DESIGN OF SUSTAINABLE, RESILIENT INFRASTRUCTURE SYSTEMS

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ABSTRACT

Rising world populations and consumption are inexorably increasing human demand for infrastructure services. Population and wealth along with other global stressors will have a direct and significant impact on the sustainability goals, technology selection, and governance strategies that are related to infrastructure quality and density. This paper will explore infrastructure and governance challenges and opportunities in addressing human service needs while aligning social, environmental, and economic goals. Ultimately, the design, implementation, operation and maintenance of these systems will need a sustainability and resiliency framework given the current and dynamic state of the world and the long time horizon of such installations.

Keywords: sustainable design, resiliency, inherency, systems thinking

1 INTRODUCTION

There has been much effort in the engineering community to address the challenges of sustainability through new designs and new approaches. The questions now being raised about these new solutions are related to their own inherent sustainability. While there is many a noble goal in addressing challenges related to renewable energy, water purification, and agricultural productivity, it is becoming increasingly clear that our current solutions are contributing to further environmental and human health goals. While there are many such examples, the following represent a few that have been highlighted recently as examples of "doing the right things wrong".

Biofuels from food crops. There has been significant emphasis placed on alleviating dependence on fossil fuel by producing fuel energy from agricultural products. One of the clearest examples of this is the emphasis in the United States on producing ethanol from corn. Whether the economics of this approach are considered by monetizing life cycle emissions [1] or direct environmental impacts including water, fertilizer, and pesticide application [2], corn-based ethanol requires, per unit of fuel produced, more fossil fuel and fertilizer inputs that emit large amounts of greenhouse gases and particulate matter than the current petroleum-based production.

This is not to suggest that producing energy from biobased resources is not an appropriate or ultimately sustainable strategy. It is rather to suggest that pursing renewable energy in way that only addresses the singular goal of reducing use of finite resources can lead to increased environmental and human health impacts and even greater stress on the earth's systems.

Water purification by hazardous chemicals. The consumption of untreated water contributes to significant human health risks ranging from cholera to stunted development [3]. The most prevalent approach to water treatment for municipal systems in the much of the developed world has focused on the use of chlorine.

There has been recent attention given to both the potential health and security risks posed by the use of chlorine for water treatment. Recently, chloroform and other halogenated organic compounds have been identified in chlorinated drinking water supplies leading to numerous epidemiological studies. In general, these studies support the notion that by-products of chlorination are associated with increased cancer risks among other health risks [4].

Since the major terrorism attacks of the past decade, water systems are giving greater attention to the security of their facilities. Many systems are conducting comprehensive "vulnerability assessments" include the storage, handling, and protection of chlorine supplies.

Again, this is not to suggest that providing safe, reliable drinking water is not critically important to improved quality of life and human development.

It is, however, to raise the question of the approach being taken to achieve this crucial goal. Must we achieve clean drinking water through the use of potentially lethal and toxic chemicals? There are many more considerations to addressing this sustainability challenge than meeting the functional goal of clean drinking water highlighting the need to systematically consider multiple sustainability criteria simultaneously.

Photovoltaic cells using rare, toxic metals. The need to harness the sun's energy to meet current energy demand is becoming increasingly clear given concerns over the acquisition and use of fossil fuels from a societal, political, and environmental perspective. The current class of photovoltaic cells is reliant on toxic- and explosive-gases, corrosive liquids, and suspected carcinogens in solid form. These risks occur throughout the life cycle with particular concern for worker safety during manufacturing and environmental exposure at end of life.

While the operation of photovoltaic systems significantly reduces the emissions of SOx, NOx, particulate matter, and carbon dioxide, these critically advances are being realized through the use and generation of hazardous chemicals. There are many emerging pathways to photovoltaic cell synthesis demonstrating that there is not an inherent trade-off between solar energy and increased risk to human health and the environment. Through innovation and green design, solar energy can be realized sustainably. This will only occur if the pursuit of solar energy is not singularly focused on efficiency but rather considers human health and environmental factors in identifying which technological pathways to pursue.

