ABSTRACT

Chemical engineers and others are thinking about sustainability and trying to design for sustainable development. Doing this presents many challenges. Some of these challenges are encompassed within traditional design parameters while others require expanded conceptual thinking. This paper sets out to describe some of the current tools available for thinking about sustainable development while at the same time setting out challenges for future work. This paper first details the first current work and methodologies in chemical engineering. It then shows how the problems of sustainable development transcend the techniques of chemical engineering available in a second mode engineering systems mindset. Focusing on core issues in sustainability, new design philosophies are articulated and emerging tools are described.
INTRODUCTION

While the news is full of problems and potential problems today, there are also many opportunities. The greatest hope is embedded within the concept of sustainability. Current large issues embedded within sustainability include changing security concerns and the need to engineer within ecological constraints. This paper will begin to sketch the development of these problems and what proactive role the technical leadership in the U.S. and world wide, including industrial leadership, could play.

Sustainability is a word that has many different meanings (Pezzoli, 1997). While some strive to define it, others, such as former Chief Science Adviser to the President John Gibbons, are comfortable with the multiplicity of meanings that have accrued to sustainability (Gibbons, 1998). As I envision it, sustainability has several key aspects. There are physical/engineering issues, environmental issues, economic issues, equity issues, and security issues. On the physical side the most fundamental issue is to provide basic services, such as food, water, energy, shelter, transportation, health care, and communication, to the world’s population. On the environmental side, most critical is the maintenance of ecosystem function. On the economics side, most critical is wealth creation since no one wants to live in poverty. On the equity side most important is the recognition of every other person as fully human, which is consistent with the principles set out in the International Declaration of Human Rights. On the security side, most critical is to build and maintain the rule of law and order in the international arena.

In order for these goals to be achieved, a number of technical innovations, organizational adaptations, and attitudinal and behavioral shifts will be necessary. While national governments and world institutions are signing declarations supporting sustainable development, most crucial will be the mobilization of industry, both new and established, to achieve the material needs implicit in sustainable development. A number of firms in the chemical industry, most notably DuPont, BP, and Shell, have recently begun to structure their company’s strategy around sustainability ideas for a variety of reasons.

Scientists and engineers, while not all powerful, neither are powerless in the project of building sustainability. By being fully engaged with the political process, the engineering and scientific communities can help create solutions and open opportunities where previously there were only intractable problems. Engineers have historically provided for the defense of the country as well as for the economic well being of the country or region. Although some engineers, such as Leonardo DaVinci, have been fully engaged with civil, military, and artistic endeavors, many of today’s scientists and engineers accept a much more limited role in non-technical affairs.

I will argue that science and engineering as conceptualized today by most scientists and engineers is a necessary but not sufficient tool for achieving sustainability. Recognizing that there are many aspects to science and engineering, chemical engineering and materials science and engineering will be used as the prototypes of second mode systems thinking in engineering. Moreover, through their choices and actions engineers cannot help but influence the social and natural world. Therefore, since the possibility space for undesirable side effects is so large, the only way to avoid many undesirable side effects is to focus on the desirable goals. In so doing, traditional design criteria must be enlarged and development of expertise in third mode systems thinking should be pursued. However, scientists and engineers are not unconstrained by their
history and institutions. Therefore, for a truly liberated approach to design, historical and institutional influences on scientific and engineering production must be considered, and if necessary new institutions must be built. This paper gives a limited analysis of the social, economic, political, and legal aspects of science and engineering relevant to sustainable development; more details will follow in a subsequent paper.

To make this argument, the first section of this paper will examine current efforts in the chemical and materials engineering communities toward sustainability. Secondly, the emergence of third mode systems thinking and a discussion of the sociotechnical element of sustainable development will be pursued. Finally, new modes of thinking that are enabled by a sociotechnical perspective will be illustrated. In this final section, first a discussion of several fundamental issues will be given, then principles for a sustainable architecture will be advanced, and finally new tools to use in working towards sustainability will be described.

CHEMICAL AND MATERIALS ENGINEERING EFFORTS TOWARDS SUSTAINABILITY

David Mindell (2000) has described three modes of systems thinking. The first, pre-World War II mode looked at systems as collections of technical parts. Edison’s work to build an electric power system is one example of such system building (Hughes, 1983). After World War II, a second mode of systems building arose in which hierarchical frameworks were prevalent and engineering science techniques were used to analyze the components of the system. Various tools and techniques, such as operations research and systems analysis, were used to build these systems. This type of systems building was perhaps best epitomized by the efforts to build the SAGE Air Defense System and put a man on the moon (Hughes, 1998). The current efforts in chemical engineering are part of a second mode mentality that is seeking to reinvent and transform itself.

The chemicals industry has gone through several successive transformations since its inception at MIT in 1888. The first one was the recognition of unit ops by Warren K. Lewis and William H. Walker at MIT in 1916. This advance allowed a great variety of processes with common elements to be simplified. For example, a variety of processes were needed to separate different materials. Upon recognition that this was the case, a unit operations devoted to specific types of separations, such as distillation or sieving, could be defined. As the chemical industry developed it was recognized that there was commonality in materials and energy flows. Bird, Stewart, and Lightfoot unified these concepts in 1958 in their classic work *Transport Phenomena*. To this day work follows in this paradigm with the core subjects of chemical engineering being thermodynamics, transport phenomena, and kinetics and reactor design (Wei, 2000).

