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THE CHALLENGE OF SUSTAINABILITY: DESIGNING FOR RESILIENCE

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ABSTRACT

Although ‘sustainable design’ has become widely accepted as a necessary component of the educational preparation of designers, architects, and engineers around the globe, it sometimes seems that ‘sustainability’ is a concept without an explicit definition. Here we propose that long–term sustainability of products and systems requires more than simply minimizing the use of energy and maximizing the use of recycled materials. Sustainability also implies that products and systems are designed for *resilience*, that is, they possess the ability to survive and evolve within changing environments, when appropriate. We present products that show some degree of resilience, and offer an example of a consumer product family that has shown considerable adaptive ability under changing market conditions. Finally, we offer some thoughts regarding how these concepts might become an integral part of design and engineering curricula.

Keywords: sustainable design, design for resilience, product architecture

1 INTRODUCTION

Our primary task as design and engineering educators is to provide our students with the tools, techniques, and intellectual resources that will enable them to create a world that does not yet exist. Unrelenting technological change coupled with poorly understood global forces makes the task of predicting which tools and resources our students will actually put to use quite difficult. Our charge becomes more problematic when we add the desirability of creating sustainable designs to the mix: how do we teach students to create products and systems that will be sustainable in the world to come, when we can have at best an imperfect image of that future world?

We generally accept that even in the presence of uncertainty, we are able to make rational predictions about what the future may hold by examining current trends. Two difficulties are apparent with this approach: first, how do we sort out significant long term trends from a constant stream of dire predictions and doomsday scenarios? The second problem is yet more daunting: how do we develop and teach methodologies that our students can use to create designs that will lead to a more sustainable society?

In the first case, our best option is to emphasize trends that have considerable amounts of momentum inherent in them, and which are stable within predictable bounds. Global factors such as energy and resource depletion, population demographics, and climate change fit into this category: they show considerable inertia and can provide the rudiments of a stable foundation for creating future scenarios.

This leaves us with the question of creating methods for designing products and systems that can be sustained in the face of unpredictable change. If we look to the history of technology and design, we find that long–lived designs typically fall into two categories: designs that *endure*, and designs that *evolve*. Designs that *endure* typically possess one of two defining characteristics: either they survive by virtue of their functional simplicity, or they survive because of the emotional attachment they engender in their users. In the first group are designs that combine pure functionality with effective form, e.g., paper clips, lead pencils, knives, hand tools, etc. In the second group we find designs that survive because of what can only be called market mystique: examples include the Harley–Davidson motorcycle, the Eames chair, and the Wagenfeld lamp.

The primary focus of this paper is on designs that attain long life by *evolving*. These artifacts also belong to one of two classes: the first class consists of designs which 'evolve' in the sense that they maintain the original form, while few, if any, original components endure throughout the entire life of the product. Examples would include the Boeing B–52 bomber, which is currently flown by the grandsons of the original pilots, and automobiles in developing countries, which are constantly being repaired and upgraded. Many buildings are also examples of this sort of evolution, as they continue to change and adapt to new uses over their long lifetimes [1].

The second set of products are those in which the outward form of the artifact changes along with the components, as new variants are introduced in order to maintain a market niche. Ecological systems are an endless source of models for this class of designs, because biological organisms alone spontaneously adapt and evolve in response to changing environmental conditions. Our claim is that sustainability over the long term requires *design for resilience*, where *resilience* is defined as either: *i*) the ability of a system to spontaneously adapt in response to changes in its environment, or *ii*) the ability of a system or product family to foster rapid adaptation by the designer to changing conditions.

Our long–range goal as designers and engineers may well be to design systems that mimic living ecological systems. Just as the machine was the paradigm for design in the Twentieth Century, biological systems seem to be the paradigm for the Twenty–first. We believe that the first examples of such artifacts and systems are emerging today. In this paper we look briefly at how the concept of resilience applies to ecological systems, and then consider some examples of products currently on the market. We conclude with some thoughts and suggestions regarding the implications of design for resilience for the education of future designers and engineers.

2 ENGINEERING AND ECOLOGICAL RESILIENCE

To define *resilience* we turn to ecological systems theory, where the concept of resilient systems has been the subject of research and discussion for at least three decades. Gunderson and Pritchard [2] credit Holling [3] with first noting the difference between definitions of resilience that emphasize *efficiency*, which they term *engineering resilience*, and those that emphasize *persistence*, which they denote as *ecological resilience*. In their formulation engineering resilience "…conceives ecological systems to exist close to a steady state. Engineering resilience, then, is the *speed of return to the steady state* following a perturbation" (emphasis added). Ecological resilience, on the other hand, "…emphasizes conditions far from any stable steady state, where instabilities can shift or flip a system into another regime of behavior – in other words, to another stability domain. In this case, resilience is measured by the magnitude of disturbance that can be absorbed before the system is restructured with different controlling variables and processes" [2].