Energy saving lighting technology based on neurotoxins. As a final example of addressing sustainability challenges in a manner that leads to further impacts on human health and the environment the recent push towards compact fluorescent lamps (CFLs) is highlighted. While the amount of mercury contained in each bulb is relatively small, the large market for lighting means that, in total, fluorescent bulbs represent a significant category of mercury-containing wastes in many mercury emissions inventories. Mercury is an element that is known to persist, bioaccumulate, and biomagnify in the environment, with known and well-documented toxicity concerns. While reducing demand through more efficient lighting technology is an important component of addressing the sustainable energy challenge, it has been shown that this approach can lead to increased environmental mercury emissions and subsequent human exposures in certain states and countries depending on the regional energy grid [5].

Recognizing that the optimal way to reduce energy demand is not through the use, generation, and emission of toxic chemicals, industry leaders are working to reduce the mercury content in lamps. Similarly, the U.S. Department of Energy's Vision 2020 project brought together researchers, manufactures, and policy makers to push for the elimination of mercury from CFLs by 2020 [6].

Given the goal of energy conservation, one must question the push towards the use of a technology reliant on a known toxin with significant potential to adversely impact human health and the environment. By considering the energy demand question in a systematic way towards a sustainable solution, the likely solution would not be CFLs. Once again, a sustainability challenge is attempting to be addressed through an unsustainable solution.

Each of these examples highlights the need for a systematic approach to designing, developing and implementing solutions to sustainability challenges. All of the challenges to sustainability are urgent and necessary. They represent noble goals in terms of addressing critical challenges to improve quality of life and human development. Often, the solutions have represented exciting and innovative science and technology. Clearly, these solutions were developed with the best of intentions. However, they all faced similar pitfalls in terms of looking to solve one challenge without considering the potential to create or contribute to additional and future challenges. The solution to sustainable energy cannot be reliant on toxic chemicals just as the solution to climate change cannot be reliant on copious amounts of fertilizer, pesticides, and scarce water.

As solutions to sustainability challenges are designed, particularly the grand challenges many of which are inextricably linked to infrastructure systems, a systematic sustainability framework must be considered. This is a necessary transformation in how engineering design is approached and practiced. The evolution of the challenges themselves and the level of understanding we have about these challenges require engineers to take on new skills, capabilities, and perspectives in how we approach our work. It is not that the skills previously learned are antiquated or need to be replaced. It is that the traditional skills need to be augmented, complimented, and enhanced with new knowledge, new perspectives, and new awareness with a sharp focus on a few key topics sustainable design, systems thinking, resiliency, and inherency.

In this way the definition of "performance" must evolve from a measure of function, cost, quality, and safety to include environment, human health and social wellbeing.

2 GREEN ENGINEERING

Engineers play a significant and vital role in nearly all aspects of delivering services (i.e., water, sanitation, mobility, energy, food, health care, and shelter) via infrastructure systems. The delivery of these services has historically contributed to adverse impacts on human health, the environment, and the economy. Green Engineering is the design, discovery, and implementation of engineering solutions with an awareness of potential benefits and consequences in terms of sustainability throughout the lifetime of the design. The Principles of Green Engineering (Table 1) [7] provide a framework for understanding and implementing green engineering.

Table 1: Principles of Green Engineering [7].

1. Designers need to strive to ensure that all material and energy inputs and outputs are as inherently non-hazardous as possible.
2. It is better to prevent waste than to treat or clean up waste after it is formed.
3. Separation and purification operations should be a component of the design framework.
4. System components should be designed to maximize mass, energy and temporal efficiency.
5. System components should be output pulled rather than input pushed through the use of energy and materials.
6. Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse or beneficial disposition.
7. Targeted durability, not immortality, should be a design goal.
8. Design for unnecessary capacity or capability should be considered a design flaw. This includes engineering "one size fits all" solutions.
9. Multi-component products should strive for material unification to promote disassembly and value retention. (minimize material diversity)
10. Design of processes and systems must include integration of interconnectivity with available energy and materials flows.
11. Performance metrics include designing for performance in commercial "after-life".
12. Design should be based on renewable and readily available inputs throughout the life-cycle.

