Viewpoint

EARTH SYSTEMS Engineering *and* Management: *A Manifesto*

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The engineering profession should learn to rationally design, engineer and construct, maintain and manage, and reconstruct the information-dense, highly integrated human, natural, and built systems that characterize the anthropogenic Earth.

The Industrial Revolution led to associated changes in human demographics, agricultural and technology systems, cultures, and economic systems. A principal result has been the evolution of an anthropogenic Earth in which the dynamics of major natural systems are increasingly affected by human activity. That does not mean deliberately designed by humans, because many things, from urban systems to the Internet, are clearly human in origin yet have not been consciously designed by anyone. But it does mean an Earth where human activity increasingly modulates all Earth systems to the point where those things that are not subject to such impact, such as perhaps volcanoes and earthquakes, are increasingly limited and rare (*1*). It is a world characterized by rapidly increasing integration of human culture, built environments, and natural systems to produce novel and complex emergent behaviors that are beyond traditional disciplinary structures and reductionist approaches. As the journal *Nature* put it in a 2003 editorial, "Welcome to the Anthropocene," roughly translated, the Age of the Human (*2*).

The boundaries reflected in today's engineering disciplinary structures, and indeed in academic systems as a whole, are still appropriate for many problems. But we fail at the level of the complex, integrated systems and behaviors that characterize the anthropogenic Earth. No disciplinary field in either the physical or social sciences addresses these emergent behaviors, and very few even provide an adequate intellectual basis for parsing such complex adaptive systems. This situation has two important implications for civil and environmental engineering (CEE) professionals.

First, it means that we as engineers cannot continue to rest on our traditional strengths, which are increasingly inadequate given today's social, economic, environmental, and technological demands. For example, a road built into a rain forest to support mineral exploitation becomes a corridor of development and environmental degradation. Similarly, a new airport in a developing country dramatically increases tourism and puts pressure on fragile, previously remote, ecosystems. Alternatively, planning for urban transportation infrastructure increasingly requires understanding the status of the information and communication technology (ICT) infrastructure, because ICT enables virtual work structures that affect potential traffic loading and peak patterns. In every case, traditional CEE approaches, although necessary, do not address the systemic impacts of the project. Infrastructure is critical but not neutral.

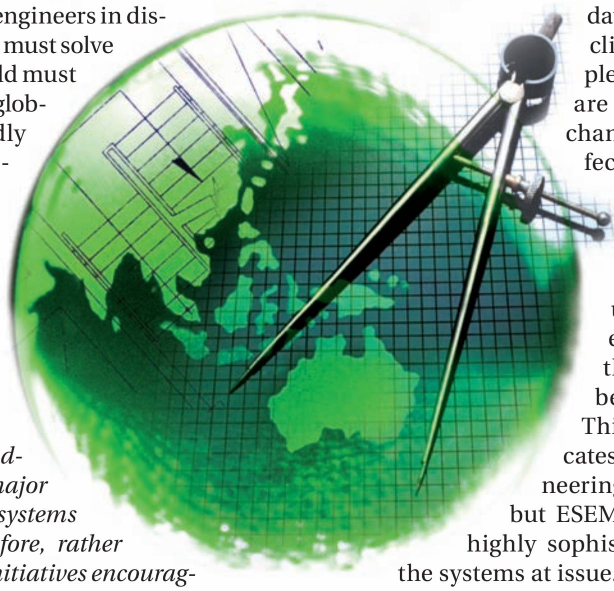
Second, from a proactive viewpoint, the anthropogenic Earth is a difficult, highly complex, tightly integrated system that challenges society to rapidly develop tools, methods, and understandings that enable reasoned responses. Engineers in general, and civil and environmental engineers in particular, must be a critical part of any such response. As problem solvers who must create solutions in the real world, we have to understand and appropriately consider this new and more complex environment within which we work and create future options for changing ecosystems, built environments, and human culture. The rational and analytical CEE culture, along with the role of CEE professionals in creating and maintaining the built environment, makes the CEE community a necessary partner—indeed, leader—in Earth systems engineering and management (ESEM).

Earth systems engineering and management

Continued stability of the information-dense, highly integrated human, natural, and built systems that characterize the anthropogenic Earth requires development of the ability to rationally design, engineer and construct, maintain and manage, and reconstruct such systems—in short, an ESEM capability (*3*). Although this is an unprecedented challenge, ESEM can draw on experience from many existing areas of study and practice. From a technical perspective, these would include industrial ecology methodologies such as life-cycle assessment (LCA), design for environment, materials flow analysis (*4*), and systems engineering (*5, 6*). From a managerial perspective, it draws on the literature about learning organizations (*7*) and adaptive management (*8, 9*). Parts of the urban planning, sociology of technology, and social construction literatures are also relevant (*10, 11*).

