The Social Consequences of Design: 
PBL Workshops for Undergraduate Researchers

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In Summer 2003 the Institute for Systems Research (ISR), a permanent institute of the University of Maryland, within the A. James Clark School of Engineering, and National Science Foundation Engineering Research Center, piloted two day-long workshops on “The Social Consequences of Design: Requirements and Trade-Offs in Large-Scale Engineering Projects,” for the first 15 participants in its NSF-funded Research Experiences for Undergraduates (REU) Site program. The program’s formal title is “Introducing the Systems Engineering Paradigm to Young Researchers and Future Leaders;” it intentionally extends research opportunities to students, including from under-resourced institutions, with limited or no exposure to the process and practice of scientific research.

The first of the co-curricular workshops centered on water remediation projects in South Florida, the second on the destruction of the World Trade Center; they were part of a “Systems Engineering and Society” series that also included “Working Together” sessions – named for the team strategy that produced the Boeing 777, described in detail by Sabbah34 -- on leadership, collaboration, and teamwork under the systems engineering (SE) rubric, and grounded in the principle Ciulla5 asserts that “[t]eamwork without tolerance of difference in opinion, gender, racial, or cultural background is unacceptable.”

In developing the workshops, we adapted the methods of Problem-Based Learning (PBL), imported from medical education and adapted to undergraduate teaching and learning by Duch, Groh, and Allen and their colleagues at the University of Delaware.9 The preparatory and background materials were compiled and synthesized from SE textbooks, scientific studies, journal and newspaper articles, conference proceedings, and materials from numerous informational and interactive websites. We drew the problem statements directly from contemporaneous or recent news items.

The principle of the Systems Engineering and Society series workshops is not to teach students a “right” or “wrong” approach to resolving conflicts between requirements and constraints, but rather to teach them that design and its consequences form a continuous process of thinking and questioning in an environment favorable to open discussion. Values issues in research are complex and open-ended. The purpose in showing students the connection between research (design) and social values is to guide students in learning to think about these issues as an integral part of what engineers do, so they will have the clarity and courage to engage ethical issues. We suggested that nearly all questions engineers, in the lab and at the job site, must answer involve the impact of their work on human beings. The effect of the workshops should be students seeing how research is integral to their other roles as engineers, and how it is pursued.
not in isolation but within a wider social agenda. They will perceive how research can advance their own beliefs and goals, and they will undertake it in a more personally meaningful way.

The SE approach to problem-solving is to develop an analytic and strategic framework by synthesizing approaches from a range of fields and identifying the best way to develop a solution. As a multidisciplinary field, SE also represents ground the REU students held in common. The workshops allowed them to explore non-trivial, open-ended engineering problems; to work in teams with REU colleagues with different backgrounds, interests, and research projects from their own; and to enable them to engage social and scientific problems in an SE context. The accompanying workshops on “Working Together” also helped students frame questions of diversity within academic and social systems, demonstrating how quality and diversity are interwoven throughout individual and collaborative work, decision-making, and evaluating needs and constraints, and how social issues are appropriately a habitual part of scientific and engineering practice.

Systems engineers are highly equipped to deal with complexity, which inheres in large, technology-driven projects. In any project, the capabilities and needs of the system to be designed are balanced with the needs of those who will be using and paying for it. Stevens et al. suggest that insufficient attention to both sets of requirements is responsible for more system failures than are flaws in the technology. In balancing these paired sets of requirements, a landslide of information must be sorted, prioritized, managed, and applied accurately; the risk of either design or system failure must be evaluated and weighed; and all designs must be tested iteratively and under conditions that are both likely and extremely unlikely to occur. The challenge may be as much to imagine as to test for them.

SE is attractive to students, not only because it is a dynamic field, but also because its definition itself is evolving, and they share with established scholars and practitioners the challenge and opportunity to contribute to it. We asked them, “What do systems practitioners mean when they say there is little consensus among themselves on how, precisely, to define systems engineering?” For our purposes, the working definition was that worked out by Kossiakoff and Sweet: “The function of systems engineering is to guide the engineering of complex systems,” which illustrates the problem we have in defining systems engineering: the thing being defined is part of the definition. Fortunately, Kossiakoff and Sweet unpack their definition for us:

- Guidance refers to leadership, management, or direction
- Engineering is “the application of scientific principles to practical ends”
- Complexity in the systems sense indicates that “the elements are diverse and have intricate relationships with one another”

Further, they discuss three factors that are pertinent to the cases in the “Social Consequences of Design” series: advancing technology, which increases risk while enabling progress; competition, which drives the search for “systems solutions through the use of system-level trade-offs among alternative approaches;” and specialization, in which the system is broken out into its constituent parts, to be “designed and built by specialists … [to manage] their interfaces and interactions.”
Central to the processes of systems design and systems management is the definition of requirements, from the points of view of the person(s) or entity(ies) requesting the work and the engineers performing it, and trade-off analysis, from optimizing choices of processes and materials, to compromising and "satisficing" among members of social communities and work groups, to the knife-edge calculus of environmental and human safety and economic profitability. The scientific modeling of environmental and economic factors takes partial account of social dynamics; there are also accompanying issues of social justice for which no computer simulation exists or is possible.