Embedded in the discussion of green engineering is the word *design*. Design is the engineering stage where the greatest influence can be achieved in terms of sustainable outcomes. At the design stage, engineers are able to systematically select and evaluate conditions of the final deliverable. This can include material, chemical and energy inputs; effectiveness and efficiency; aesthetics and form; and intended specifications related to traditional definitions of performance. The design stage also represents the time for innovation to meet the intended goals without unintended consequences by utilizing a sustainable design framework. Sustainability, in this way, is not a design constraint, but rather as an opportunity to leapfrog current designs and drive innovative solutions that consider systematic benefits and impacts over the lifetime of the design.

The design phase offers unique opportunities in the life cycle of an engineered system, such as infrastructure systems. As shown in Figure 1, it is at the design phase of a typical product that 70 to 75 percent of the cost is established, even though these costs will not be realized until much later in the product life cycle. The environmental costs are analogous to the economic ones. For example, it is also at the design phase that materials are specified. Material selection often dictates the production process as well as the operation and maintenance procedures (i.e., painting, coating, rust inhibiting, cleaning, and lubricating). As soon as a material is specified as a design decision, the entire life cycle of that material from acquisition through processing and the end of life is now included as a part of the environmental impacts of the final design.

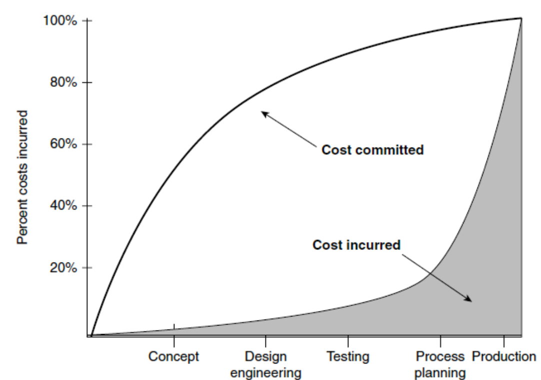

Figure 1: Percent Costs Incurred versus Design Time Line - The costs can be thought of as economic or environmental. During the design phase, approximately 70 percent of the cost becomes fixed for development, manufacture, and use.

It is, therefore, at the design phase that the engineer has the greatest ability to affect the environmental impacts associated with the final outcome. This process is similar for the design of infrastructure systems such as water supply systems, wastewater treatment plants, buildings, transportation systems, and residential or commercial

development. It is also important to note that design phase is when the engineer has the opportunity to incorporate increased efficiency; reduce waste of water, materials and energy; reduce costs; and most important impart new performance and new capabilities. While many of the other attributes listed can be achieved through end-of-pipe approaches, only at the design phase can the actual design characteristics be improved. When the design itself is improved through innovation and sustainability principles, value is added while offering an improved environmental and human health profile.

3 INNOVATION IN INFRASTRUCTURE SERVICE DELIVERY

There are many ways to define innovation, but the one that is most useful for this area is that innovation is the actual implementation of knowledge. As Schumpeter argued, there are many clever inventions in the world, but it is only the ones that are put into use in the wider economy that impact growth and development [8].

There are three main perspectives that are used to study innovation. The first, is the national innovation system perspective, including the work of Amsden and Nelson [9, 10]. This perspective has its origins in the economics literature, and is largely a top-down formulation. Within any nation, innovation is seen as the outgrowth of a variety of systems. The key stakeholders are the decision makers, usually with the government. The process of innovation itself, from research to firm-level commercialization and market acceptance, are largely treated as a black box.

The business literature presents a second, bottom-up, firm level perspective. This literature examines how firms actually go about developing and implementing innovations, and the factors, from the firm and organizational perspective, that can impact success. Within this body of literature, innovation drives economic growth through the financial success of firms, which are also employers and investors in the larger economy.

The third perspective is of innovations that include public goods component. This literature has its origins in agricultural economics. Ruttan has written extensively on "green revolution" innovations. These were developed in public research institutes and commercialization took place through the work of agricultural extension services [11]. Public health is another example where innovations have a strong public goods aspect. These in turn drive development directly, through improvement of quality of life and livelihoods, which then in turn result in macro-scale economic growth.

