CONSTRUCTION AND THE ENVIRONMENT: RESEARCH FOCI FOR A SUSTAINABLE FUTURE

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ABSTRACT

A workshop was sponsored by the National Science Foundation that united many professionals and researchers from both the construction and the environmental fields to outline initial recommendations regarding the interaction of the built environment with the natural environment to develop research foci for a sustainable future. The workshop entitled Construction and the Environment: Research Foci for a Sustainable Future *produced a final report identifying three main research focus areas:*

1. *Data collection and monitoring of the impact and effectiveness of sustainable construction with the development of ubiquitous sensors and monitoring devices.*
2. *Development of improved or novel construction materials with a focus on the full life-cycle of these materials. Included with this would be a national program for information collection and dissemination.*
3. *Development of decision making tools and models. These models should include both sustainable designs incorporating human factors and also models representing the interactions between the natural and built environment. The intention is to develop methods that reduce negative interactions and promote positive ones.*

All these research foci must include a widespread educational component and should embrace substantial collaborative efforts between the social, physical and applied sciences and engineering communities, as well as the construction industry, government agencies and regulatory communities.

BACKGROUND AND INTRODUCTION

The construction industry is a significant contributor to the economy of the United States: by most estimates, it generates about $879 billion dollars in annual revenue and directly employs approximately 7 million people (US Census Bureau 2000, US Department of Labor 2002). The construction industry creates the physical infrastructure for the nation that forms the foundation of economic activity and other essential activities in our lives. By some estimates, the structures produced by the construction industry represent over 62% of the nation's wealth. Therefore, continuing improvements in the efficiency and productivity of the United States construction industry can have significant impact on the national economy. However, the deleterious impact construction has on the surrounding environment is well documented. Research must be conducted to develop new means to minimize these impacts.

The workshop entitled *Construction and the Environment: Research Foci for a Sustainable Future* was conducted on January 13-14, 2005 on the campus of the University of South Carolina in Columbia, South Carolina. The workshop was co-sponsored by the Civil and Mechanical Systems (CMS) and the Bioengineering and Environmental Systems (BES) Divisions of the Engineering Directorate of the National Science Foundation (NSF). The overreaching goal of the workshop was to unite the construction, civil engineering, and environmental engineering groups in academia and connect them with industry, related industry groups, and regulatory agencies to develop a 'construction and the environment' research plan for the future. The two-day workshop allowed for the interaction of concerned professionals over critical topics facing the construction and civil engineering research communities as they focused on environmental protection and future sustainability issues.

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The objective of the workshop was to produce clear recommendations for future research in the area to include suggested timelines and prioritization of these research efforts. This report will not only aid the National Science Foundation in developing a strategy for its research agenda, but it will also serve as a tool for other organizations interested in promoting and conducting new research in these areas. The workshop aligned its approach with the goals of the *Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century* report (NSF 2003), for it brought together diverse groups of academics, government officials, regulatory agencies and private organizations to define key research areas that affect the future progression of construction practice, with a focus on environmental impacts at all phases of construction.

The goal of the report was to lay the foundation for the beginnings of a new research agenda focused on construction and the environment that can be implemented by the National Science Foundation. The shaping of research priorities for the future is critical to advance the current state of practice in environmentally sensitive construction. The workshop provided the basis for further research and education into such areas as the novel use of highly sensitive sensors in construction and monitoring, innovative on-site storm water management, and construction utilizing improved eco-materials that are currently unavailable. These areas are emerging research fields where currently collaborative efforts remain traditionally focused, without seeking input from a broader intellectual base to include the social sciences, the natural sciences and other anthropogenic related fields. To facilitate this broad focus, the workshop attendees were composed of a diverse set of academics, industry professionals and community leaders encompassing a wide range of intellectual expertise including the regulatory and implementation viewpoint on the issues discussed.

In addition to direct benefits to both the environment and the construction industry, the workshop aided in developing an understanding of barriers to realizing the benefits of such collaborations and the diffusion of the ideas generated into diverse industry sectors. Valuable insights in balancing research and educational activities were developed. The research plan produced by this workshop will have profound effects on the research community for the next decade. One of the thrusts of the workshop was to synthesize the research agenda with an education effort. This will assure the availability of a workforce ready to embrace environmental issues in the construction industry and become "champions" of environmentally sound construction. As the field matures, information disseminated from these research programs will work its way into classrooms and texts, leading to an engineering workforce educated in this field and more sensitive to issues related to construction and the environment.

OBJECTIVES

National Science Foundation representative and cosponsor of the workshop Richard Fragaszy, Program Manager, Geomechanics and Geotechnical Systems Civil & Mechanical Systems Division addressed the group and challenged them to develop cutting edge new research agendas and ideas, while asking bold new questions. He highlighted the fact that the NSF is currently not funding this type of research primarily because this field is viewed as one that incorporates a lower level of technology and that there is no vocal research community.