The ways in which organizations, which are systems of individuals and roles, perform trade-off analysis are artifacts of their cultures, and may be seen very differently from inside than from outside. Researchers approaching a trade-off issue from outside an organization need to understand its needs and limitations before they can determine what is both appropriate and feasible in terms of the organization’s values, without sacrificing or ignoring their own. In each workshop, we encouraged students to assume or become aware of a variety of roles, to gain a deeper sense of the parts different individuals play or played in the systems life-cycles of real-life cases:

(1) “‘Getting the Water Right:’ Restoring the Kissimmee and Reclaiming the Everglades” (focusing on competing social goods)
(2) “The Creation and Destruction of the World Trade Center” (focusing on human factors and risk assessment)

Method and Presentation

More flexible and personal than the case study method, PBL is, in the words of experienced practitioners, “ill-structured” (addressing problems with no obvious or definite resolution), complex, authentic, and collaborative. Because – like systems engineering – it focuses on process rather than product, it enables students to acquire problem-solving and decision-making skills by analyzing background materials to arrive at a less structured conclusion than a traditional case study requires. Finally, students tackle PBL cases concurrently with learning content, rather than relying on previously acquired content knowledge. This was ideal for our purposes; because none of the 2003 REU students came from a civil or environmental engineering background, no one held an advantage from earlier coursework. Everything they needed to refer to in order to participate fully was provided. We made the following recommendations as they prepared for the workshop activities:

(1) As we are taking a systems approach to each topic or problem, focus on what you believe you would need (tools, methods, etc.) to arrive at a solution, if you were a member of a real-world organization tackling the issue, rather than trying to figure out what the actual solution would or should be.
(2) We will be using the “garbage can” method of organizational brainstorming: all ideas are welcome and all judgments suspended. This does not mean that your ideas themselves are “garbage,” but rather that everything is thrown onto the middle of the table and discussed before being either adopted or eliminated.
Although the students had not had experience with PBL in their college courses, we expected that they would still be able to understand, and appreciate, the open-ended, no-one-right answer nature of PBL questions. Open-endedness also characterizes the kinds of problems that systems engineers address:

Engineering disciplines are built on quantitative relationships, obeying established physical law, and measured properties of materials, energy, or information. Systems engineering, on the other hand, deals mainly with problems for which there is incomplete knowledge, whose variables do not obey known equations, and where a balance must be made among conflicting objectives involving incommensurate attributes.22

Because we did not expect students to bring specific content knowledge, what we hoped they would carry away is a deeper understanding of their imagined roles as prospective researchers, builders, and reformers, through observation of their own thought processes and interactions with their team members. We strongly encouraged them to introduce their personal experiences and related interests. Each of the cases is built around the decision-making processes, amid competing social and commercial goods, that led, in the first case, to the destruction of the Kissimmee River watershed and the degradation of the Everglades, their subsequent and on-going restoration, and the role in both of the US Army Corps of Engineers; and, in the second case, to building the Twin Towers on land long occupied by thriving small businesses, and incorporating design flaws that may have increased risk and contributed to their collapse.

“Getting the Water Right:” Restoring the Kissimmee and Reclaiming the Everglades

In 1962, in order to accommodate a burgeoning population and corresponding demand for housing and infrastructure in South Florida, safe from flooding and other natural depredations, the Army Corps of Engineers straightened the winding Kissimmee River into a canal. Thirty years later, confronting severe ecological degradation and politically sophisticated environmentalists’ demands to reverse it, a partnership including the Corps of Engineers undertook the Kissimmee River restoration project, which is scheduled to be completed in the next decade.16

Watching closely, and following the progress of the Kissimmee restoration, are advocates for the Everglades. Flood control was also the rationale for draining the Everglades, a Corps of Engineers project begun in 1948.16 It was considered a success story and influenced decisions that led to the draining of the Kissimmee watershed, and so attitudes and policies toward the Everglades seem to have come full circle.15, 17-20 Water remains the central issue; progress toward “getting the water right” with respect to “quantity, quality, timing, and distribution of water,”6 what began as essentially a “relatively routine [hydrologic] engineering exercise”7 became a paradigmatic systems problem.

Like restoring the Kissimmee, reclaiming the Everglades also requires “a comprehensive and integrated scientific study”7 comprising several major research projects, as much as prodigious feats of engineering.4, 23, 41-45 Because the goals of enhancing ecological values and enhancing economic values and social well-being compete more often than they intersect, and because restoration projects on this scale have seldom been undertaken, “[i]n the face of … uncertainties and surprises, the ability of the [Everglades] restoration plan to achieve its stated
restoration goals depends on fully incorporating and maintaining scientific research throughout the restoration program\(^6\) (emphasis added). This is critical because “[s]cience has the potential to inform ongoing restoration policy and management decisions to the extent that restoration targets and measures actually capture and measure progress toward society’s goals and measures.”\(^6\) The project’s science must therefore be located within its management strategy, with clear goals, system conceptualization, learning-organization characteristics, and continuous feedback loops; “[s]cience-based restoration will occur only in science is strongly integrated into the decision-making processes that most critically impact the state of the ecosystem.”\(^6\) This is consistent with systems engineering’s theoretical identification with synthesis (Greek *systhima* or *syntithene* = bringing together in harmony).

