The role of ergonomics in creating adaptive and resilient complex systems for sustainability

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Abstract. Anthropogenic-led changes to our biosphere now threaten to disrupt human health and wellbeing and perhaps even our existence as a species. The principle aim of this paper is to demonstrate what human factors and ergonomics can learn from the study of how natural systems operate. This paper will demonstrate how a complex systems understanding is required to unpack problems, to identify solutions, and to select places in the system where interventions will have the greatest impact.

Keywords. green ergonomics; sustainable system-of-systems; adaptation; mitigation.

1. Introduction

Human actions (and inactions) have already led to serious disruptions to various climate, biological, biochemical, and geochemical systems at the local and global level including acid rain, ozone depletion, ocean acidification, aquifer depletion, biological extinctions, and climate change. The impact on human health and wellbeing (to individuals, groups, and communities) has also largely been negative for the majority of people on the planet including starvation and war in the most extreme cases and increases in asthma and psychological distress in less severe cases. The IPCC (2014) predicts that these deleterious effects on human health and wellbeing are only likely to increase, well beyond 2100. The indisputable fact that these changes are anthropogenic, Crutzen (2002) refers to this new geochemical age as the anthropocene, and will result in significant negative impacts on humanity, places these problems firmly in the path of the human factors and ergonomics (HFE) discipline. Moray (1995) even outlined these global problems to the HFE community in his keynote address to the International Ergonomics Association Congress in 1994, although the response was initially quite slow. In 2008 the International Ergonomics Association's Technical Committee on Human Factors for Sustainable Development (HFSD TC) was launched. The HFSD TC aims to explore the ways in which the HFE discipline can understand, model, and ameliorate these negative effects. In addition, new concepts such as ergoecology (García-Acosta et al., 2012), green ergonomics (Thatcher, 2013), a sustainable system-of-systems model for HFE (Thatcher & Yeow, 2016a), and supply-chain ergonomics (Zink, 2014) have been introduced to the HFE discipline to help focus our attention on these pressing and highly complex issues. This paper uses models and theories drawn from how biological and social systems function to show what we can learn about creating sustainable, adaptable, and resilient HFE systems that work in concert with natural systems; a design philosophy known as green ergonomics (Thatcher, 2013).

1.1 Sustainable system-of-systems for ergonomics

The sustainable system-of-systems (SSoS) model for ergonomics was developed based on a biological understanding of sustainability (see Costanza and Patten, (1995) for an understanding of sustainability in natural systems), a social understanding of sustainability (see Elkington

(1997) on the triple bottom line for business), and the work of Wilson (2014) on HFE systems. Following Wilson (2014), systems of interest to HFE are those that include at least one human and examples are human-technology systems, human-human systems, and human-technology-organisation systems (amongst many other variants). The framework that holds these concepts together is known as a system-of-systems. According to Maier (1998), a system-of-systems has five characteristics: (1) component systems should demonstrate operational independence (i.e. the component systems usefully exist on their own without the necessity of a system-of-systems); (2) each component system actually operates independently in practice; (3) evolves new purposes, functions, and components that can be added, removed, or modified; (4) displays emergent features and side-effects that are not inherent or predictable; and (5) component systems should be geographically dispersed. A human body alone is therefore not a system-of-systems because the component systems are not geographically dispersed (except perhaps at an atomic level) and the component systems (e.g. the digestive system, the cardiovascular system, or the neurological system) cannot operate independently except in extremely rare circumstances (e.g. during a heart transplant).