Workshop Breakout Sessions

The first day of the workshop, participants were assigned to groups based upon their expertise and their research areas of interest. These small groups were assigned specific areas of research to discuss and develop a list of potential future research topics that would advance the state of the art of the current knowledge base in that field. Group members identified critical issues facing researchers, industry professionals, and communities and brainstormed around these themes. Facilitation of the groups was provided by workshop committee members and student volunteers who were responsible for taking notes as the groups developed their strategies. This ensured that all of the discussed issues were captured for possible use within the final document. The group moderators then developed summary documents of their groups' suggestions and ideas, which were then presented to all workshop participants for further discussion and idea generation. Table 1 summarizes the breakout sessions held on the first day of the workshop with a very brief list of some of the main discus-

TABLE 1. Summary of Breakout Sessions Day 1

Session	Moderators	Students	Participants	Main Topics
Infrastructure (Roads, Pipelines)	R. Corotis C. Hendrickson	A. Sharrard A. Horton	I. Adiguzel, S. Bae D. Castro-Lacouture J. Easley, K. Gardner K. Janoyan, S. Matthews T. Van Dam, R. Nichols A. Scanlon	Sensors Energy Interdisciplinary Nature Functionality
Stormwater Infrastructure	A. Davis H. Inyang C. Fiori	F. Montes C. Brakewood S. Nunez	H. Landphair P. Lederer, M. Akram M. Darwish, G. Filz	Quality & Quantity Materials & Design Sensors & Metrics SocioeconomicS
Residential Housing	L. Haselbach C. Boyle A. Horvath	E. Piggott S. Beheiry	T. Rogers, D. Eisenberg D. Liou, B. Luke A. Pearce, J. Vanegas	Roadmap: Sustainable Economic & Sociopolitical Regionality Cultural Barriers Coupled Built Systems
Construction Materials	C. Hendrickson L. Haselbach	A. Horton F. Montes	D. Castro-Lacoutrure K. Gardner, D. Liou A. Scanlon, T. Van Dam J. Vanegas	Less Consumption Novel/Smart Materials Monitoring, LEED® Lifecycle Analyses
Impact of the Construction Phase	A. Davis H. Inyang C. Fiori	E. Piggott A. Sharrard	I. Adiguzel, S. Bae J. Easley, G. Filz H. Landphair, R. Nichols	Socioeconomic/Legal/Political Environmental Impacts Equipment Alternate Fabrication In-situ Treatment
Quality of Life (QOL): The Built Environment	R. Corotis A. Horvath C. Boyle	C. Brakewood S. Nunez S. Beheiry	D. Eisenberg, K. Janoyan P. Lederer, B. Luke S. Matthews, A. Pearce T. Rodgers	Innovative Use —Underground Space —Biological Systems Classifying Risk Defining QOL Community Issues Long term Design
Lifecycle Costs: Construction Phase	A. Davis C. Fiori L. Haselbach	A. Horton S. Beheiry	I. Adiguzel, M. Akram M. Darwish, T. Van Dam K. Gardner, K. Janoyan S. Matthews, A. Scanlon	Incorporating Sustainability into Design/Construction/ Demolition Risk Analysis, Modeling Tools Metrics/Quantification Collaboration
Lifecycle Costs: Materials and Facilities	R. Corotis C. Hendrickson A. Horvath	C. Brakewood S. Nunez E. Piggott	I. Adiguzel, M. Akram M. Darwish, T. Van Dam K. Gardner, K. Janoyan S. Matthews, A. Scanlon	Performance Risk Benefit/Cost Determinations LEED® Type Methods
Regionality and Global Issues	C. Boyle H. Inyang	F. Montes A. Sharrard	D. Eisenberg, P. Lederer D. Liou, B. Luke R. Nichols, A. Pearce T. Rogers, J. Vanegas	Traditional vs. New Methods Cultural Understanding Multiple Stakeholders Transnational Network Energy, Economics, Standards and Technology

sion topics. Educational issues were discussed in all breakout sessions.

The first day concluded with a combined session to summarize the needs and focus areas for the second day. The results of the first day identified common themes that participants were interested in discussing further. The consensus of the group was that there is no one definition of sustainability. It is context sensitive. Participants also agreed that to develop any type of successfully implementable research agenda, it must include a rather broad perspective. The research must be collaborative in nature, drawing on the expertise of other fields and adapting scientific research work already completed into the built environment. There is also an underlying need to make improved and informed decisions when it comes to the ultimate impact of the built environment on the natural environment. Because of the high level of interaction with the public regarding any issue surrounding the built environment, extensive understanding of human factors must be incorporated into the research as well as consideration given to the economic, social fabric, political climate, and regulatory nature of the topic being researched. In order to accomplish this successfully engineers and scientists must shift their traditional research paradigms to embrace these other disciplines and their input to the research conducted. The feedback that is necessary for successful use of any new research is from the end user of the product. If the product will not be used, or if there is a lack of sufficient evidence that the intervention or new product or process is within code, meets required regulations or does not offend a particular socioeconomic group, it will remain just a good idea. This does not meet the NSF goals for broader impact on society. The research conducted must influence a broad spectrum of individuals and consider the overall benefits to the public in general. Each group also emphasized that education is the critical component of whatever research direction is taken. This includes integration into curriculums from K-12, undergraduate and graduate programs and education of the professionals making decisions regarding design and use of materials, along with regulators and code writers who may not appreciate the sensitive nature of the built environment-natural environment balance from a broad sense. With all of this in mind, the group had yet to develop any bold new questions, so the focus of the workshop shifted. The moderators challenged the workshop participants to develop a bold new research project/idea that included the challenge of the creation of a balance between the built and natural environment. Their focus was to view the issues 20 years into the future and set no boundaries or limitations on their ideas. These were meant to be out of the box, ground-breaking, edge of experience ideas that NSF would typically fund.