Synthesis is the process of accumulating, interpreting, and articulating scientific results to increase understanding. Regional synthesis is required to bring scientific knowledge into the Restoration Plan’s adaptive management program. Synthesis also contributes to negotiation and conflict resolution, so that learning can continue as construction and implementation proceed. … [S]trong synthesis and management of information is essential to make it possible to learn from interactions among restoration projects and across the whole ecosystem, and to enable managers to adapt to new information, correct mistake[s], and reduce waste of money. Synthesis also reveals risks and uncertainties so that resiliency can be incorporated into restoration plans. … ‘Synthesis is essential to the Greater Everglades restoration as it will enable ongoing learning when change is common and uncertainty is high.’”\(^6\)

Many fields or branches of science and engineering are involved in the Comprehensive Everglades Restoration Project (CERP); the science in one piece or sub-project may be narrow, but because this is a systems problem, with each decision and action affecting the whole, the application is very broad. Systems engineering is technology-intensive, and it may be useful to bear in mind that the technology needed to repair the damage to the Kissimmee and Everglades ecosystems is more advanced and sophisticated, by an order of magnitude (at least in a rhetorical sense), than that which caused it. The restoration projects, in other words, could not have been undertaken successfully in an earlier period. For example, advanced technology has enabled highly detailed computer simulation and modeling. Two programs in particular, ATLSS\(^{44}\) [Across Trophic Level System Simulation] and ELM\(^{37}\) [Everglades Landscape Model] are used in the Restoration Project. (The REU students were encouraged to interact with these programs, adding to the realism of the exercise.)

The staggering complexity and interactivity of the CERP is evidenced by the fact that not all program goals (requirements) are reciprocal, mutually reinforcing, or compatible with each other. For example, restoring the habitat of one endangered species may impact another as adversely as human population growth. Quality of life issues are crucial for South Florida residents; in fact, the “greatest challenge” to the project is “maintaining public support, and thus political and financial support.”\(^6\) The project must provide clear, continual evidence of change/Improvement that is the proximate result of the CERP rather than other, unrelated factors (“exogenous forces of change”\(^6\)), as well as an appropriate timeline for reporting results. Neither ecological nor economic values and social well-being can be advanced at the expense of the other; “until targets and measures are set for defining compatibility of the built and natural...
systems, the Restoration Project will not have explicitly addressed possible tradeoffs and conflicts between ecological restoration and other policies, statutes, and social demands.

A guiding principle of the CERP is that “‘each incremental step is viewed as an experiment accompanied by one or more hypotheses that predict how that step will improve the system’ (USACE 1999), a concept generally termed adaptive management.”

Adaptive management is a general concept that could refer to a broad range of approaches to achieving ecosystem restoration. However, the minimal elements of any truly adaptive management scheme include (1) clear restoration goals and expectations, (2) a sound conceptualization of the system, (3) an effective process for learning from future management actions, and (4) explicit feedback mechanisms for refining and improving management based on the learning process. The extent to which the Restoration Plan will meet the restoration goals and expectations rests in large part on a well-designed framework for creating and supporting these four elements.

In both adaptive management and conventional project management, each phase of a systems engineering project defines, rather than merely drives, the next. Verification and validation support both concepts of management by measuring progress, reducing uncertainty, and providing information for decision-making. Conceptually, the phases can be ordered according to Table 1, below.

Table 1. Correspondence between system and project life cycles

<table>
<thead>
<tr>
<th>System life cycle</th>
<th>Statement of Task</th>
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<tbody>
<tr>
<td>User requirements</td>
<td>Program goals, objectives, and planning approach</td>
</tr>
<tr>
<td>System requirements</td>
<td>Data and information aspects, including needs for basic hydrologic and water quality data, environmental resources information, display and dissemination, and monitoring needs</td>
</tr>
<tr>
<td>Architectural design</td>
<td>• Use of hydrological and hydroecological simulation models</td>
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<td></td>
<td>• Technological aspects of civil works facilities</td>
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<td></td>
<td>• Best agricultural and management practices of nutrients management</td>
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<td></td>
<td>• Wildlife management</td>
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<tr>
<td>Integration &amp; verification</td>
<td>Decision support systems</td>
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<tr>
<td>Installation &amp; validation</td>
<td>Research requirements to support analyses for decision-making and implementation</td>
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Sources: Committee on Restoration, Stevens et al.