On the basis of these discourses, a tentative and partial, albeit instructive, set of initial ESEM principles can be developed.

Given our current level of ignorance, *only intervene when necessary, and then only to the extent required, in complex systems*. This follows from the obvious need to treat complex, adaptive systems with respect, because their future paths and reactions to inputs can seldom be predicted. It supersedes formulations such as the precautionary principle, which, in holding that new technologies should not be introduced if the risks cannot be known, demands an unrealistic level of knowledge of the future. Moreover, engineers in disciplines such as CEE who must solve problems in the real world must accept the world as it is—globalizing, growing rapidly economically, with a population nearing 7 billion, and heavily reliant on technological systems. Intervention is thus not discretionary, as some would rather fancifully wish, but it nonetheless must be careful and rational.



The capability to model and dialogue with major shifts in technological systems should be developed before, rather than after, policies and initiatives encouraging such shifts. Although projections of technological evolution are seldom accurate, we could do much better in developing frameworks, tracking systems (including metrics, especially ones that signal potential danger), and families of scenarios that would help us perceive problematic trends, and perhaps steer technological evolution to increase social and environmental benefits, in real time. Such systematic tracking capabilities can help avoid some of the costs of premature adoption of emotionally appealing technologies. Recent examples might include the current infatuation with the hydrogen economy or the massive effort by the U.S. to create a corn-based ethanol energy economy. The point is not, of course, that technology shifts may not be beneficial; the point is to improve their design and management as they evolve within the real world.

A characteristic of complex systems is that *the network that is relevant to a particular analysis is called forth by that analysis*. Accordingly, *it is critical to be aware of the particular boundaries within which one is working and to be alert to the possibility of logical failure when one's analysis goes beyond the boundaries*. For example, to perform a study of New York City's water supply by considering only the five constituent boroughs of New York would result in a flawed assessment, because the system being analyzed (water provision to the city) is not mapped adequately by the political boundaries of the city. Similarly, the application of an LCA tool that implicitly relied heavily on energy consumption as a proxy for environmental damage to a product where toxicity was a primary issue might well result in dysfunctional conclusions. For example, replacing chlorofluorocarbon-cleaning technologies with aqueous ones in electronics manufacturing makes sense from a systems perspective, even though the latter is more energy-intensive.

A point that is critical to an understanding of the anthropogenic world is that *the actors and designers are also part of the system they are purporting to design, creating interactive flows of information (reflexivity) that make the system highly unpredictable and perhaps more unstable*. As scientists develop data on the effects of global climate change, for example, people's perceptions are changed. This, in turn, changes social practices affecting the climate. Thus, activities at the levels of the emergent behaviors of these complex systems must be understood as processes and dialogues, rather than simply problems to be solved and forgotten. This is an issue that bifurcates engineering: most engineering still involves artifacts, but ESEM requires ongoing and highly sophisticated dialogues with the systems at issue.

Implicit social engineering agendas and reflexivity make macroethical and value implications inherent in all ESEM activities. To achieve long-term clarity and stable, effective policies, these normative elements must be explained and accepted, rather than hidden.

Conditions characterizing the anthropogenic Earth require democratic, transparent, and accountable governance and pluralistic decision-making processes. Virtually all ESEM initiatives raise important scientific, technical, economic, political, ethical, theological, and cultural issues in an increasingly complex global polity. Given the need for consensus and long-term commitment, the only workable governance model is one that is democratic, transparent, and accountable (*12*, *13*).

We must learn to engineer and manage complex systems, not just artifacts. An obvious result of the above analysis is that the anthropogenic world—and ESEM as a response—requires that far more attention be paid to the characteristics and dynamics of the relevant systems, rather than just to constituent artifacts. This does not negate the need to design artifacts; ESEM augments, instead of replaces, more traditional activities.

Ensure continuous learning. Given the complexity of the systems involved, our relative ignorance, and the recognition of engineering as process, it follows that continual learning at the personal and institu-

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tional level must be built into project and program management. Some experience with this approach already exists. High-reliability organizations, such as aircraft carrier operations or well-run nuclear power plants, usually have explicit learning structures (*5*). Similarly, the adaptive management approach to complex natural-resource-management challenges, such as in the Baltic Sea, the Everglades, and the North American Great Lakes, is heavily dependent on continual learning (*8, 9*).

Unlike simple systems, *complex, adaptive systems cannot be centrally or explicitly controlled*. Accordingly, it's important to understand not just the substance of the system—the biology of the Everglades or the Baltic, for example, or the physics and chemistry of the troposphere—but also inherent systems dynamics. Where in a system, for example, do small shifts propagate across the system as a whole, and where are they dampened out? The famous example of the butterfly that flaps its wings and causes a storm elsewhere in the world may be iconic, but what is perhaps forgotten is that millions of butterflies flap their wings thousands of times each day, without causing an ensuing storm. Perhaps the really interesting question, then, is why one flap has such an impact, when the others don't (*14*).