The current juncture puts it had another crossroads. Some, such as former department head of chemical engineering at MIT and current Dean of Engineering at Princeton James Wei, support product engineering as the third paradigm for chemical engineering (Wei, 2000). The main thrust of the argument is that firms such as DuPont can add value and obtain profits by manufacturing products that integrate their chemicals and materials. One example of such efforts is DuPont’s efforts to build a polymer into a light emitting diode for a flat panel display.
Most recently the chemicals industry has gone through a slump in financial performance as well as a decimation of public confidence in the industry. The systems that were built on the achievements of the first two paradigms epitomized large second mode systems thinking. There were large centrally funded projects. Capital projects were large, especially in the oil industry, and required market forecasts and steadily growing chemicals usage to ensure a steady stream of revenue that would pay for the initial capital investment (Kipnis, 1990).

As chemical engineering matured and grew as a field distinct from mechanical engineering in the 1930s, it attracted people look for “glamour” (Landau, 1994). After the Great Depression and World War II, the reputation of chemical engineers soared. They were responsible first for a variety of products that helped win WWII, including oil and rubber. Later, through the production of a wide variety of polymers, chemical engineers helped build the material comfort that Americans enjoyed in the post-War period. Therefore, the environmental protests of the 1960s came as a shock to the professional identity of the chemical engineers.

Initially resistance to chemical technology by environmentalists was not welcomed, as engineers were unwilling to think about environmental questions when confronted by environmental activists. However, within the limits of the existing technology, chemical engineers soon began to think of creative solutions. These solutions progressed through different stages including end of pipe treatment, pollution prevention, and design for environment until the current desire to do environmentally conscious process design was reached (Cano-Ruiz, 1998).

To remake themselves for the 21st century, chemical engineers have begun work in several major, exciting areas: environment, biochemical and biomedical engineering, and advanced materials development, including nanotechnology. Work to improve the environment includes efforts to develop alternative synthesis methods, including self-assembly and efforts to perform reactions in aqueous solvents as opposed to organic solvents, and work to develop alternative chemical reactors, including microreactors, which reduce the volume of the solvents, needed.

Work in biomedical engineering includes tissue engineering and metabolic engineering. A variety of basic science and engineering questions are being investigated. Although the motivation of individual investigators varies, the motivation at some point in the project chain is to improve human health. Much excitement has been generated in the business community over the sequencing of the human genome and the commercial prospects for genomics and proteomics, and investigators are beginning to reap the benefits of that interest. Methodologically, much of the work that is being done views the cell as a chemical reactor. DuPont has a particular interest in bioderived feedstocks, meaning small molecules from biological sources, which can be used in high volume synthesis reactions. Other work, such as that done by Monsanto, has focused on producing genetically modified organisms for alleviating world hunger through improved food production.

Finally, advanced work is being done on a variety of enabling materials. For example, NSF has funded a variety of Materials Research Science and Engineering Centers. One, located at Purdue in the 1990s, for example, focused on technology enabling heterostructures. These III-V and II-VI heterostructures could be used for a variety of new devices, including faster transistors, the building block of computing and
communications devices, and for faster detection of signals, including detection of enemy fighter plane signatures.

The major underlying assumption in most of the work is that the work will contribute positively to either a body of knowledge or to solving a human need. While this is true at one level, it may be called into question at other levels. For example, past product design efforts have caused some of our most serious environmental problems. One of the most notable examples of this was the success of chlorofluorocarbons (CFCs), a nonvolatile, non-toxic refrigerant that was developed in response to the volatility and corrosive nature of previous refrigerants. After the product gained large usage, an ozone hole was detected over Antarctica, causing the subsequent phase out of CFCs.

While much work is being done, two major concerns remain. One is a concern largely expressed in the first world about technology going out of control (Joy, 2000). The second, largely voiced by those in the third world but which is increasingly being heard in the first world, is a political economic critique of the distribution of the fruits of scientific and engineering endeavor.

Additionally, the current product design focus, while allowing chemical engineers to think about supply side substitution, does not allow for thinking about demand side reduction or modification, which may be necessary to reduce the environmental footprint of the North. Although this hints at the intertwined nature of material and chemical usage and other socioeconomic issues within the chemical industry, before solutions can be envisioned, further details about the problems and the third mode of systems thinking need to be presented.

While this reinsertion of the sociopolitical into “pure” science may be undesirable to some, it removes the false dichotomy between pure, applied and policy relevant science; furthermore, it allows for a Jeffersonian approach of funding interesting problems while housing them within the pursuit of a larger welfare goal. By being engaged with current vital problems that acknowledge the complexity of the world, unwanted spillovers from a “pure” research lab ceases to be a problem.

REINSERTING THE SOCIAL AND POLITICAL INTO “TECHNICAL” PROBLEMS

The third mode of systems thinking acknowledges the complex interactions of society and technical systems. Thomas Hughes laid some of the early groundwork for this thinking by suggesting the idea of the social shaping of technology. He noted that while people shape technological systems, those same systems shape people by enabling and limiting their range of possible actions.

Each of the core problems in sustainable development, even the physical/engineering questions such as provision of food, water, energy, shelter, and transportation, has aspects of a sociotechnical problem. This section provides examples of the key questions that illustrate the socioeconomic angle of the major categories (physical/engineering, environment, economic, equity, and security) of sustainable development. Additionally, the hidden sociopolitical aspects of the chemical and materials research questions in the previous section are discussed. Finally, it details some of the reasons for the separation between second mode systems engineering and some barriers to achieving third mode systems thinking.