The SSoS model for HFE developed by Thatcher and Yeow (2016a; 2016b) has three major components (illustrated in Figure 1):

1) A nested hierarchy of complexity

According to Gunderson and Holling (2002) natural ecosystems are organized into nested hierarchies based on their complexity, spatial influence, and relative time scale, where each system is regulated by its own set of interdependent processes. At the smallest, micro-level (e.g. a tree) the ecosystem is dominated by biophysical processes (e.g. anatomy and physiology). At a larger, meso-level (e.g. a forest) the ecosystem is dominated by processes that determine the structure and succession of entire organisms (e.g. disturbances such as fires and storms, and the relative composition of species). At an even larger, macro-level (e.g. a continent) the ecosystem is dominated by climatic, geomorphological, and biogeographical processes (e.g. changes in climate, continental drift, etc.). The SSoS model for HFE (Thatcher & Yeow, 2016a; 2016b) represents possible HFE systems in a hierarchy of complexity and spatial influence. Graphically the model represents HFE systems in a hierarchy from simple HFE micro-ergonomics systems (e.g. tasks) that are encompassed by ever increasing layers of complexity/spatial influence (e.g. jobs, teams, organisations, and communities). The preferred nomenclature of Thatcher and Yeow (2016a; 2016b) to describe the relative "levels" in the hierarchy comes from Wilson (2014) who described the elements of the hierarchy as the HFE "target" system (the initial, specific system of concern) that interacts with "sibling" systems (i.e. systems with equivalent complexity and spatial influence), "parent" systems (i.e. systems that are of greater complexity or spatial reach), and "child" systems (i.e. systems that are less complex and have a tighter spatial reach).

2) A focus on multiple, simultaneous goals

For social systems (i.e. systems that include humans) the SSoS cannot be considered sustainable unless it recognises multiple, simultaneous sustainability goals of humans in the system across the hierarchy. The multiple goals that were used as an example in Thatcher and Yeow's (2016a; 2016b) articulation of the SSoS model were Elkington's (1998) triple bottom line of social, economic, and natural capital. HFE systems, by definition, include people (i.e. social capital) that either manipulate natural capital (i.e. raw materials or information) in order to create or maintain economic capital. From a triple bottom line perspective, the goals are inextricably linked, such that a failure to balance all the goals simultaneously will lead to a potential collapse (i.e. non-sustainability) of the SSoS.

3) Consideration of issues over time.

The SSoS model also considers a time dimension. Costanza and Patten (1995) noted that no natural system exists indefinitely and that all systems have a natural lifespan. They argued that the natural time lifespan of any system was "consistent with the system's time and space scale" (Costanza & Patten, 1995; p. 195). A larger, complex system should therefore have a longer natural lifespan than the smaller, less complex system that it encapsulates. If a system fails to reach its natural lifespan then this will result in instability across the hierarchy of systems. The implications of these timespans for HFE systems are discussed more fully in Thatcher (2016). For the purposes of this paper a simple example will suffice. If the target system of a single human-job interaction terminates prematurely (e.g. through burnout, a safety event, or a person leaving the organisation) this causes instability in the hierarchy. The team to which this person belongs will become disrupted (i.e. the parent system) and the tasks that the person normally completes will go unperformed (i.e. the child system) or will involve the reorganization of tasks in the team (i.e. the parent system). In Figure 1, these natural termination points are actually represented as ovals rather than as a single point to illustrate another property of natural systems, adaptive cycles, which are explained next.