We as engineers cannot continue to rest on our traditional strengths, which are increasingly inadequate given today's social, economic, environmental, and technological demands.

Whenever possible, engineered changes should be incremental and reversible, rather than fundamental and irreversible. Accordingly, premature lock-in of system components should be avoided where possible, because it leads to irreversibility. In complex systems, practices and technologies can get locked in quickly—that is, coupled to other systems and components in such a way as to make subsequent changes, including reversion to previous states, difficult or impossible. Thus, tightly coupled networks are more resistant to change than loosely coupled networks, an effect that can be reduced by ensuring that, when couplings to other networks do exist, they are designed to be as loose, and as few, as possible. This supports the more general goal of reversibility: under conditions of high uncertainty and complexity, easy reversibility is a desirable option should the system begin to behave in an unanticipated and undesired way.

ESEM projects should aim for *resiliency, not just redundancy, in design*. Redundancy provides backup capability in case a primary system fails, and it is commonly designed into high-reliability systems such as jet airplanes. Redundancy assumes, however, that the challenge to the system is of a known variety. Resiliency, to the contrary, is the ability of a system to resist degradation or, when it must degrade, to do so gracefully even under unanticipated conditions (*15*).

Developing an ESEM capability

One way to begin responding to the challenge of the anthropogenic Earth, as well as continuing the process of clarifying and better understanding ESEM, is to develop a model research agenda. The complexity of the challenges does not allow for more than a partial and exploratory exercise at this point, and the examples given below are also idiosyncratic in that they reflect a CEE perspective on ESEM. In addition, it is a legitimate concern that any discipline, including CEE, that attempts to train professionals to design, engineer, manage, and interact with such complex systems is doomed to overreach and fail. Nonetheless, it is also important to remember that these effects, from climate change to massive urbanization, are already occurring, and our failure to accept responsibility for them does not diminish human impacts but is merely an evasion of our ethical duties. CEE has an important role here: its projects are frequently the vehicle by which these large and complex systems are affected, and CEE education—rational, quantitative, problem-oriented, systems-based, and pragmatic—is a solid base upon which to build the required expertise and insight.

Accordingly, in addition to its specific research goals, any ESEM research agenda should aim to support the development of highly transdisciplinary research programs capable of looking at Earth systems at emergent levels (including, importantly, the social science dimensions; in many such systems, ideology and politics are as important as any physical feature of the system). It should also support an overarching program that mines specific research areas for general principles and learning that over time can be leveraged into development of a rational, responsible, and ethical ESEM framework.

Integrated urban infrastructure systems. Given accelerating urbanization (*16*); increasing urban vulnerability to natural disaster or deliberate attack; and the cultural, physical, and built complexity of urban systems, the emergent domain of urban infrastructure systems as comprehensive wholes is grossly underappreciated. Yet, at this point no U.S. government agency, research funding organization, or engineering discipline has the mission or research support for understanding urban systems as integrated systems. This is a near-term concern because of the increasing demand for replacement and new infrastructure. At the same time, the nature of urban systems is changing profoundly as ICT capability is increasingly integrated into all levels of urban functionality: sensor systems, smart materials, smart buildings, smart infrastructures, and the like. Especially as ICT systems are redesigned to be autonomic—virtualized, self-defining, self-monitoring, self-healing, and learning-capable at all scales from chip to computer to regional and global ICT grids (*17, 18*)—the implications for urban system design, performance, and behavior accelerate in complexity. Moreover, the increasing role of urban systems as nodes in energy, financial, and virtual information networks adds many layers of information complexity to built urban environments (*19*). Such research should contribute to a new CEE competency in urban-scale systems design and management.

Sustainable infrastructures. Growing populations, economic development, accelerating technological change, urbanization, and aging and failing existing infrastructure systems are increasing the need for sustainable infrastructure systems. Although ESEM provides some conceptual basis for developing such systems, clearly the translation of social interest in sustainability to the implementation of sustainable engineering of any type has just begun and is currently marked by an intellectually confused jumble of superficial, ideological, and heuristic approaches (*20*). Accordingly, a research program to help define sustainable infrastructure and to develop appropriate methodologies, analytical methods, and tools is needed. This is urgent because the time to understand and deploy sustainable infrastructures is now, instead of after newly built environments with decades of active life are constructed. The new National Science Foundation initiative called Resilient and Sustainable Infrastructures, under the Emergent Frontiers in Research and Innovation program, is clearly a step in the right direction, but whether it leads rapidly to the large transdisciplinary effort to solve the problems of urban environments remains to be seen.