Concerns over basic material needs such as food, water, energy, transportation, shelter, and clothing exist in both the North and the South, but the nature of these
concerns is very different. For example, the major causes of death in the United States, heart disease and lung cancer, are diseases of old age and life style. However, in Africa infectious diseases abound, and outbreaks of cholera in places like Peru are caused in large part due to public sanitation problems. Additionally, while engineers in the Western United States work to provide quality of service from the existing power grid, much of the developing world remains without power (Verhovek, 2000).

Problems that exist in sustainable development include large North-South equity issues over material usage and the associated environmental effects. The most visible place where this fight is taking place is in the controversy over global climate change. The concerns on the part of the developing countries in the South is that the North has already developed, and in the process the North has taken the very natural resources, such as forests, which the South is now being told to conserve. Moreover, the current pollution related problems are the result of pollution induced by Northern industrial polluters; the South does not want to stop its economic development on account of Northern missteps.

Underlying issues in technology transfer are debates over wealth creation and security. It is widely acknowledged that technology is necessary for quality of life improvements. However, there is not a clear strategy or way for companies or nations to transfer the benefits of technology to developing countries (Mutambara, 2000). Some of the problems relate to concerns over the current intellectual property rights (IPR) regime. There is a mismatch between corporate interests to obtain ownership and patent protection against other large corporations and the interests of local citizens who are concerned with corporate control of a common resource (Shulman, 2000; Gleick, 2000). Others concerns over technology transfer relate to concerns about national security (Busch, 1999). Other concerns relate to uncertainties in the effects of technological modifications either to the natural systems or to traditional societies (Shiva, 1998).

Beyond mere transformation of existing chemical processes for tools to produce new products lie underlying questions about which products to produce, at what environmental cost, and for which markets. Moreover, the answer to these questions will influence the successive development of chemical and materials technology. It is known that sometimes companies choose the Mt. Everest answer for technology development; for example, Monsanto chose some of its early unpopular genetically modified crops because “they were there,” i.e. it was technically possible to create them (Jasanoff, 2000). It is currently not clear how much DuPont is doing to achieve sustainability beyond its business-as-normal strategy; their advertisements are certainly smart public relations to heal a wounded company in a wounded industry by appealing to a global constituency. However, as Monsanto has found out, smart PR does not replace the substance of good technical and management decisions.

Although the motivations are large for accepting a third mode systems challenge of understanding, designing, and building sociotechnical systems, some scientists and engineers may not choose to move in this direction. Some choose to remain in a reductionist second mode mindset because they are fascinated with the pursuit of the knowledge of nature and believe a reductionist mindset is the quickest way to achieve that knowledge. Others rightly point out that the reductionist knowledge is necessary for the systems architect to do his or her work. Others are more constrained by their dislike
of the political process. Still others do not have the training, the skills, the personality, the incentives, or the time to do anything about larger sociotechnical systems.

Before globalization and sustainable development will be successful and viable, mobilizing scientific and engineering effort to understand sociotechnical systems, among other concerns, needs to be addressed.

NEW WAYS OF THINKING

Structuralists in political theory have detailed the institutions that make up our social world, while poststructuralists have indicated the fluidity and malleability of these institutions. This recognition that we both have these institutions and that they can be altered makes the idea of sustainable development possible. But in order to avoid ideology and before grand success can be proclaimed, smaller, more concrete steps are necessary. Subtexts of this section include the arguments that values matter, values are embedded in technology, and values do not preclude wealth creation; the challenge is to re-envision both the structures in which corporations work and subsequently the strategies they should employ for technology development and business success.

This section will detail several key interrelated issues that underlie the seemingly intractable current socio-technical questions and propose different ways to think about the design questions. Namely, security, the environment, and selected economic issues will be addressed. From the discussion of the issues, new ideas for strategies, tools and design philosophies emerge. The beginnings of new tools for envisioning the global environment will be detailed. Tools consist not only of physical artifacts, but also of linguistic, financial, and legal technologies. This paper will focus on new economic frameworks; other tools will be detailed in subsequent papers. Finally, it will outline several new engineering frameworks with which to think about the design of sociotechnical systems relevant to sustainable development.

Issue Analysis

Firms have employed a variety of strategies to achieve business success. One of these has been to secure large government and military contracts in the building of the military-industrial complex. Such firms include Hughes, Lockheed Martin, Boeing, HP, TRW, and Raytheon. Other firms have benefited greatly from extracting resources from the earth. Such firms include Shell, ExxonMobil, and BP.

The unifying question is how to think about each firm’s underlying business model when there are a number of security and environmental externalities inherent to their business models. Before their business models can be restructured and new technology choices can be made, the underlying dimensions of the security and environmental questions need to be understood. While a critique of these existing companies’ business practices may be useful, the point of this analysis is to extract the principles on which a truly sustainable business model may be constructed. These principles can then be combined with emerging technologies for true business success.
Security Analysis

This analysis provides a discussion of security as achieved by response to threat. The analysis then moves beyond threat to discuss issues of trust and mutuality. Next, the role of the engineers is examined and suggestions for actions engineers can begin to take are provided.