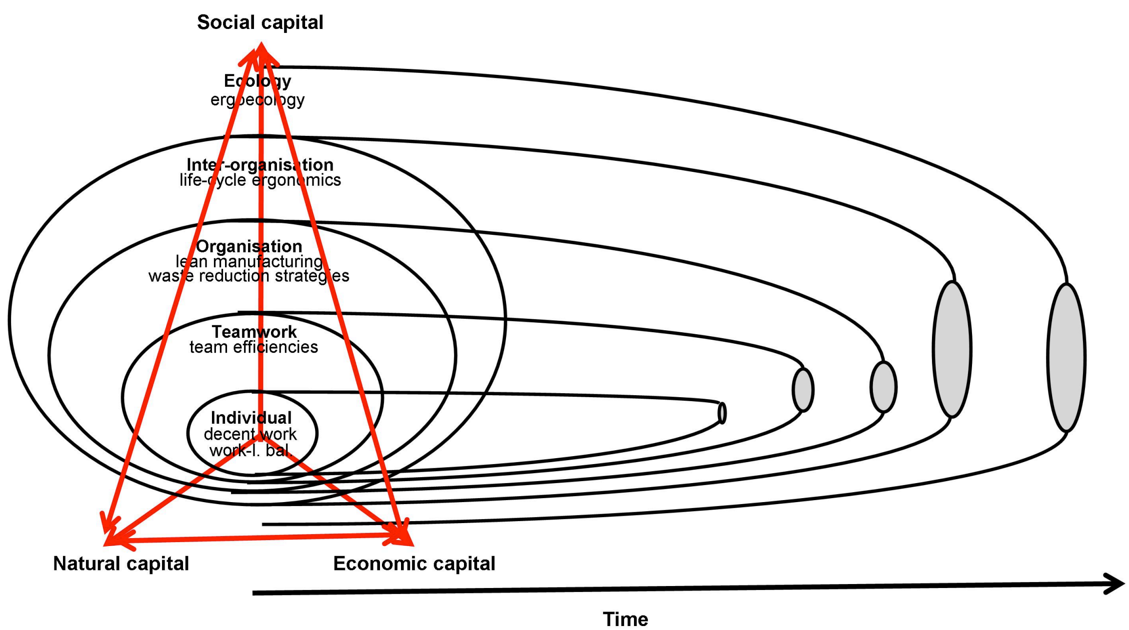

Figure 1. Sustainable system-of-systems for HFE.

1.2 Adaptive cycles in hierarchies

Gunderson and Holling (2002) suggest that most natural systems don't always just terminate; rather they are in a constant state of adaptation. Of course, natural systems will permanently terminate at some point (usually due to highly stochastic events), but a system is likely to go through multiple iterations before terminating. Gunderson and Holling (2002) called these dynamic processes adaptive cycles, based on ecological lifecycles of growth and re-organisation. They proposed that there are four stages that each system passes through (illustrated in Figure 2). The four stages are 1) entrepreneurial exploitation (r); 2) conservation and consolidation (K); 3) release and creative destruction (Ω); and 4) re-organisation and destructuring (α). The r stage is usually relatively short, where the system rapidly sequesters resources/stock from its environment. The K stage is (relatively) the longest, where the system accumulates and holds resources/stock. The Ω stage signifies a loss of resilience in the system and is also characterised by being of relatively short duration. The α stage is also very rapid and involves the re-collection and re-organisation of resources/stock. This stage could involve the re-organisation or re-envisioning of the system, or in some cases, the termination of the system. HFE systems follow a similar pattern. As a simple example, consider a system where a human interacts with a new tool. As the human encounters a new tool they begin to learn the different applications associated with the system (r-stage). Once these applications are learnt they can be enacted with increasing confidence and reduced effort (K stage). At some point a new tool will become available, or new applications will become possible with the tool (Ω stage). This will involve a re-organisation of human behaviour as new areas of enactment are possible (α stage) or an abandonment of the tool in favour of a new tool (termination of the task-tool system).