We offered the students a quick sketch of the (often multi-)organizational context in which large-scale engineering projects are conceived, developed, and carried out. According to Bolman and Deal, “Just as frogs, flies, and lily pads coevolve in a swamp, organizations develop in tandem in the context of shared environments.” Furthermore, Morgan reminds us that “[t]hey do not live in isolation and are not self-sufficient …[but] exist as elements in a
complex ecosystem.” The largest is society itself, “the massive ecosystem in which business, government, and the public are all embedded and coevolve.”\(^2\)

The environmental restoration movement is an outgrowth of society’s realization that its political, cultural, and physical environments are linked, and that the survival of the whole depends on that of each part; the demise or destruction of any one element threatens the health of all the others. In organization theory, this is referred to as close coupling. The CERP is characterized by tight coupling between constituent projects. This both imposes constraints, especially with respect to scheduling, and (together with frequent and rigorous assessment) provides quality control: “Close and thorough coordination…is required to ensure the continuity and integration of…separate efforts to avoid having them become disjointed parts of an overarching task.”\(^7\) However, just “[a]s in nature, relationships within and between ecosystems are sometimes fiercely competitive, sometimes collaborative and interdependent.”\(^2\)

In the systems model, organizations behave rationally, as though they could think, plan, and make decisions on the basis of information they gather, synthesize, and interpret; this is also referred to as the cybernetic or learning-organization model,\(^2, 25\) or, colloquially, as running itself. This concept is important to understanding how such a project as the CERP evolves strategy, acquires and maintains momentum, manages change, and sustains communication and reciprocity among constituent projects. It is too large and too complex to be subject to the deliberate direction of a single individual, or even for one person to have more than a fundamental conceptual grasp of all its elements.

Organizations form only one link of the chain conceptualized by Booher;\(^3\) the others are technology, and people. The systems engineering subfield that studies this nexus is referred to as human factors engineering, which is defined as the “the comprehensive integration of human characteristics into system definition, design, development, and evaluation to optimize the performance of human-machine combinations.”\(^3\) For example, when “pilot error” is cited in the investigation of an airplane crash, human factors specialists may actually have identified interaction between user and technology as the proximate cause of the disaster. Furthermore, “the environment” in the Everglades restoration includes the human environment: where people live, and what they value, and their cultural preferences and norms, all of which impinge on what they may or may not be willing to sacrifice from one good in order to achieve another.

**Problem statement, getting started, and reporting out**

The background for the Kissimmee/Everglades problem statement was recent news that a portion of an established Cuban American neighborhood would be condemned and taken for a water rectification project:

Congress has approved a plan to destroy 77 homes at the edge of Everglades National Park, jump-starting efforts [Modified Water Deliveries Project of 1989, or “Mod Waters”] to restore flows to the ailing River of Grass….The revival of “Mod Waters” would also help the much larger $8.4 billion Comprehensive Everglades Restoration Plan, the most ambitious environmental project in history. The law authorizing the overall Everglades restoration in 2000 specified that several key elements could not proceed until Mod Waters is complete. … Environmentalists had pushed for a buyout of the entire 8.5 Square Mile Area, but most were happy with the compromise, which is to buy out 44 percent of the land.
and 12 percent of the homes. The residents of the area, however, were furious, even though their congressman, Rep. Mario Diaz-Balart (R-Fla.) attached language requiring the Army Corps of Engineers to offer owners of the 77 affected homes land elsewhere in the neighborhood. …The original Mod Waters plan would have protected the entire neighborhood, but park officials warned that it would also drain 30,000 acres of Everglades wetlands, defeating the purpose of the plan. The compromise, they say, will allow true restoration.17

“Critical human forces” are involved in the Restoration Project, including both decision-makers and those whom their decisions impact. The science of the Restoration Project has both cognitive and affective (emotional) aspects that are brought to bear in critical policy decisions like reviving the “Mod Waters” project. There are also other “social dynamics of importance” that can be neither predicted nor anticipated. Engineers, community leaders, elected officials, and citizens engage in dialogue and negotiation to understand, and to the extent possible resolve, contested issues. Therefore, the problem statement directed students that

Your role in this workshop is as engineers assigned to address members of a homeowners’ association in the 8.5 Square Mile Area. The requirements include, but are not limited to, the rehydration of the River of Grass. The constraints include, but are not limited to, the condemnation of four acres of land in the 8.5 Square Mile Area; compensation of affected homeowners; and the desire of residents to preserve the character of their neighborhood. Using the systems life cycle template corresponding to the Statement of Task, provided above, propose how you would prepare your presentation to the homeowners.”

We gave the students suggestions on how to get started:

Begin by asking yourselves these questions:

- What do you already know (educated guesses count for the purposes of this exercise)?
- What do you need to know?
- What do you need to do in order to find this information?
- What do you want to know?

Follow up by laying out the project requirements, as you perceive them. You may want to identify the different customers or constituencies and come up with requirements for each. (They are related to What do you need to know? but are not exactly the same thing.) Remember, no right or wrong answers; throw everything you want onto the table (or into the garbage can). Tackling the requirements should not be intimidating.