While there is a long history of the study of innovation, the dynamics that occur at the intersection of innovation and sustainable development are less well understood. Innovations in this area are designed to improve sustainability explicitly, and not just through the indirect economic impacts. They have an explicit public goods aspect, above and beyond general societal returns from knowledge spill-overs. Traditionally, innovation is viewed as a process that allows for optimization along the economic dimension. Innovation for sustainable development also requires optimization on a second and third set of dimensions – environmental and social impact. And so, successful innovations for sustainable development must be economically competitive with existing technologies and functional at this new level of performance, that is simultaneously providing improved environmental and social systems.

There are elements where innovation for sustainable development differs from general innovation. This specifically includes expanding the definition of performance from criteria related to cost and safety to include indicators for environmental impact, human health, and societal benefit. These innovations address a technical problem, provide an economic benefit, but also must perform against additional environmental and social criteria. This expanded concept of "performance" can be difficult to measure. It also introduces the possible need to make decisions with complex trade-offs, either between environmental criteria (solid waste outputs vs. energy use), environmental and human health criteria (reduced energy demand vs. toxic chemical exposures) or between environmental and economic criteria. Of course, if a trade-off of this type exists, one could argue that there is a need for further innovation to resolve the conflict.

Innovation for sustainable development also has the potential to reshape how we view the role of innovation in the overall sustainable development of nations around the globe. In the development community, there is a long-standing acknowledgement that innovation is important for a state's development [12, 13]. However, the perspective has been largely incremental in nature. That is, the strategy most commonly advocated in the literature (and on which a great deal of policy advice has been based) is for developing countries to invest behind the technological frontier. This provides a foundation on which to build further advances and to develop competency and expertise in a given area [14]. But there is a complementary view that has begun to be voiced that it is possible, in some cases, to improve development outcomes by employing a strategy of "leapfrogging" over older, less efficient or less profitable activities [15-18]. Some commonly cited examples of this are the adoption of cellular phones to replace wired phones in Africa, Manila and China [16], and the use of electric-arc

furnaces in the steel industry in developing nations [16].

On some occasions, the optimal sustainable “leapfrog” solution may not involve the design of a physical product or system. Creating physical entities to perform intended functions necessarily has an environmental and economic burden. One significant mechanism to reduce these burdens is to provide the same service or function without the creation of a physical entity. This implies that design objectives must be defined in terms of the function they provide rather than the form they take.

By designing for intended function rather than a prescribed physical form, organizations can realize life cycle benefits by eliminating the need to acquire and manufacture raw materials, produce a final product or process, and then manage it at end of life. For example, rather than designing the physical infrastructure for telecommunications, including poles and wires that must be established to connect throughout the built environment, the design goal could be to provide high-quality resilient telecommunications. In this way, the designer may innovate to develop cellular phones, which require many fewer resources (natural and economic) in terms of physical infrastructure while meeting the same intended goal. Of course, it is necessary to evaluate the environmental and economic costs, benefits, and trade-offs of these two designs that serve the same functional purpose.

4 TOWARDS SUSTAINABILITY

Sustainable engineering is defined as the design of human and industrial systems to ensure that humankind’s use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment [19]. From this definition it is clear that “design” figures prominently into the discussion of delivering infrastructure services sustainably. To advance this goal, there is a need to consider three fundamental characteristics and design explicitly for them. That is, design for 1) a dynamic world, 2) systemic resiliency, and 3) inherency.

4.1 Design for a Dynamic World

Figure 2 depicts trends from 1750 to 2000 of some major stressors on the sustainable delivery of infrastructure services. These curves all represent exponential change with these changes occurring on a global scale and, more importantly, that the rate of change is increasing.