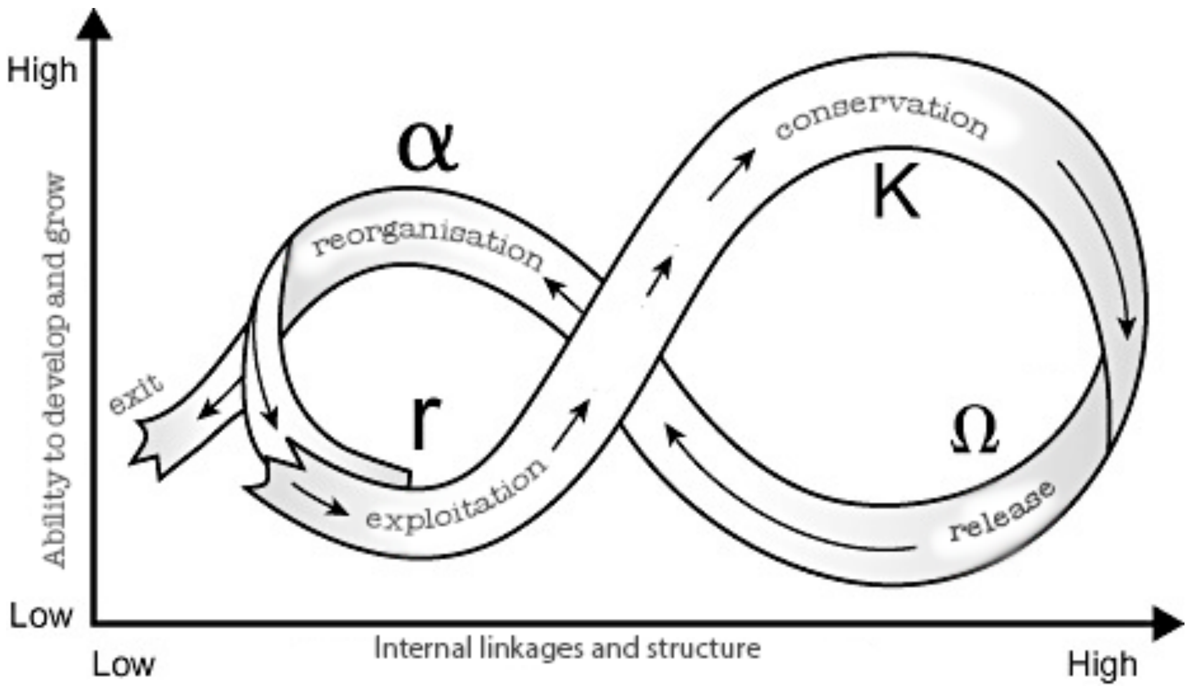

Figure 2. The adaptive cycle, adapted from Gunderson and Holling (2002; p. 34)

The other major component of Gunderson and Holling's (2002) model is that adaptive cycles are ordered in a "panarchy". A panarchy is similar to Costanza and Patten's (1995) and Thatcher and Yeow's (2016a; 2016b) nested hierarchy, in that systems are ordered according to complexity, size in space, and periodicity over time (i.e. the SSoS model as it has been described here). Gunderson and Holling (2002) describe the relationships between the different levels in the hierarchy. When a faster and smaller system (i.e. a child system) reaches the Ω stage, these creative destructive changes can provide an opportunity to disrupt/influence changes in slower and larger systems (i.e. parent systems), particularly when those systems are experiencing low resilience at the end of their K stage. Gunderson and Holling (2002) refer to this as a "revolt" process. For example, as task-tool interactions accumulate new applications (i.e. a release in the Ω stage of the child system) this may disrupt the existing organisation of work in the person's job (i.e. prompting change in the parent system). For HFE, identifying child systems that are in the Ω stage may also uncover required changes in their parent systems. Meadows (1999) used the term "leverage points", to signal these strategic places in the system's cycle where small changes (in child systems) might have big overall effects (in parent systems). Similarly, when a small and fast system (child system) is in the α stage, the options for new processes will be constrained by the processes in the larger and slower system (parent system) in the K stage. Gunderson and Holling (2002) called this the “remember” process. For example, the team culture and team roles (i.e. the parent system) of a system in the K stage will act as a stabilizing force to any changes in person’s job tasks (i.e. the child system). To phrase the “revolt” and “remember” mechanisms differently, child systems revitalize the target system and parent systems stabilise the target system (see Figure 3).