Once you have established a list of requirements, re-read the scenario above; possible trade-offs should emerge from this, but don’t start your exercise by negotiating and anticipating compromises! Requirements do not constitute desirables or a wish list; they are necessary. In some cases you may decide what began as a requirement is in fact an option, but draw up your list on the assumption that each item is indispensable, even though some may conflict with others.
A suggested outline for reporting out included:

1. Present list of requirements for each constituency;
2. Describe briefly why these are requirements; and
3. Discuss conflicts, if any, among requirements across constituencies, especially the needs of the project vs. the wishes of the homeowners; this will be your trade-off analysis.

The Creation and Destruction of the World Trade Center

The goal of this workshop was to introduce systems concepts in a social context that is recent, familiar and urgent. The primary, just-in-time reference was Federal Emergency Management Agency (FEMA)/American Society of Civil Engineers (ASCE), World Trade Center Building Performance Study, together with the PBS video “Why the Towers Fell.”

Wasteful. Eyesore. Seedy. These descriptors were applied liberally to the prospective WTC site by its developers, who proposed building the trade center complex as an economically and socially superior use of land occupied by the funky, beloved Radio Row. Today, in the 30s and 40s between Broadway and 8th Avenue, you can still get a sense of what Radio Row may have been like as you walk along streets lined with electronics and camera shops, but the real Radio Row was an artifact of the time when appliances were maintained and repaired rather than discarded and replaced. Its store owners were not only merchants but also craftsmen; it was not rebuilt, and a community and culture vanished.

Proud, strong, and tall. Brave and stalwart. Heroic. Contrast these eulogies for the Twin Towers with the adjectives dismissing Radio Row. It is outside the scope of this workshop to determine whether the World Trade Center formed a culture, equivalent to that of Radio Row, that can (or should) be reconstituted; the depth of pain in nostalgia for the towers is not for the passing of an era but for the loss of three thousand dead. However, even if all occupants had safely and successfully evacuated the WTC, their spectral workplaces would be more than objects of interest and, eventually, historical speculation. Robertson observes, “In my mind, the loss of life and the loss of the buildings are somehow separated. The loss of the buildings is more abstract. The buildings represented about 10 years of concerted effort both in design and in construction on the part of talented men and women from many disciplines. It just isn’t possible for me to take the posture that the towers were only buildings … that these material things are not worthy of grieving.”

Something like our country’s present pain also inheres in the relics of the African Burial Ground, which came to light more than two hundred years after the Black victims of a 1741 racial plot were laid to rest. The historical memories of dominant civilizations are filled with the sadness of their subaltern members.

Complexity plays out somewhat differently in the case of the WTC, which illustrates how large systems, characterized by complexity, are also characterized by the costs and risks inherent in complexity that can be mitigated but not eliminated. Cost and risk may also be constructed differently by the public than by designers and builders; a simple example is the complaints about additional time and money spent increasing security at airports. What is an inordinately
long time to a traveler is the blink of an eye to an engineer designing passenger and luggage screening systems and performing trade-off analyses. However, both constructions occupy points on the same continuum from resistance to initial acceptance to normalization.26,46

We suggested that the origins of the World Trade Center towers were in the engineer’s lab; the architect of such structures as the WTC must be, and in this instance was, primarily an engineer.8 A modern engineering research laboratory or commercial firm is also a system, composed of individuals (employees and customers) and the technology on which they depend and with which they interact.

Complex systems are typically formed from interacting elements, which themselves are increasingly “intelligent” and partially autonomous. A complex system cannot be managed in the head of a single person, but it is always essential to see such systems as a single entity, and at different levels of detail.39

The projects on which they are engaged, and those projects’ end products, also are systems, having both distinct and linked requirements, which, together with design, impact quality, cost, schedule, risk, and feasibility.40 These can be defined differently within different parts of the system. For example, the Port Authority of New York and New Jersey, a public entity, owned, developed, and managed the WTC, whose tenants included both public and private entities, giving rise to a range of commercial and societal interests. Fire protection codes, which are determined by panels representing a variety of stakeholders and users, are a case in point. The panels are populated with, among others, manufacturers of various fire protection systems, academic experts, and government officials, all of whom bring to the table different sets of requirements, constraints, and approaches to trade-off analysis. This is not necessarily adverse (or cause for suspicion), as it means that different perspectives are available to decision-makers.

The Twin Towers constituted a complex system in which engineering design played a crucial role in both their creation and their destruction, and which offers a glimpse into the processes of requirements and trade-off analysis. The non-standard design of the towers included a truss system devised for convenience during construction – the trusses were lightweight and easy to raise hundreds of feet in the air. This left them susceptible to fire, however, as they would heat up quickly. Part of the building design process is setting parameters for the minimum time a building must maintain its structural integrity; for the World Trade Center to achieve an x-hour fire rate, the trusses would have needed to be coated with insulation to increase their survivability, allowing all occupants to exit safely, and the insulation failed. Some engineers believe the trusses may not in fact have been insulated; others speculate that the planes’ impact dislodged it. In any case, heat transfer was insufficiently studied and understood to provide adequate insulation.