Security is a crucial element of sustainable development. While there are many ways to think about security, there are several underlying elements that are common to international, domestic and personal concerns about security. First, feeling secure is largely an emotional state rather than a technical question. However, technology can and does play a role in achieving security.

There are different ways to think about security depending on whether one is looking at the international level or the personal level; however, a commonality is threat and threat reduction. When thinking about threats, it is possible to avoid conflict in certain situations. Such conflict avoidance measures can include crossing the street to avoid a menacing figure to avoid personal threat or signing treaties of appeasement on the international level. However, it is not always possible to do this, as shown by the aggressor who will also cross the street in pursuit or by Adolf Hitler’s actions in response to Neville Chamberlain’s policy of appeasement. If conflict avoidance is not possible, people could choose to not defend themselves based upon the argument that any weapons that are created only contribute to the problem of violence by causing escalation. However, this is not effective in providing for one’s security in a threatening environment and only leads to martyrdom. On the other hand, people could opt to defend themselves through the use of weapons. This could act as a deterrent if the defendant has force superiority and the aggressor may choose another means of achieving his goal. If the aggressor were persistent, then an arms race would ensue so that the defendant would be confident that he could match the aggressor’s threat. This is seen in some gang warfare as well as in the arms race during the Cold War. Second, the aggressor could pursue a weaker victim, thereby alleviating the threat to one’s own person, but not eliminating the system-wide threat. This was seen in the pursuit of satellite states by the former Soviet Union during WWII.

Many security systems achieve security by making it more costly to attack the security system than to attack someplace else. This is the equivalent of redistributing the security burden on someone else. This is seen in America in the prevalence of gated communities that effectively separate high income Americans from low income Americans. On the national level of engagement, the security efforts by one country may result in a spillover effects that threaten another country.

The question of how to break the cycle of violence and the build up of arms is an urgent one. One way is to begin to build bridges. Building trust is done in many ways and at many levels. It is not possible to build trust immediately, nor may it be possible to build trust with every person. However, it is possible to take systematic steps towards building trust. To build trust a climate of honesty, openness, credibility, consistency, and respect is needed (Bement, 1996). The key is a sufficient level of trust between individuals and organizations so that threats are reduced. While moving forward, it is crucial to note that the possibility for betrayal exists. This possibility exists by definition.
However, by making cautious moves, individual actors can limit their liability in a particular situation.

Everyone is affected by security concerns, and engineers are no exception. The level of effect can be different depending on where one is. For example, some individuals may not be able to walk on certain streets late at night. On an international level, people may find themselves constrained by fear and unable to talk to another group; or people may live in fear of attack by a neighboring nation state. Concerns about security also impose product design costs since time and energy needs to be devoted to making a system “secure.”

Part of the question, then, is what role do scientists and engineers play in the security building enterprise. Historically, they have built tools for the state or polity that are then used by the military. However, this approach saw its logical conclusion in the arms races towards mutually assured destruction in the Cold War. No longer can games without technological limits be played for removing all technological limits would result in global catastrophe. Current security concerns include physical security in war zones, but there are also concerns over food, water, and energy security, which affect many people. Engineers are clearly engaged in the production of technical artifacts, which create security, threaten the security of others, and require security for their proper operation.

Before it is possible to truly lay down one’s weapons, it is necessary to consider the possible causes of attack. Acknowledging that nation states are composed of both laws and people, it is important to look at the personal and structural reasons for violence. These personal reasons may include fear, material want, boredom, ignorance, or greed. And on international levels, these reasons may include power struggles, diverting one’s populace, and the desire for additional resources. The causes of violence in individuals have been analyzed as being caused either by nature or by nurture. If individuals are taught ways of violence, than it is no surprise that is how they react to conflict. Additionally, there may be biochemical reasons why individuals act in such a way.

The solution to these problems is two-fold. There needs to be a large commitment on a societal level to non-violence. This commitment will produce a buffer effect for low-level conflict and allow younger individuals to learn and grow. Some initial work at healing large-scale national conflicts includes that done by Nelson Mandela in South Africa with the Truth and Reconciliation Commission. On an individual level, people can be trained in of the ways of nonviolence and once trained these individuals can act as buffers and dampers in the system to ameliorate conflict. This is seen in the efforts of Gandhi and Dr. Martin Luther King, Jr. But the efforts of several far-sighted, strong, well-intentioned individuals are not enough. Our institutions and technologies must follow suit.

For the United States to be a significant player in building relationships, a strong commitment on the part of the state department to nation building and other development processes must be made. Progress in this area includes work done by the former President Jimmy Carter towards waging peace and work at the Carr Center for Human Rights at Harvard University.

Secondly, the efforts to understand the brain will eventually result in treatments for brain malfunctions that cause certain dangerous behaviors. In thinking about such treatments, society must be careful to avoid misuse of technology. Additionally, even if
the efforts in brain and cognitive science and gene therapy do not produce ways to treat either the underlying genetic defects or the symptoms, the percentage of emotionally disturbed individuals is relatively small. Therefore, if a critical mass of people trained in non-violence exists, the system stability will still be maintained. There is much present work on the biology of violence, including that by Niehoff (1999), which needs to be integrated into the way engineers view the world to open up further possibilities.