Representations of the two types of resilience are shown below in Figure 1, where the ball represents the state of the system, and the curve the "stability landscape." Engineering resilience is identical to the notion of robustness, as represented in Figure 1(a). Robustness is measured by the speed with which a system that is perturbed returns to an equilibrium state. Ecological resilience, on the other hand, is defined as the distance the system can move away from equilibrium before finding a new equilibrium state, i.e., a radically different ecosystem, as shown in Figure 1(b). Here, speed of return to equilibrium is not the metric of interest; rather, we are interested in the ability of the system to find a new equilibrium state that may be far removed from its initial condition, but which also enables survival. This second type of resilience clearly is more applicable to products that are introduced into rapidly changing markets, where the exact contours of future systems are both unknown and constantly changing.

Fiksel [4] asserts that ecological resilience, because it emphasizes the notion of persistence under changing conditions, is essential to achieving sustainability over the long term. He notes four key characteristics of resilient systems: *diversity*, defined as the existence of multiple forms and behaviors; *efficiency*, which is performance with minimal resource consumption; *adaptability*, the flexibility to change in response to stresses; and *cohesion*, the existence of unifying forces or linkages. Products are appearing on the market that possess many of these characteristics to some degree.

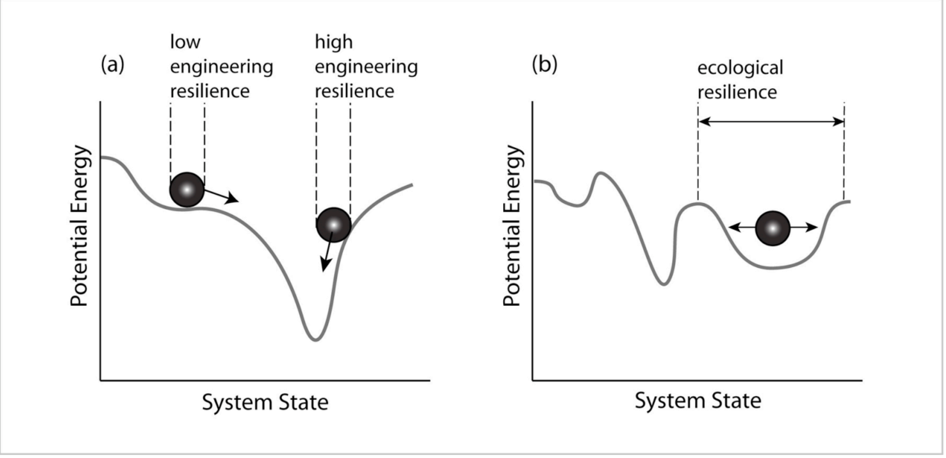

Figure 1. Engineering and ecological resilience, after [2]

3 THE EMERGENCE OF RESILIENT PRODUCTS

We begin by imagining what a fully resilient product or product family might look like. Referring to Figure 1(b), imagine that the curve represents the global marketplace, and the ball the market position of a family of products offered by a particular firm. Ecological resilience implies that when the intended market for a product family undergoes a fundamental shift and enters a new equilibrium state, due perhaps to population demographics, changing technology, or economic factors, the product is able to survive in a new market niche. What we might term a *fully resilient* design would be able to find its own equilibrium point completely without the direct intervention of the designer.

As an example, one can imagine a scenario a few decades in the future, when a colony of robots may exist on the surface of Mars, sent to construct a habitat for humans ahead of the first manned mission to the planet. In such a scenario, the robots would be essentially autonomous agents working in an environment that is constantly changing due to their own actions. As the habitat is constructed, the specific tasks needed will change, and hence the robots would themselves change their configurations. As an example, early on a robot might need to configure itself to burrow under the surface; later, it might reassemble itself as a welder, or as a part of a life support system.

While such a scenario might seem to be completely beyond the bounds of what is currently possible, consider this: the operating system for the computer on which this paper is written periodically checks for upgrades and alerts the user when new software is available for installation. Often these upgrades have been created in response to threats to the stability of the operating system, i.e., computer viruses or worms. As consumers, we have become accustomed to our computers upgrading their anti–virus software on schedule. Is there any theoretical reason why an operating system could not *sense* when it is under attack, determine the specific ‘pathogen’ in question, seek out ‘antibiotic’ code on the internet, and install it without even informing the human user that it had done so? In the realm of computer software we are clearly close to realizing the goal of creating independently resilient systems.

One might argue that this scenario does not represent true resilience, because the software code that disinfects the virus is the conscious product of human software designers. However, we might call this ‘intelligent resilient design’ as opposed to truly ‘Darwinian resilient design’: that is, products evolve only when designers cause them to evolve, and not as the consequence of their initial ‘design DNA’.

We find examples of this process at work when we look at hardware, as well. One of the most successful examples of products that have achieved long life by evolution is the Kodak family of One–Time–Use Cameras (OTUC), which have been on the market since 1987 [5]. These cameras have gone through numerous changes while dominating their market segment for two decades. Referring to Fiksel’s four characteristics of resilient systems – *diversity*, *efficiency*, *cohesion*, and *adaptability* – this family of cameras exhibits all four. The product family is quite diverse, with new variations appearing on the market on a more or less continuous schedule; they are highly efficient in terms of energy and material use, with approximately 90% of each camera either re–used or recycled; they cohere as a product family with a brand identity that is extremely strong; and finally they are quite adaptable, as shown by their ability to survive even as the remainder of the market for film cameras has evaporated.