Because the collapse constituted atypical behavior as the result of fire, the above does not help resolve the disagreement among engineers about whether the impact or the subsequent fire was the proximate cause of the towers’ collapse; Building 7, for example, burned and collapsed without a direct impact occurring.10 It does, however, suggest a focus for scientific research to prevent building collapse as direct or indirect consequence of fire. Many fire protection
engineers advocate more science, which translates to performance-based codes, in the code development process. Scientifically grounded codes can be traced to tests rather than to discussions between individuals with non-scientific agendas, directly linking the social consequences with its physics.

People have … come to appreciate how complexity changes the risk equation, how it makes risk harder to calculate by making it difficult to understand all the ways that things can go awry. But equally important, complexity can amplify risk. The more complex a technology, the more ways something can go wrong, and in a tightly coupled system the number of ways something can go wrong increases exponentially with the number of components in the system. The complexity also makes a system more vulnerable to error.27

A key aspect of systems engineering is its interdisciplinarity, and the FEMA/ASCE report underscored this in its recommendation that multiple disciplinary communities be brought together to improve future building designs. This does not translate to seeking compromise among competing special interests (although such compromises may be reached); it does emphasize the interdependence of the different parts of a tightly coupled system as well as of those who will use it. Prieto notes that

the events of September 11 were attacks on an “engineered,” built environment, a hallmark of our society, which thrives on human proximity, connectivity, interaction, and openness. The very fabric of our “civil” society is tightly woven.32

The variety of disciplines engaged both in building and in studying the destruction of the towers is more evident than in the case of the Kissimmee/Everglades Restoration Projects. Students taking roles as particular disciplinary representatives to address the problem statement is therefore more feasible.

Pool characterizes addressing risk as “the most vexing problem facing technology.”

Traditionally, scientists and engineers have seen risk as a purely technical issue, one that can be boxed off from the rest of a technology and handled separately. But for modern complex technologies this is often impossible. When risk is involved, technical and nontechnical issues can get tangled to the point that they are impossible to separate.27

Nontechnical and intangible factors, “independent of scientific knowledge,” inhore in questions of both risk and trust: Are the answers known? Who knows them? Will they be truthful about what they know? Can scientists and engineers, and those (such as the government) with whom they have shared their knowledge, be trusted to share it with us? How much sense of safety are we entitled to? How much uncertainty are we expected to accept? Trust is at the heart of any discussion of the impact of risk on the public; it is, after all, the intangible that allows us to plug in our coffee makers, start our cars, climb into our apartment or office building elevators, and cast our votes. “It is up to the larger society to weigh the engineers’ opinions about risk and decide how much faith to put in them…a democracy must allow the public to decide which risks to consider and how much emphasis to place on each.”27
Kossiakoff and Sweet\textsuperscript{22} treat risk as implicit in and integral to the nature of systems engineering, which they embed within the purview of project management (this differs structurally, although not substantively, from Stevens \textit{et al.}\textsuperscript{40}). The overlapping area is of particular interest, as it encompasses both risk management and customer interaction; in other words, managing risk and addressing customer requirements are functions of both systems engineering and project planning and control.

Systems engineering tasks include the activities of the systems engineering staff in guiding the engineering of the system through all its conceptual and engineering phases. This specifically includes activities such as requirements analysis, trade-off studies, test requirements and evaluations, system design requirements, configuration management, and so on, which are identified in the systems engineering management plan. Another important activity is the integration of specialty engineering into the early phases of the engineering effort, in other words, concurrent engineering.\textsuperscript{22}

The expectation is that the level of risk will decline over time through progressive states of system development; this is critical because at each of these stages, the cost of mitigating risks increases. It is important to note that this is not a naturally occurring phenomenon but the result of effort invested in scientifically based analysis and decision-making. In other words, it can be expected only when it is deliberately addressed through the expertise of reliability, safety, and human factors engineers, among others.\textsuperscript{22} Properly carried out, risk assessment eliminates alternatives based on untested or unproven technologies and approaches; identifies “the weakest and most uncertain features of the design;”\textsuperscript{22} and apportions time and effort among identified risks.

To compare the potential importance of different sources of program risk, it is necessary to consider two risk components: the \textbf{likelihood} that a given component will fail to meet its goals, and the \textbf{impact} or \textbf{criticality} of such a failure to the success of the program. Thus, if the impact of a given failure would be catastrophic, even a low likelihood of its occurring cannot be tolerated. Alternatively, if the likelihood of failure of a given approach is high, it is usually prudent to take a different approach even if its impact may be low but significant.\textsuperscript{22}

As noted above, cultural factors contribute to the way in which members of an academic discipline, organization, or community approach risk and risk management; the optimal approach is a combination of tight and loose coupling among elements (think of the trusses and their roles in raising the building, supporting its structure, and resisting fire) that is impossible to achieve in practice.\textsuperscript{25, 27} “[T]echnology cannot be made safe by adding extra safety systems, for that only increases its complexity and creates more ways for something to go wrong.”\textsuperscript{27} Risk management remains what it will always be, an inexact science to the extent that it is scientific at all.