With this worldview, the question of what should engineers and scientists do arises. One, scientists and engineers need to regain their voice in the political process. (Mukerji, 1989) Many have opted out or chosen to be tools of the state. Others can, and do, design tools to promote development, either individual development and freedom, or national GDP growth. There is a body of political science literature that supports the linkage between economic development and regional stability (Oye, 2000). This supports the idea that the best long term way to achieve physical security is to transform from security by dint of arms to security through economic interlinkages.

It is not possible to think about designing technology for a completely open world when threats exist. There have been some attempts, most notably in the open source software community. Additionally, the technology development process in Gaviotas, Colombia is radically different than technology development in the U.S. (Weisman, 1999).

The larger question of phase-in presents itself. Trust building begins slowly and must first exist on a peer-to-peer basis before it can exist on a nation-state-to-nation-state basis. There may be individuals who defect, but if they are rational actors they will know that it is in their best interest not to defect. If they are not rational actors, then they may defect and attack. The solution in this case is to be able to defend oneself and other communities. However, an additional step of showing the attacker that there is a better way to live is necessary. It is possible to imagine now that one’s identity may be formed around being a renegade or a free rider. This points to the importance of developmental psychology to help elucidate what factors make these people act in such a way. As Garry Wills (1994) points out, even renegades have certain rules and modes of operating. Therefore it is possible to envision a situation where members from different groups are able to talk and negotiate. This idea has already begun with the United Nations; efforts through the growing body of NGOs may play a significant role in threat reduction in the future. Two examples of such political technology include Women Waging Peace and the Carter Center’s efforts to wage peace.

There are several major barriers to the phasing in other strategies for obtaining security including a first mover disadvantage, entrenched interests, and a perception that the U.S. would be weak to follow this strategy. The idea of a first mover disadvantage refers to the idea that the country to reduce its weapons stockpile first will be at a strategic disadvantage. The military/defense/offensive services should be viewed as a stepping stone until it is possible to move beyond physical security into economic security. As stronger relational ties are being developed, threats are reduced, and the need for military hardware is reduced if this strategy is pursued. This will result in a systematic reduction of risk of armed conflict since the underlying cause will be addressed.

Second, as production ships to other more directly life supporting activities, industrial structure will need to shift focus. This, while a large issue due to entrenched
ways of working, is possible to change. Moreover some basic defense capability will be needed for the foreseeable future to handle low-level conflicts and peacekeeping missions so certain workers will need to be retained.

Third, leading from strength is essential, and the United States must be seen as leading from the strength of principles of human rights. Therefore it is crucial that not only the legal structure of the International Court of Justice is in place but that people know about it. By reaping a peace dividend and using it to help build quality of life for everyone in the world, the U.S. will not only be helping to fulfill the promise of the dream of sustainability, but it will be properly using its great military, economic, and political force in harmony with its founding principles of life, liberty, and the pursuit of happiness.

It is vital that scientists and engineers in the U.S, the builders and architects of the material world, understand these issues because technology embeds and reflects values. One of the first social theorists to identify this issue was Bruno Latour (1992). He identified the speed bump as the sleeping policeman. A policeman exerts authority on a street and is able to cause motorists to slow down or stop. In other cases the speed bump will cause the motorist to slowdown or stop. In both cases the motorist may ignore the signal but there will be consequences for that decision. In the case of the speed bump, the designer has chosen the consequences of ignoring the presence of the speed bump. Therefore, designing for freedom and security is not just a possibility, it is a necessity because the alternative to the intentional is at best a muddled try and at worst a complete debacle. Engineers and scientists of various stripes have realized this throughout history. For example, industrial designers are officially charged with designing for utility (Ulrich, 2000). To this point, however, no one has been charged with thinking about sociotechnical systems and harnessing them for sustainability.

As with any game, it is crucial to have people to play different roles; most scientists and engineers are not interested in the social aspects of the game, but it is crucial that scientists and engineers recognize the game they are playing and the ramifications of their work for the game. We are in a period of needing to renegotiate security and think about creating the safe spaces we need. The opportunity is that a more holistic understanding of security may emerge and more people may be brought into the game. The danger is that an aging physical security apparatus may become increasingly difficult and costly to maintain, in part because of the other peacetime opportunities for well-trained scientists and engineers.

**Environmental Analysis**

Just as security is being renegotiated, so is our philosophical, theological, and practical understanding of our interaction with the environment (Barbour, 1990). Before detailed design tradeoffs can be considered, it is important to understand what type of game companies and people are trying to play. There is a growing consensus that it is necessary to engineer within ecological constraints (Schulze, 1996). The challenge in doing this is that we have neither the economic signals that reflect true environmental costs nor a full understanding of our environment. In the mean time, engineers must continue to make design decisions and build systems to meet the needs of a growing global population. One emerging economic tool is the idea of ecosystem services.
Additionally, important dialogue between engineers and ecologists to find common ground has been started (Schulze, 1996).

Most engineers look at their work on a local scale. These considerations may even include moral concerns. For example, if an engine blows up, an engineer will perform a failure analysis and prevent the engine from failing in that mode again. If it is necessary to substitute one engine for another, that substitution may be made. Or if neither of the first two options is possible, the engineer may post a warning sign.

One of the big issues now is that a lot of the environmental concerns are due to diffuse non-local effects of pollutants. The question arises of how and what to do about it. It is irresponsible for engineers to argue that nothing needs to be done, but the professional engineering community acknowledges this point even if environmental activists do not acknowledge the engineers’ position. The more relevant debate is the one over which institutional structure(s) will replace the current arrangement. Currently, experts from corporations and plaintiffs argue in court to establish credibility. Once this is done, laws for acceptable exposure levels are written or rewritten and/or fines are levied.

