subsystems could be viewed as existing at three levels: micro (small, fast changing), meso (medium, slow changing) and macro (large, very slow changing). The peculiarity for this separation is that for any holarchy in a metastable state, the details of the micro holons processes are too small and fast to be anything but background noise to the higher level holons. In this respect, resilience is demonstrated when disruptions are responded to by micro systems rapidly and dynamically, leaving the next level holons to overcome any constraints in the macro system – the system adopts successfully to the new metastable state. If the damage to the lower level holons is irreparable, then the disruptive effects are passed on to the next higher level, and so on. The system becomes destabilized when several cycles of these adaptive behaviors are met with failures all the way up to the whole system.

We also learn that the management of disruptions for the holarchies versus single (hierarchical) systems are quite different. Our final word is related to the way resilience is different in these two types of systems. We adopt from the works of Keating et al[33] and offer the following table for comparison with SES relevant entities (Table 1):

Table 1. Distinctions Between Unitary Systems and Holarchies

Area	Unitary System	Holarchy

Objective	Achieve a purpose	Optimize holarchic functions
Expectation	Solution specific	Appropriate response to disruption
Boundary	Fixed	Fluid
Problem	Defined	Emergent
Approach	Intellectually rigorous	Intellectually adaptive
Resilience	Recovery	Anticipation, survival, recovery, learning

Finally, other than resilience, two other related aspects of the SES holarchies determine their future trajectories:

- *Adaptability*: the capacity of agent/actors in a SES holarchy to have influence (i.e., to manage resilience to at least a manageable level).
- *Transformability*: the capacity to create a fundamentally new engineered system when technological, environmental, and social conditions make the existing holarchy untenable (or a preferred alternative becomes available).

Understanding these mechanisms can be expected to provide new insights into the structure of sustainable engineered systems and eventually become an enabler in evaluating resilience management strategies.

5. Conclusions

In this paper, we have defined sustainable engineered systems (SES) as a branch of complex socio-technical system, rooted in the field of systems science. To formalize the ability of SES to survive any external disruptive event, we sought the knowledge base available in the field of resilience engineering (RE). Among the properties of complex systems, it seems feasible that resilience, survivability, and robustness can be made explicit and verifiable. RE is concerned with building systems that are able to circumvent adverse events through anticipation, survive disruptions in key processes, recover from negative consequences, and grow through learning and adaptation[10].

We began by describing RE in detail and defined the types of disruptions that RE is expected to address. From the perspective of RE, the success of SES is defined by the ability of the system to monitor the changing risk profiles resulting from disruptions, and take timely action to prevent the likelihood of damage, given the system's unique temporal-spatial signature and conditions. The forms of disruptions are also important in building resilience into SES. Having predictive sensing and graceful degradation increases resilience, by allowing time for corrective actions. It is also important for complex SES to learn from disruptive events, and increase their capacity to account for uncertainty. The sources of disruptions in SES can be human agents, automated agents, hybrid agents, and any other predictable or unpredictable systemic disruption.

To deepen our understanding of RE for SES, the embodiment of SES in ecological systems was characterized as complex adaptive systems in light of the fact that most ecosystems exhibit high levels of complexity, which occur at intermediate degrees of integration, and disturbed by low levels of perturbation. There is also a need to further explore specific features of ecological systems that make them distinct (diversity, memory, cross-scale interactions, sensitivity to environmental variability) and their implications on resilience design for such systems. We need to define, understand and be able to predict ecosystem behavior from a resilience perspective. Resilience as a property of SES may include:

- Early warning indicators of impending disaster
- Time-varying sustainment strategies for the system throughout its life-cycle
- Dynamic and proper level of optimization
- Ability to address multiple time-variable scales for ecosystem resilience
- Ability to characterize the interconnectedness of the system components and speed and rate of disturbance
- Ability to perform trade-offs between resilience and other ecosystem properties

We also offered a promising direction to quantify SES resilience using formulations given in meta-stable ecological systems. The concept of "fold bifurcation" was introduced within the context of adaptive holarchies. Holons were defined as autonomous, self-reliant units that possess a degree of independence and handle contingencies without asking higher authorities for instructions. The multi-agent autonomous subsystems could then be viewed as existing on three levels: micro (small, fast changing), meso (medium, slow changing) and macro (large, very slow changing). The peculiarity for this separation is that for any holarchy in a metastable state, the details of the micro holons processes are too small and fast to be anything but background noise to the higher level holons. We believe that resilience is significantly increased when disruptions are responded to by micro systems rapidly and dynamically, leaving the next level holons to overcome remaining constraints at higher levels. Thus, if the damage to the lower level holons is irreparable, then the disruptive effects are passed on to the next higher level, and so on. The system becomes destabilized when several cycles of these adaptive behaviors are met with failures all the way up to the whole system. The expansion of time here is the key to increasing resilience.

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