The stressors and impacts of this “dynamic world” have come to suggest that there is a need to expand our design considerations in infrastructure systems, which typically have useful lifetimes meant to last for decades (and often function beyond their designed lifetime). It is also necessary to

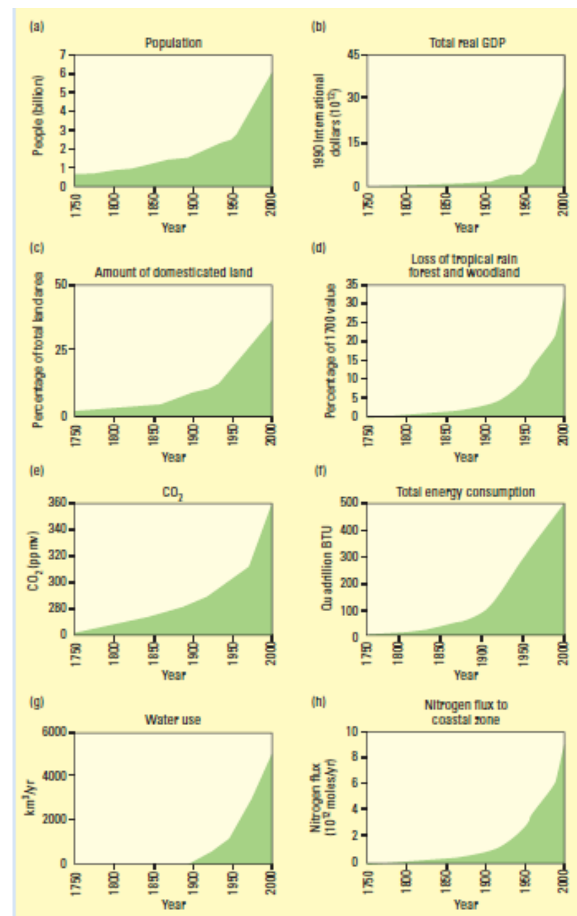

Figure 2: Global trends over time of stressors (a–f) and the corresponding trends in water quantity and quality (g–h). (a–e, g, and h adapted with permission from [20]; f adapted with permission from [21]).

acknowledge that the conditions in which the design will function over its life cycle will take place in a world of rapid and increasing change. Recognition of this interconnectedness has led the African Development Bank and other development organizations [22] to agree that integrating adaptation responses into development planning, which includes improvements in infrastructure services, is an important way to address climate change impacts on the poor.

For example considering wastewater treatment services, is a sanitary sewer an appropriate technology in a city that will become water-scarce by 2025? Sewers require on average up to 75 L/capita-day, whereas other sanitation technologies are available that require no water [23]. Sewers can also distribute nutrients over a wide spatial scale, whereas other sanitation technologies can consolidate nutrients at the community level. And if a sewer project is deemed appropriate today, what should the community do to prepare for future effects of climate change? These questions raise the issue of how to best meet basic human needs for water and sanitation,

including technology selection and governance strategies, under increasingly variable and increasingly water-scarce circumstances. They also raise broader questions of why we continue to design infrastructure solutions that have an extended lifetime without considering the dynamic global conditions and the increasing rate of change [24].

Enhancing performance over the lifetime of the infrastructure system will require the system to have the ability to adapt and evolve, emergent properties, and resilient performance. This is not to say that each component of the system must necessarily perform better or different over the lifetime, this is about enhancing the performance of the overall system.

4.2 Design for Systemic Resiliency

Traditionally, scientific and engineering research has been deeply rooted in the reductionist approach. That is, hold all variables constant except one and fully understand each parameter as an individual. While this has led to tremendous breakthroughs and advances in our knowledge, there are clearly attributes of the overall system that cannot be captured in this approach, including synergism, antagonism, and feedback mechanisms.

As an example, Figure 3 presents the interdependencies between common infrastructure systems. From this, it is clear that addressing energy challenges independent of water considerations will lead to the fragmented and unsustainable designs currently in place to deliver infrastructure services. This figure reinforces the earlier discussion of how "doing the right things wrong" has occurred and why it will continue to occur without an explicit consideration of the greater system dynamics. Of course, this is analogous to other system considerations such as life cycle and supply chain. In fact, one can consider each node in Figure 3 to have both a life cycle and supply chain to deliver that service creating a system of systems. While this leads to increasing complexity and multivariate optimization, it is critical that these are at the least acknowledged and the best integrated into the design solution. Furthermore, this system of systems may lend itself to the realization of resilient system.