For corporations to live up to their promises of corporate responsibility and stakeholder value, corporations must be proactive in thinking about the environment. In this case, environmental expertise must be embedded throughout the corporate community. Likewise, community environmental expertise must be increased; http://www.scorecard.org is one example. This is happening in several areas. Communities are posting online the top chemical polluters. Secondly, there may be competitive advantage to being ahead of the regulatory curve, and some firms are recognizing this (Oye, 2000). Thinking about the trade-offs in design decision-making is crucial; a variety of tools, including life cycle analysis are being developed to help with this task.

Economic Analysis

Everyone wants to be rich. And today parts of the world are richer than ever before in standard economic terms. But there are problems in equity between the North and the South that, while invisible to the average American, are causing fissures in international negotiations such as the Kyoto Protocol.

Competition is central to the American economic ideas. Efficient production and innovation are both the results of competition in microeconomic theory. Competition can also produce environmental destruction and social dislocation in the rush to reach the goal.

Much of the description of social and spiritual dislocation is found in literature. Microserfs by Douglas Coupland and Nudist on the Late Shift by Po Bronson serve as modern ethnographic analyses of high tech workers in the information age. Both authors highlight the one-dimensional nature of the workers’ lives. More recently critiques about the soullessness of American culture have ranged from plays such as Valparaiso by Don DeLillo, books, such as The Diagnosis by Alan Lightman, and studies such as Bowling Alone by Robert Putnam, which is couched in current economic language. Putnam’s work is particularly significant since he has collected eighty years worth of data, operationalized the degree of interconnection, and has shown it to be decreasing since the
end of the 1960s. While he acknowledges there are many causal factors, he attributes some of the decline to technology-enabled factors including an increase in commuting time and an increase in television watching.

It is crucial to understand the type of game that is being played when thinking about competition. Most people focus on rival exclusive goods. Historically this has been perhaps necessary in ages of shortages. Today, as the basic needs are being met, people have the opportunity to focus on non-rival, exclusive goods; rival, non-exclusive goods; or non-rival, non-exclusive goods. Targeting one’s energies on pursuing non-rival, non-exclusive goods will prevent some arguments and petty jealousies that occupy much of some people’s time.

As Bruce Mazlish (1998) notes, the current economic system is a set of social conventions. Examining the root of competition and how it may be harnessed most effectively is crucial. Some like to compete and win because winning garners praise. Others like to win because it provides tangible material benefits. The problem with the view of many on Wall Street or in big industry is that they are divorced from much of natural and social reality. This results in an impoverishment of social relations as well as obliviousness to environmental destruction.

While some do notice this deficit, the challenge for the systems architect is to find a way to achieve acceptable levels of material, natural, and social (relational) wealth. Once the view shifts to this vista, though, new possibilities open up. If people have a newfound appreciation and admiration for non-exclusive, non-rival goods, such as sunshine, the stresses on the existing industrial, environmental, and social structures will be decreased.

It is not possible to prescribe what others should want or predict what whole economies will produce and consume. But it is clear that there are some negative feedback loops in operation. For example, much of today’s consumer driven culture is fed on push marketing, which results in a higher consumptive load being placed on the systems. By rethinking wealth, it may be possible to develop healthier modes of commerce that are consistent with human health and environmental health needs. To avoid politically impractical suggestions of wealth transfer, it is necessary to think about development economics, return on investment, payback, and market incentives in new ways.

Principles for a Sustainable Architecture

What would a sustainable value structure look like, and how would it be translated into material goods and services? There are four main principles which I will discuss: separation of the fruits of scientific investigation from weapons of mass destruction, provision for the basic needs of everyone as defined by Maslow, provision for environmental health, and provision for the opportunity to secure wealth.

Separation of the fruits of scientific investigation from weapons of mass destruction

On the one hand, scientists are privy to the wonders, joys and mysteries of nature thanks to their scholarship. On the other hand, the fruits of that scientific investigation have often been converted into tools to decimate other parts of nature, including fellow
humans. Based on a basic respect for other humans, this weaponization of new technologies must be brought to a stop. Additionally, based on current problems with weapons proliferation, new technologies such as biotech and nanotech must not be weaponized. The only way this goal of non-weaponization will be achieved is if there are other methods in place to guarantee security. Therefore it is crucial to identify and address the material and relational needs underlying sources of conflict. The question of material needs will be addressed in the next sections; for the question of relational needs, much work remains to be done.

Provision for basic needs

If the basic needs of people are satisfied, that will mean people can focus on different modes of competition. Since many of the problems associated with getting basic services to individuals in lesser developed countries are politically driven, politically savvy engineers and companies will be needed. Some of the problems include political corruption as well as inefficient markets due to state control of the enterprise.

Provision for environmental health

Engineers and the public as a whole are beginning to realize that while we are living in a second, man-made creation, the original creation is still vital to human well-being. As such, the idea of engineering within ecological constraints has been proposed. However, if an industrial ecosystem that is in harmony with the natural ecosystem is to be built, several key ideas have yet to be fleshed out. Two of these that will be fleshed out later include ecosystem services and industrial ecology. Additionally, work in the emerging areas of infotech, biotech, and nanotech can be harnessed for sustainable development.