There is no such thing as a perfectly rational approach to risk. Engineers hate to admit that, but it’s true. Every judgment about risk, even those made by scientists, reflects the culture in which it was formed.\textsuperscript{27}

The original risk analysis conducted on the design, structure, and materials for the WTC towers included whether they could sustain the impact of a medium-sized airliner, perhaps lost in
fog while trying to land at an airport. Despite this, the towers collapsed following such an impact. Civil, structural, and fire protection engineers, as well as engineers trained as project managers, were assigned to investigate why this happened. The students’ role in this workshop was to take the roles of those various engineers and try to see through the lenses of different disciplines.

Problem statement, getting started, and reporting out

The problem statement arises from Ground Zero being also substantially a gravesite. The efficient use of the property to provide needed office and other commercial space that would normally be the focus for rebuilding after a deliberate, remarkably accident-free demolition is therefore only one, and not necessarily the first, consideration in the reconstruction plans. The site’s nature as a cemetery is not symbolic but real, and the family members of the World Trade Center dead express their concerns clearly and urgently.

A group of relatives of people killed in the Sept. 11 terrorist attacks on the World Trade Center said several structures being built at the site encroach on the footprints of the twin towers. . . . “We’re doing everything possible to respect the footprints, but we cannot compromise safety,” Greg Trevor, a spokesman for the Port Authority of New York and New Jersey, said.

The victims’ relatives have said they feel that the footprints of the towers are sacred, and that they want them to remain free of new development. Some questioned whether the structures would be temporary and said they believe rebuilding officials could have worked around the footprints.\(^1\)

We suggested to the students:

Imagine that you are a member of the firm with the winning bid to rebuild the WTC. You have access to all the information available to the FEMA/ASCE teams, as presented to you here. The requirements include, but are not limited to, providing equivalent office and retail space to that in the original towers. The constraints include, but are not limited to, the desire of the victims’ families that the new building’s design be respectful of their loved ones’ remains. Using the template (which you may modify as needed) of the systems life cycle, propose how you would design the new building, demonstrate to prospective new and returning tenants that it will be safe for them to occupy it, and satisfy the families that the sacred character of the site has been respected.

Then, to help them get started, we suggested:

First, form two teams (9 members/8 members) in order to reflect the membership of a systems design team. Designate a leader – the systems engineer (you can take turns playing this role). Other members are: two structural, two fire protection, and two electrical engineers, and user representatives (assume that the users are the developers and owners of the prospective building). Substitute or add other disciplines as desired or appropriate. Then, using the life cycle chart below as a basis, sketch a plan for the new WTC from design to installation and validation; at each stage, focus on identifying and
assessing risks. You may know more than you think you do, but remember, you don’t need to have any expertise or experience with the content of “your” disciplines; you can guess at or even invent facts, and you don’t need to limit yourselves to numerically- or empirically-based data. Systems engineers generally prefer not to quantify risk, as this may artificially minimize or inflate actual risk. This is an advance over the historical position that

[risk] was considered a technical issue, one best left to the experts. And for the most part, the engineers agreed. Risk was a question whose answers could be found in facts and figures, in engineering calculations and materials testing.

Remember also that risk is shared equally among all of the members of the team, so don’t base your choice of role on how little trouble you think your decisions are liable to get you into. However, your understanding of your personal learning style is a valid basis for deciding you would be effective in a particular role. Next, discuss your relationship and responsibilities to the stakeholders – including, but not limited to, bereaved families. How do the risks impinge on each stakeholder or class of stakeholders? Finally, ask yourselves:

- When is an engineer a manager?
- When is an engineer not a manager?
- Do you believe that the design and management functions (an oversimplification) are distinct from one another?
- How similarly, and/or how differently, do engineers and managers approach risk analysis and decision-making?
- Are their approaches primarily cooperative or adversarial?
- Who is in the best position to synthesize facts and probabilities?
- How would you distinguish engineering management from systems engineering?

We left the choice of how to report out or present their recommendations to the teams’ discretion, as long as they attempted to think about the above questions and incorporate at least some of them in how they would respond to issues of risk and trust in rebuilding on or near the WTC site. As with the Kissimmee/Everglades exercise, we provided a conceptual table:

<table>
<thead>
<tr>
<th>System life cycle</th>
<th>Stages of WTC site development</th>
</tr>
</thead>
<tbody>
<tr>
<td>User requirements</td>
<td>(Identify all stakeholders [may not be limited to users])</td>
</tr>
<tr>
<td>System requirements</td>
<td>(Including, but not limited to, office and other commercial space needed; costs and other constraints)</td>
</tr>
<tr>
<td>Architectural design</td>
<td>(What is the distinction between system architecture and structure architecture?)</td>
</tr>
</tbody>
</table>
| Integration & verification | (From your disciplinary perspectives, address these questions:  
- What do you know?  
- What do you need to know?  
- How will you find it out?  
Then, synthesize the answers across disciplines) |
| Installation & validation | (What do you expect your research to have demonstrated?) |

Source: Stevens et al. 1998, pp. 8-9
Lessons Learned and Future Plans

From the beginning, we tried hard to convey to the students how important their critical comments and suggestions would be to the continuing development of the workshops in subsequent years. We noted that as graduate students or professionals, they might find themselves, as experts, invited to talk to future REU students, and that we looked forward to learning with and from them.