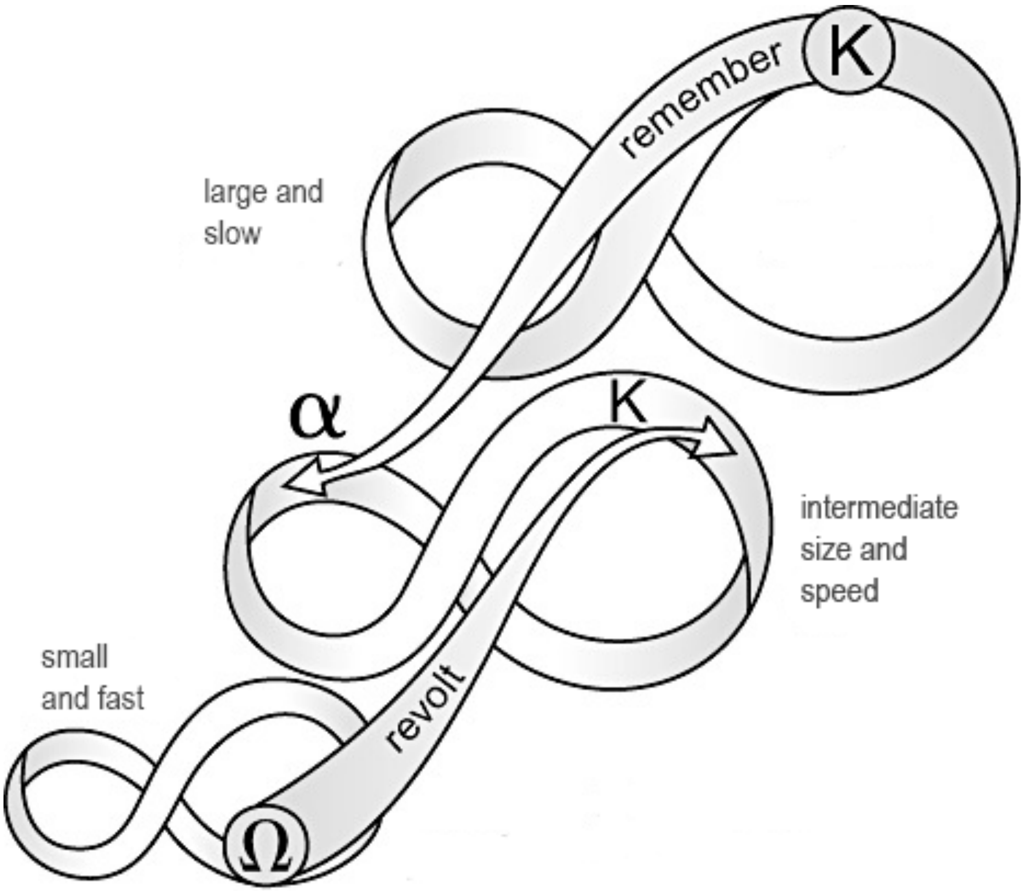

Figure 3. Panarchy interconnections between systems, adapted from Gunderson and Holling (2002; p. 75)

Linking social and natural systems, Gunderson and Holling (2002), noted that a target system is stabilised from changing too rapidly by the slower changes occurring in the parent. This allows for continuity and therefore the conservation, or sustainability, of the target system. A parent system that is too unstable will prevent the target system from stabilising and is hence unsustainable. Similarly, a target system is invigorated and regenerated by the faster changes happening in its child systems (i.e. the system itself is sustainable). These rapid changes in child systems allow parent systems to innovate and adapt to changing conditions (a core component of resilience). Target systems that resist change from the child systems cause the target system to become brittle and unsustainable. This brings us to the concept of resilience.

2. Resilience in HFE systems

There are as many definitions of resilience as there are branches of resilience science in engineering, ecology, and systems theory. For the purposes of this paper the definition of system resilience will suffice. Meadows and Wright (2008) define system resilience as the "system's ability to survive and persist within a variable environment" (p. 76). In the HFE literature, the concept of resilience is most frequently associated with resilience engineering (Hollnagel et al., 2006; Sheridan, 2008). Resilience engineering though, focuses on how an HFE system "bounces back" from unforeseen and uncontrollable perturbations, changes, or variations in order to facilitate system safety. In natural systems, we are less concerned about resilience that leads to system safety per se, and more interested in the system returning to equilibrium. Of course, when humans are in the system, safety is one of the importance goals for achieving this equilibrium. Resilience in natural systems refers to the "persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist" (Holling, 1973; p. 17). This definition describes systems that have a single equilibrium point. Holling (1973) noted that there are also systems that have multiple equilibrium points. Therefore, some disturbances may result in the system settling at a new equilibrium point. It is believed that the Earth's temperature and climate system may be one of these multiple equilibria systems, although one of the uncertainties is whether humanity would survive into this new equilibrium state.