Providing for environmental health also has implications for where we should go with our product design and marketing efforts. If people are seen as living within a natural and a built world in which they both deplete resources and steward the resources, this also has implications for how they prioritize their efforts. One way of structuring the built and natural world is by looking at the envirospace that encompasses industrial space. Intertwined with and permeating both is information space.

Provision for the opportunity to secure wealth

While the provision of basic goods and services is necessary from a humanitarian and security point of view, many individuals won’t see this aspect, nor will they necessarily care. Many people will want to compete to achieve personal wealth. The challenge is to funnel the competitive energy into games which both provide rewards to the players while avoiding unwanted externalities. If individuals recognize different modes of wealth, it becomes easier to discuss tradeoffs.
Economic Tools

Although their contributions are vital and understanding their policies is crucial for development, a discussion of World Bank and IMF fiscal and monetary policies will not be given here. Rather attention will be focused on several emerging economic tools and sets of tools. In particular, social returns on investment (SROI), ecosystem services, and alternate development funding mechanisms will be discussed.

Social Return on Investment

The growing community of entrepreneurs who have grown up on venture capital is spawning a new culture of individuals which wants social improvement but which is looking for ways to measure it. References can be found at http://www.redf.org and http://www.net-impact.org.

Social return on investments is gaining currency as a way for firms to quantify the returns on their assets. As firms are able to legitimately promote the welfare of developing countries, they can take credit for it in their annual reports. Additionally, socially responsible investment funds are being established. While a large demand for them has yet to exist, their very existence is a harbinger of things to come.

Ecosystem Services

Economists are beginning to look at ecosystems as multiproduct firms. The challenges include determining how to value environmental services as well as how to measure environmental services. There are many challenges ahead, but several strategies seem to be needed. Arrow, et. al (2000) recommend “precautionary and adaptive approaches coupled with mechanisms to tighten cost and benefit loops and to internalize externalities, including local empowerment and common property resource management.”

Alternative International Funding Mechanisms

Proposals for alternative funding mechanisms to promote goods for lesser developed countries have been proposed. For example, Jeffrey Sachs (1999), noting that health is a major component of development, has proposed a market mechanism that will promote the development of medicines needed for diseases in Sub-Saharan Africa. The problem to this point has been the existence of a need with no ability to pay. Sachs proposed a general model of a Western government, such as United States, offering to buy a guaranteed number of vaccines for the affected country. This has the effect of establishing a market since pharmaceutical companies can then decide to pursue this project on the same basis as they would any other project. The same arguments for hurdle rates and ROI’s apply. The only difference is that a government instead of an HMO is going to pay.

From a governmental research funding perspective, the results are more applied in nature, and there is the potential for fewer public goods resulting from the research findings. There is a need for an empirical study to quantify the public goods, but there is
also the need to look at the public benefits in another way. This is a chance for the U.S. government to support a program that is unprecedented. In this way hope and the beginnings of a vibrant community can emerge from the United States’ economic and technical development policy.

**Engineering Tools**

**Global Models**

A variety of global models have been developed. One of the earliest was Jay Forrester’s systems dynamics models. As global climate change became a growing concern, a community of climate modelers arose. Their models have attempted to indicate the impact of emissions on global climate change. A big challenge is to separate anthropogenic effects from naturally occurring climate cycles. Critiques of these models exist since sometimes they are in use beyond their range of validity.

These models show first hand the complexity of the world and the impossibility of a centralized knowledge assessment. This recognition is beginning to dawn on environmental regulators, and other mechanisms for ensuring environmental quality are being proposed. One idea is the devolution of responsibility from the Federal government to a more local level. Various environmental monitoring devices would be needed to make this effective. Ron Prinn at MIT is working to establish a global environmental monitoring network; the results of this monitoring could be displayed on the Internet so accuracy would be ensured through the ability of many pairs of eyes to monitor the data. In this case, the monitoring function of the federal government would be spread through the private voluntary sector, including non-governmental organizations.

Perhaps the most valuable insight a mental global model can have is as part design philosophy or ethic, rather than in giving quantitative information. Construct a Pareto chart for addressing human needs by thinking of people’s needs as described by Maslow’s hierarchy of needs. Then think of the distribution of where the greatest human needs are. In doing so, there are clear human development needs that are not being addressed by the current market system. Currently it is much easier for an engineer to go work on optimizing a very small need, such as improving a particular type of shampoo, than it is for an engineer to go work on big need such as helping to provide a sustainable water supply. One solution, then, is to think about how such needs could be addressed by tools and resources within the system. Tools in the product design category play a role in this thinking.

**Product Design**

Product design as described by Ulrich and Eppinger (2000), includes the notion that product design is a collaborative concept that also depends upon customer feedback. Ulrich and Eppinger also acknowledge that they were largely focused on discrete mechanical components, as opposed to continuous chemical processes with which the large chemical producers are intimately involved. However some of the lessons learned by Ulrich and Eppinger are relevant to the current concerns facing the chemicals industry.
Ulrich and Eppinger emphasize the need for a structured design methodology. This design methodology ensures that the major questions in the design are addressed. In order to determine the characteristics of the design requirements, they outline survey methods, which allow the developers to identify the key needs and requirements of the customer. Additionally, Ulrich and Eppinger provided the way to prioritize the list of design needs for the product. Once this has been done, the designer has the ability to proceed with the design. Integrating design and marketing in product development makes for a product that more successfully meets customers needs. In so doing, both the customer and the designers benefit; the customer obtains a product that is truly desirable, and the producer obtains greater customer loyalty.