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Technological convergence. A number of authors, from the dystopian Bill Joy (*21*) to the techno-optimist Ray Kurzweil (*22*), have written about the subject of technological convergence, generally understood as including the accelerating development of the fields of nanotechnology, biotechnology, information and communication technology, applied cognitive science, and robotics as well as their mutually reinforcing integration. These converging technologies constitute major Earth systems in their own right, and their complexity and challenging philosophical, religious, ideological, and economic implications are just beginning to be recognized. However, some of the major arenas where effects of technological convergence can first be seen are in areas familiar to CEE professionals, including urban and regional integrated infrastructure design (as the example of the urban systems and ICT discussed above suggests), in energy technology and infrastructure design, and the like.

What is most challenging, perhaps, about technological convergence is not just its effect of turning natural systems—from the carbon and climate cycles to biology at all scales—into design spaces (and commodities). Rather, as humans gain the tools to design biological and cognitive systems, it also turns the human into a self-reflexive design space. In doing so, the feedback systems, and concomitant increases in system complexity, become truly daunting. CEE traditionally has been based on the assumption (unspoken because it was so clearly fundamental and valid) that the environment must be designed and built for the human. As both parts of that assumption become design spaces, and thus interact in new and dynamic ways, engineering becomes new, more complex, and ethically challenging in ways that have never before been part of our professional experience. Although research programs designed to respond to this unique challenge do not lie entirely within CEE's ambit, we can bring significant skills to transdisciplinary research efforts.

Resilience of complex Earth systems. That complex natural Earth systems are increasingly vulnerable is evident from the destabilization of stratospheric ozone by chlorofluorocarbons or from the global climate change dialogue. But the increased vulnerability is also apparent with more anthropogenic systems: recent years have seen several significant challenges to social stability and order, ranging from extreme weather events to terrorist attacks to substantial cultural conflict. Although each incident is unique and unfortunately too often tragic, the key to understanding and responding to these constellations of challenges is to recognize that although each is expressed uniquely, they all represent emergent characteristics of the anthropogenic Earth—including, critically, information and cultural networks—at unfamiliar scales and levels of complexity. Thus, although immediate responses have necessarily relied primarily on specific engineering, institutional, and policy responses to particular incidents, the range of challenges, their systemic nature, and the practical impossibility of adequately addressing each one individually argue for adopting a more comprehensive systems perspective. This should be based on the principles of enhancing infrastructure, social, and economic resiliency; meeting security and emergency response needs; and relying to the highest extent possible on dual-use technologies that offer societal benefits, even if anticipated disasters never occur.

Patterns of the built and human environments play an important role in vulnerability. Thus, for example, the damage and disruption from weather events such as hurricanes or from natural disasters such as tsunamis are more disruptive and extensive than in the past because of changing demographic patterns (urbanization, for example) and the relocation of economic activity near more risky areas, such as geologically active Pacific Ocean coastlines. Disease epidemics and their associated economic and social effects are more challenging given the modern transportation infrastructure and globalized patterns of commerce and travel. Terrorism is not new, but terrorist access to weapons of mass destruction is. Cultural conflict is as old as historical records, but the Internet and ubiquity of exposure to others create an environment where a few cartoons in a small northern European country can ignite global unrest.

CEE professionals have important roles in virtually all of the examples given, including designing adequate levees; hardening buildings and infrastructure against attack and enabling rapid restoration of services and the built environment; and constructing energy, transportation, and ICT infrastructures that have profound and varied effects across regional and global natural systems. We should thus be leaders in enabling systemic understanding and enhancement of resilience across not just the built environment but also Earth systems as a whole. This is a substantial challenge: how can we, as the CEE community, begin the complex process of building the transdisciplinary capabilities necessary to understand, work, and live rationally, ethically, and responsibly in the world that we have already created?

The anthropogenic Earth is a difficult, highly complex, tightly integrated system that challenges society to rapidly develop tools, methods, and understandings that enable reasoned responses.

These research challenges, and many others that undoubtedly come to mind, are "wicked" problems, because they are irreducibly complex and highly transdisciplinary, and require substantial changes in the way we think about CEE and engineering in general. Learning to work across the disciplinary divides involved will be exceedingly difficult and personally challenging for many individuals. Many engineers are not accustomed to accepting a leadership role in such a difficult task, but our age has its own imperative.

Activity in each area will be complicated because not enough trained individuals are available to begin many programs in these areas. Peer review also will be a challenge, both because finding appropriate panels will be nontrivial and because that process tends to be highly conservative when faced with profoundly transdisciplinary proposals. In many cases, ideological and even religious feelings run high.

But against all of these barriers lies one fact. We do not have a choice in deciding whether these emergent behaviors will occur: they are here, now. We only can decide as engineers and professionals whether to respond to these behaviors rationally and ethically or by ignoring them, retreating to wishful fantasy, and evading our professional and, indeed, personal responsibility to ourselves and the future.

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