Fiksel (2003) provides a summary of the characteristics of resilient systems that should be taken into account during design. A revised version of Fiksel's (2003) characteristics (see Table 1) provides a useful framework for HFE design that incorporates the concept of resilience for the first two levels in this table. The last two levels represent resilience at the broader level of socio-economic systems in society and the broader ecosystem.

Table 1. Characteristics of resilient systems, adapted from Fiksel (2003; p. 5333)

	Diversity	**Adaptability**	**Cohesion**	**Efficiency**
HFE product systems	Multiple product configurations, extensions, and options	End-user customization; recovery from failure	Distinguishing product identity and features	Value at relatively low total user cost (e.g. ease of use, usefulness, etc.)
Macroergonomic systems	Diverse business strategies; diverse workforce	Organisational learning; flexibility of leadership	Distinct corporate culture; strong relationships with partners	Efficient decision processes
Socio-economic systems	Ethnic, cultural, institutional, and political diversity	Transparency and flexibility of influential institutions	Strong national or regional identities; strong relationships with partners	Cost-efficient resolution of human needs
Ecosystems	Biodiversity	Tolerance and assimilation of disturbances	Clear habitat boundaries; strong networks	Efficient ecological cycling of nutrients and energy

Building on the characteristics of resilience in biological systems, Fiksel (2003) identified four general characteristics of resilience: diversity, adaptability, cohesion, and efficiency. Diversity refers to whether the system contains multiple forms or behaviours. More forms and behaviours give the system a greater chance to recover from unusual disturbances. Adaptability refers to the ability of the system to be flexible. This is equivalent to elasticity in an engineered system. In nature, systems that have cohesion through many linkages between elements in the system are better able to return to equilibrium. Finally, systems that efficiently use energy and resources have a greater chance of returning to equilibrium without exhausting those resources. These resilience characteristics are also encapsulated in the six values proposed by Lange-Morales et al. (2014) for HFE to facilitate a sustainable world.

3. Types of HFE responses: mitigation and adaptation

Incontrovertible evidence now exists from climate scientists, summarized by the IPCC (2014), that large-scale disturbances from the larger, slower, more complex systems (such as the global climate, political systems, and social systems) are already happening and the size of these disturbances will increase. According to the complex, adaptive hierarchies/panarchies presented in this paper (Gunderson & Holling, 2002; Thatcher & Yeow, 2016a), these parent "remember" processes will force the smaller, shorter, and less complex child systems (which include the traditional HFE systems of macro-, meso-, and micro-ergonomics) to make adjustments. Similarly, targeted "revolt" changes in these smaller, shorter, and less complex child systems can be used to direct how these larger, longer, and more complex parent systems will respond. Incropera (2016) refers to these two design options as adaptation and mitigation respectively. Once parent systems have started changing it is necessary to consider HFE designs that enable the child systems to be adaptable to these changes in a way that ensures the resilience of the target system. Similarly, child systems and target systems can influence the direction of adaptation of their parent systems through HFE mitigation design. Most suggestions from the HFE community have assumed that design through mitigation is the only path to ensuring a sustainable future. Examples of mitigation design in HFE abound (Hanson, 2013; Thatcher, 2013), including the design of low-resource systems and products and the design of jobs that ensure low-resource use and eco-efficient/eco-productive behaviours. Clearly there is also a need to think about how HFE might contribute to the design of adaptations to meet the challenges associated with changes occurring in our parent systems.

4. Concluding comment

As a concluding comment it is important to note that addressing these highly complex, dynamic problems is not a task that HFE can achieve on its own. On this point, Moray (1995) recognized the need for multidisciplinary teamwork during the identification and design phases to identify, understand, and ultimately to design solutions to these problems. HFE professionals will need to co-construct knowledge and solutions with biologists, engineers, anthropologists, political scientists, and climate scientists, amongst many others.

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