Ulrich and Eppinger (2000) point out the satisfaction many people receive from product design. One thing they leave out, though, is a sense of larger mission, such as that found in the moon shot. Yet that desire for larger purpose still remains, as seen by the longing expressed in the previous art, as articulated by political leaders such as Al Gore in *Earth in the Balance* or George Bush in his campaign slogan “Prosperity with a Purpose,” or as expressed in the current Hewlett and Packard and DuPont advertisements.

Part of the challenge for the systems architect is to think about creating a challenge that is commensurate with the goals and objectives of the people carrying out the task. Additionally, if the goal is development oriented, respecting the dignity and worth of others in lesser economically developed countries must be at the top of the list.

Ulrich and Eppinger’s product development tools provide ways to do that if people are willing to look. The existence of multifunctional, cross disciplinary teams enables some people to work more closely to the problem while others can stay at home in the office. No longer does development have to be a choice of hardship in poor areas and harsh climates or sitting from afar and making dictates. The current product design sensibility is scalable to address international development needs. Since the tools are coming into existence and large multinationals are interested in capturing market share, facing into the material needs of the developing world should be a top priority.

**Systems Architecture**

The key systems architecture approach looks at where value is added either in the product or in the process. The value in the current mature American economy is often in the process since that is where additional benefits can be added (Crawley, 2000).

Systems architecture, allows the designer the flexibility of considering different types of design options before settling on a specific physical instantiation in the solution. System architects are beginning to examine how legacy systems affect future design options. Additionally, the concept of types and antitypes allows one to classify design failures that inevitably occur and build on those mistakes. Moreover, systems architects realize that some of their design flaws are the result of problems previously reserved for moralists, i.e. ignorance, sloth, greed, and pride. Furthermore, in considering material, aesthetic, spiritual, mental, and emotional needs, architects are moving into design space previously reserved for the rumination of philosophers (Crawley, 2000).
Industrial Ecology

Industrial ecology is a new way of looking at material and energy flows. Metaphors between natural ecosystems are drawn and ways to mimic the flows and processes in natural ecosystems are investigated. Some initial work centers around three main areas: tracking material and energy flows, a case study evaluation of industry interlinkages, and questions over design philosophy.

When Greenpeace advocated a ban on chlorine due to its presence in various toxic organic chemicals, studies were done to track the flow of chlorine in the global ecosphere (Ayres, 1997). The purpose of these studies was to determine whether it was feasible to eliminate chlorine from the industrial sphere. It was found that the benefits of chlorine are substantial, and that it is not possible to eliminate chlorine from the global industrial sphere. An example of a map of flows is given in Appendix A. This example shows lead flows in the U.S. economy in 1993-94.

One example of the new type of study was done in Kalundborg, Denmark (Ehrenfeld, 1997). This study was in a sample of the spontaneous emergence of the symbiotic industry interlinkages. The industrial interlinkages are shown below (figure taken from Ehrenfeld, 1997):
These examples add flesh to the design philosophies espoused by the industrial ecologists. These principles include a desire to close loops, minimize flows, pursue symbiosis, and obtain high degrees of network interconnectivity. Homeostasis is also used as a mental metaphor. Additionally, a no pollution mentality is held since pollutants are material or energy that is a by-product of the activity of one part of the system that has an unintended disruptive effect on another part of the system. The goal is to make the pieces work together in harmony.

Although industrial ecology is a nascent field, it is important in being able to think about creating a material infrastructure that supports a global economy. At least in theory, it addresses the problems of scalability faced by today’s technological solutions.

CONCLUSION

This paper has discussed several main topics. First it gave an example of the transition from second mode systems thinking to third mode systems thinking by focusing on chemical and materials engineering. Additionally, it provided a discussion of the sociotechnical element underlying sustainability discussions. Finally, it discussed the individual scientist’s and engineer’s role and the role of corporations in helping to make the transition to sustainable development. While acknowledging the importance of technology, the importance of social, economic, and political institutions in shaping the technology was also discussed.

The question of whether large industrial firms like DuPont, Shell, and BP are serious about helping to achieve sustainability remains open. However, there are a large number of tools and an increasing body of theory on which these firms and the scientists and engineers that they employ may draw. Corporations need to continue to push for the development of tools for architecting sustainability lest they become fodder for Dilbert-esque satire due to the hollowness of their claims regarding sustainability. The best way to achieve sustainability is to understand the multi-faceted goal as best as possible and engage in successive iterations of tool building and testing.

Future work includes detailing specific engineering needs. Work to this end has been started by the NSF. Details can be found at http://www.nsf.gov/nsb/tfe/nsb99133/reports/nsb99133i.pdf.

Additionally, creating interlinkages between different communities, such as the high tech start up arena and the international development community, is necessary.

Third, thinking through the implications of environmental awareness, democracy, and technology development is necessary. Shutkin (2000) and Sclove (1986, 1995) have made a start on this project.

Building communities that can discuss and live the ethic of sustainability is necessary.

Finally, a more full discussion of the political, economic, social, and legal aspects of this question is necessary. Particularly important are ways of waging peace or building infrastructure that promotes security.
APPENDIX A

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