The ability of these products to adapt provides insights into why they have been so successful. As digital technology has revolutionized the market for image capture and storage, companies that produce film and cameras have been under tremendous pressure to either adapt to changing technology or perish. At Eastman Kodak, the response was to abandon the mid–range film camera market while moving selected components of these cameras down–market. A good example of this strategy is the two–element *Ektanar*© lens, which was previously available only on Kodak’s more expensive cameras. This high–quality lens was successfully introduced into the OTUC family in 2001. Because the system architecture of the cameras was able to easily adapt to a change in the lens configuration, Kodak could continue to exploit this successful technology, even as an entire market segment disappeared. By doing so, they made a significant improvement to their down–market product, bolstering its market position, and thereby enabled it to survive into an age dominated by digital technology.

An important point to note here is that the success of this product line over the past twenty years is due not to any breakthrough technology or proprietary advantage, but is primarily due to the system architecture of the product line. Although almost every aspect of a product's life, from material selection to manufacturing to reusability is affected by product architecture, the topic has only recently been given its rightful place in American engineering design texts (see, for example, [6] and [7]). The system architecture is often the key factor in determining the adaptability and evolution of a product family. While modular architectures allow for the greatest degree of flexibility in component and sub–system sharing across the product portfolio, they also exact a penalty in terms of performance per unit mass. At the other extreme, highly integrated architectures often constrain material selection and manufacturing process, as well as component sharing, due to the complex component geometries they typically require.

A look at the architecture of the Kodak camera family reveals an intelligently designed, highly evolved merger of modular and integrated components at different functional levels. At the highest level, the camera is a modular architecture: functional sub–system boundaries are well–defined, and components are shared extensively across the entire portfolio. In some cases, functional sub–systems and components are identical: for example, the flash circuitry is wholly contained within a single circuit board. In other sub–systems, e.g., the film handling system, the function is shared by a group of components that are designed such that identical components can be shared across the entire product range. Many of these components are themselves quite integrated, in some cases performing multiple functions – the camera frame, for example, carries out at least seventeen discrete functions. Other components are totally modular, performing only a single task, but are used across the entire product range.

The point is that the overall architecture shows different levels of integration and modularity within each functional level. What is key to the resilience of the product family is how efficiently the design can be adapted to specific user needs and desires. Replacing the original single–element lens with the more capable Ektanar© lens is one example; enclosing the basic outdoor camera in a tough polycarbonate/elastomer case and making it waterproof, thereby creating an "extreme sports" model, is another. Designing a product line so that disassembly is simple, with components made from two or three thermoplastic resins that facilitate recycling and re–use, affords tremendous cost savings in energy and materials.

By taking the time to create a flexible, coherent, and highly adaptable product architecture, Kodak's designers and engineers have evolved a product family that continues to do well, in spite of digital technology that has destroyed much of the rest of their product environment. Our contention is that the system architecture is key to the design of this truly resilient, sustainable product family. The single–use camera is an excellent example of how 'design for resilience' can allow companies and products to survive in difficult, rapidly changing environments.

4 EDUCATING DESIGNERS AND ENGINEERS FOR THE FUTURE

What possible connection do these ideas have with the difficult task of educating young designers and engineers for an uncertain and unpredictable future? Designing resilient systems such as the Kodak One–Time–Use camera demands an extremely high level of skill and effective communication on the part of the design team. The rudiments of this kind of sophisticated knowledge can be taught at the university level, but only when the traditional, and in some senses artificial, boundaries between disciplines are overcome. Students must be made aware that answers to the problems that confront us today will not be found in any single discipline, but will require the ability and a willingness to work across disciplinary boundaries to find solutions.

Programs that integrate engineering, product design, and architecture in particular are absolutely necessary for the future. Engineers intending careers in product design must leave the university with a thorough appreciation for design, marketing, psychology, ecology, anthropology, and biology, in addition to their own specific domain knowledge. Design and architecture students need a much deeper understanding of the more technical aspects of design. This means not just the traditional courses in materials and processes, but also kinematics, energy systems, biology, cognitive psychology, and anthropology. All design–related programs should expose their students to thinking and designing at the systems level. Basic courses in systems thinking that are appropriate for undergraduate students in architecture, engineering and design need not require a heavy dose of mathematics. What is important is that our students gain some exposure to concepts such as emergent behavior, complexity theory, and basic systems architecture, and that they understand how these concepts can be used to develop truly sustainable designs.

Toward this end, we have begun team–teaching seminars in sustainable design to students in several disciplines at Ohio State University. The faculty participants are product designers, architects, and mechanical and systems engineers. The students come from a variety of fields of study, including engineering, architecture, product design, and marketing. Our first iteration of the course proved successful and we have identified a range of opportunities, both for the course and for similar collaboration in the future. We are convinced that the only way to successfully impart the principles of sustainability and resilience is through such cross–disciplinary activities.

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