Achieving sustainability will arguably require the development of resilient, adaptive infrastructure (and industrial and societal) systems that mirror the dynamic attributes of ecological systems. The concept of resilience has emerged as critical characteristic of complex, dynamic systems in a range of disciplines including economics, ecology, pedology, psychology, sociology, risk management, and network theory [25]. Resilience can be defined as the capacity of a system to tolerate disturbances while retaining its structure and function [26].

Engineering research has emphasized resilience or robustness as recovery from perturbations, but

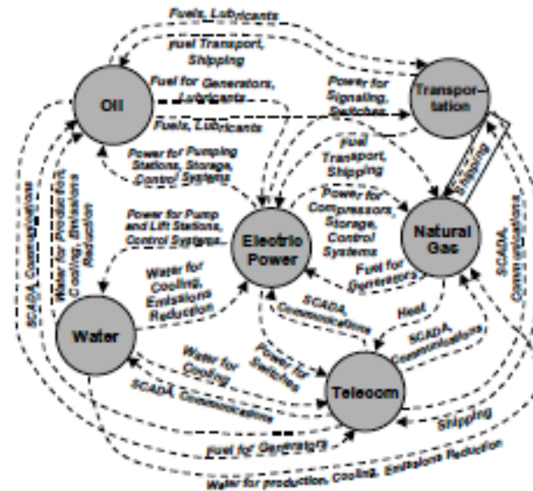

Figure 3: Interdependencies in critical infrastructure systems [27].

ecological resilience also emphasizes adaptive capacity, which may lead to new equilibria [28].

There is an ongoing to debate in the literature [29] of whether a resilient system must fully recover to its original functional state or if a resilient system may evolve to a new functional state. There is a tremendous difference from a design perspective to ensure that infrastructure service systems must *recover* to their original state versus be *resilient* to significant perturbations to the system (i.e., weather events, terrorist attacks, climate change) continuing to provide some reasonable level of service that is not identical to the original state (Figure 4).

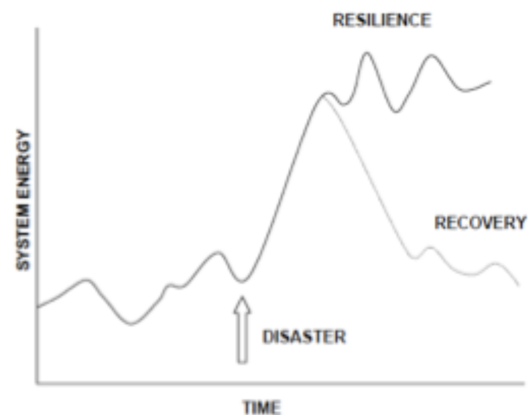

Figure 4: The relationship between organizational resilience and recovery [29].

Resilient systems, including biological and socioeconomic entities, are able to survive, adapt, and grow in the face of uncertainty and unforeseen disruptions, particularly relevant in terms of the "dynamic world" discussion presented previously. Resiliency tends to increase if a system has diversity,

redundancy, efficiency, autonomy, adaptability, cohesion, and strength in its critical components. While the term resiliency is commonly used, a rigorous definition is difficult to find and system parameters that can be used as design specifications remain even more elusive. Does the design of a resilient system mean that critical components are self-correcting, repairable, redundant, autonomous (i.e., the failure of one component does not cause the failure of other components), and/or fail-safe? These are some suggestions towards design considerations of a resilient system but there is much work to be done to explore specific and operational design specifications that will result in a resilient system.

Traditional systems-engineering practices have tried to anticipate and resist disruptions, but may be vulnerable to unforeseen factors. An alternative is to design systems with *inherent* resilience by taking advantage of fundamental properties described above [25]. This is well aligned with Green Engineering, which seeks to design products and processes with *intrinsic* characteristics that reduce or eliminate hazardous effects [7].

4.3 Design for Inherency

"The term 'intrinsic nature' does not indicate a factor's temporal status, but rather refers to its underlying and defining nature" – Buddhist scholar

The history of environmental protection in recent decades can largely be described as the effort to reduce risk to human health and the environment by controlling the exposure to various hazards. Whether it is done through control technologies such as smokestack scrubbers to minimize the release of toxics to the air or effluent treatment to minimize the release of toxics to waster, or respirators and personal protective gear to minimize exposure to humans, the purpose is the same; to reduce exposure by changing the circumstances and conditions by which hazards are handled.