How close the students felt to the topic helped to determine how successfully they engaged the problem; the other key determinant was how clear we made our own expectations, and how much time we gave them to prepare. In an effort to make the experience low-key, and not impose a homework assignment, we did not pass out the material on the Kissimmee/Everglades case until we actually convened for the workshop; the students told us afterward that while they understood the goal, they would have appreciated being able to read the material at their leisure beforehand, and we applied this lesson to the World Trade Center workshop.

Student comments were also divided between wanting more facilitator control and enjoying the more relaxed design, that is, between being told what to do and figuring out how they wanted to proceed on their own, which was our intent. Teachable moments occur with engaged students even in unlikely circumstances, and the facilitator was able to take advantage of one team’s ridiculous plan to train alligators to intimidate (non-lethally) the reluctant homeowners of the 8.5 Square Mile Area into agreeing to accept the buy-out. Even this silliness revealed students’ identification of the homeowners and their intransigence as a problem to be overcome by any means, including the threat of violence. It also challenged her to recover the discussion and keep the workshop on track, and it reminded us that sensitivity to social concerns is not acquired in a day. The students were able to see and acknowledge their view of human beings as obstacles, and to explore other ways of seeing the homeowners and their problems.

A notable missed opportunity was revealed when students did not specifically consider the various impacts of large-scale engineering projects on communities of color. We attribute this to our own failure to ask them directly to address it; they had previously shown they were sensitive toward and willing to engage diversity issues in an unsentimental, intellectually honest way. In subsequent iterations of the workshops, we will be explicit and intentional in our expectation that students explore issues of who owns and is displaced from property taken for environmental and construction projects. Although Cuban Americans in South Florida are a politically formidable force, and therefore a relatively protected group, it is not inconsequential to the discussion that a Latino neighborhood is marked for sacrifice; the WTC site is twice (and possibly more times) a burial ground, but in earlier cases has not been held sacred but to relegated to part of New York’s archeological record. We would like students to consider whether environmental racism can be embedded even in environmentally desirable projects as well as in waste dumps and incinerators. This will produce a richer, more reflective discussion than generic, ostensibly “color-blind” references to “homeowners,” “shopkeepers,” etc., and fulfill our objective of infusing diversity in the workshop content.
The World Trade Center workshop drew the students’ full attention, because the subject commanded their complete respect. Despite having read about other instructors’ experiences “teaching to” the 9/11 attacks, and bringing our own feelings to the project, we did not know what to expect. The facilitator began the session by telling them that if it was too much for them they would be excused; they watched “Why the Towers Fell” in silence, and some of them cried. They seemed to be very much moved by, and to identify with, the anguish of Leslie Robinson and the other engineers who designed and built the WTC, as well as with the victims. They spent the rest of the day completely absorbed in addressing safety concerns, and their discussions were animated but intense.

We did not explicitly relate the issues involved in rebuilding at Ground Zero to engineers’ professional ethics; this was not wholly an oversight on our part. First, we were reticent about venturing into still-raw emotional territory. Second, we were wary of giving students the impression that in encouraging them to think about the proximate cause of the collapse, we expected them to assign blame and fault. They did, in fact, wish they knew a way to comfort Robinson and his colleagues, and moreover, they did not think this humane impulse was incompatible with a clear-eyed examination of causes. Therefore we believe we gave up an advantage; the students’ design ideas were informed not only by their major disciplines but also by the kinds of questions they had about the WTC following the reading and video presentation. We believe their responsiveness created an opening to a discussion of professional responsibility that we will develop in future iterations of this workshop.

Overall, however, we believe we made a promising start with the workshops, and the students corroborated this in their evaluations of the program. We had presented the workshops as a significant part of the program in both our proposal and our recruiting materials, and several of the students had indicated that they were part of the program’s appeal. The 2003 REU students were also an extremely good-natured, cohesive group who were demonstrably willing to collaborate with both us and their colleagues. There were no class clowns or slackers; the alligator team spent as much time on the structure of their plan, setting out the steps in training their saurian enforcers, as did those who worked out sober, socially appropriate solutions. Working with these young adults for 12 weeks enlarged and deepened our own understanding of, and respect for, the interests and capabilities of a diverse group of undergraduates.

The 2003 students unanimously recommended repeating the WTC workshop, and most recommended keeping the Kissimmee/Everglades workshop as well. We plan to update and upgrade both, and (with the students’ encouragement) add a third on the loss of the Columbia Space Shuttle; we will also include as guest speakers some of the writers on whose work we have relied so extensively. A facilitator version of the workshop text is also being developed, so that others will be able to use design and materials, with their own modifications. Ultimately, new knowledge, unfolding events, and further student contributions will ensure that the “Social Consequences of Design” workshops continue to be a challenging and absorbing element of our own REU program as well as be transferable beyond it.

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