The emerging approach in sustainable design is to design the inherent nature of our chemicals and materials to be intrinsically less hazardous rather than trying to control all of the conditions and circumstances. Just as the substances we use have inherent properties such as boiling point, melting point, etc., they also have inherent properties related to hazard – their ability to cause adverse consequence. The basic properties underlie a substances' ability to manifest its hazard. Just as science has mastered the manipulation of many of these properties to impart certain types of performance – flexibility, color, conductivity – we are now able to begin to design these properties so as to minimize their inherent hazard. While we are at the beginning of this scientific ability, already there is insight on ways to limit bioavailability, promote degradation, decrease persistence and bioaccumulation [30]. Similarly, characteristics such as renewable and biobased are inherent properties to the chemicals or materials under consideration for the design. As we consider how to systematically design resilient, sustainable systems, inherence will be one essential element of the design criteria.

Analogous to designing for inherent characteristics at the chemical and materials scale, the interactions of these chemicals and materials can also be designed to impart inherent properties into the overall system. This is much more difficult and philosophical in terms of designing a system to have inherent properties such as self-repair or fail-safe. Given the added complexity to imparting inherent properties at the system scale, the following examples, namely flame-resistant polymers and self-healing materials, are provided at the chemicals/materials scale but with the intention of spurring inspiration for innovation at the systems-scale.

Flame-resistant plastics. Westmoreland has developed materials in conjunction with the Federal Aviation Administration that addresses an important safety as well as an environmental and human health issue. Perhaps as one step toward alternatives to flame retardant additives in polymers, Westmoreland has designed a material that, upon exposure to flames, will undergo molecular rearrangement into a material that is incapable of sustaining fire [31]. This material may be appropriate for fuselage internal walls and does not produce the type of toxic and acrid fumes that many common polymeric structural materials traditionally produce as a result of fire. In this case the desired performance characteristic is exceeded while the risks associated with a traditional "sub-component" of polymer systems, namely flame-retardants, are eliminated. This is an example of providing the service of flame resistance without the need to develop and handle actual flame retardants, which are often toxic posing human health risks.

Self-healing polymers. Structural polymers are susceptible to damage in the form of cracks, which form deep within the structure where detection is difficult and repair is almost impossible. Cracking leads to mechanical degradation of fiber-reinforced polymer composites; in microelectronic polymeric components it can also lead to electrical failure. Microcracking induced by thermal and mechanical fatigue is also a long-standing problem in polymer adhesives. Regardless of the application, once cracks have formed within polymeric materials, the integrity of the structure is significantly compromised. We have developed a structural polymeric material with

the ability to autonomically heal cracks [32].

Autonomic healing is accomplished by incorporating a microencapsulated healing agent and a catalytic chemical trigger within an epoxy matrix. An approaching crack ruptures embedded microcapsules, releasing healing agent into the crack plane through capillary action. Polymerization of the healing agent is triggered by contact with the embedded catalyst, bonding the crack faces. The damage-induced triggering mechanism provides site-specific autonomic control of repair. An additional unique feature of our healing concept is the utilization of living polymerization (that is, having unterminated chain-ends) catalysts, thus enabling multiple healing events. Our fracture experiments yield more than 90% recovery in toughness, and we expect that our approach will be applicable to other brittle materials systems (including ceramics and glasses) [33].

5 DESIGNING TOMORROW

To advance the goal of a sustainable future, it is critical that the solutions designed to sustainability challenges are in and of themselves sustainable. Based on many of the current technologies developed and implemented to address the greatest sustainability challenges – energy, water, food production – it is becoming increasingly clear that this is not the approach being adopted. In order to design sustainable solutions, including those related to infrastructure services, three specific design strategies are presented: Design for a Dynamic World, Design for Systemic Resiliency, and Design for Inherency. These design strategies have potential to move engineering design significantly closer to doing the right things right.

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