Throughout the first day, the group identified issues and problems that exist in the industry and then focused on asking interesting questions about how to solve those problems. The first morning session on the second day developed themes for the 'bold and new' research areas from participant ideas. Each participant then went to the breakout session that interested him or her the most. This enabled the researchers to discuss ideas with like-minded individuals, thereby facilitating the goal of the workshop which was to generate research related conversations amongst diverse individuals with varying expertise. The workshop laid the foundation for multiple new working relationships between people who would have otherwise never have had the opportunity to interact.

The topics used for these breakout sessions fell into six broad categories, five of which are listed in Table 2.

The sixth category was educational needs, a resounding theme throughout the workshop. The education efforts which were determined to be needed for sustainable construction include:

- Professor development and training, to include the building of laboratories for sustainable technology
- Undergraduate integration throughout the entire engineering and construction curriculum
- K-12 "Engineering Academy"- Introduction to sustainable ideas at an early age
- Education for Contractors
- High school: Integration across the curriculum
- Modules that meet current curriculum requirements and needs
- "Consciousness Raising" at all levels of the public/private sector
- Professional Organizations/Societies Continuing Education

TABLE 2. Summary of the Breakout Sessions on the Second Day

Topic	
Building Materials	National research center & web-based access to information Easily accessible decision support methods Standards development High tech sensors and materials Low tech or traditional material use/re-adaptation Plastics & Polymers: Petroleum versus other raw materials Novel concrete research New adaptive, smart, and multi-purpose materials Lifecycle analyses of materials: Initial cost concept challenges Regionality analyses of materials New ideas in residential construction: multi-system, multi-functional
Modeling and Metrics	Modeling Processes Data Needs & Metrics Modeling Decision Making
Resources and Land Use Planning	Construction Equipment Redesigning transportation infrastructure Pollution including noise pollution Alternative fuels (biomass, etc.) Stormwater
Data Acquisition, Monitors & Sensors	Functionality of structure over time Innovative sensors and their lifecycle Phases to monitor (construction/operational)
The Future (Vision 2045)	Steady state communities: Mixed use layouts Integration of nature and the built environment High quality of life: Ecological and human health Information rich with virtual reality capabilities, wireless, and 'moneyless' system of commerce Transportation infrastructure needs: cars/mass transit/alternates Decentralized infrastructure: water (storm/potable) energy, waste Adaptation to population growth and cultural dynamics

- Filtering of Relevant Information and Data (Instead of a system overload)
- Teach what people practice, practice what we teach, and teach what we research
- Reconciliation of the varying "depth" of multi-disciplines
- "Trans-disciplinary" approach to education by development of an exciting environment
- Integration of education
  - Humanistic side of education
  - Social, philosophical, and other social science classes
  - Cultural undergraduate education
  - Innovation and creativity
- Graduate level coursework and curriculum

Workshop Closure and Summary

The workshop ended with a joint session of all attendees and Rick Fragaszy addressed the group. He stressed that NSF needed to hear from the construction industry group. Traditionally funding has not been large in this area due to the lack of a vocal research community. The workshop served as a connection for individuals within these research areas to discuss ideas and develop a stronger, more vocal group. The workshop also led to the identification of the fact that other workshops should be held to continue the dialogues that were initiated here with a more specific focus in order to develop specific research priority areas.

WORKSHOP OUTCOMES AND RECOMMENDATIONS

Throughout each breakout session there were overarching themes that surfaced throughout the discussion. While each session addressed specific areas of sustainability from various viewpoints, there were critical research areas that dominated the discussions in each breakout session. These critical areas or themes are summarized below and include:

- Sensors and monitoring devices
- Novel or improved construction materials
- Decision making tools and models of sustainable issues and interactions between the built and natural environment
- A need for education at all levels
- Collaboration amongst various disciplines

Sensors and Monitoring Devices

One of the NSF goals within the area of nano-technology involves the development of new instrumentation and standards, particularly for imaging, characterization and manipulation of materials and systems in three dimensions at the nanoscale. The development and implementation of sensors and monitoring devices is a critical area that was identified throughout the workshop breakout sessions. Development of sensors to aid in the improvement of the planning, design, construction and maintenance of infrastructure, industrial, commercial and residential construction efforts is paramount. Additionally, new and innovative construction methods and materials, byproducts of construction such as stormwater, emissions, and pollutants will also require novel, disposable and innovative sensor adaptation and development.

Specifically, there is a need for inexpensive, widespread sensors so that conditions can be monitored and structures can be built and operated more efficiently. Sensors deployed in this environment must be wireless, nanoscale, ubiquitous, and sustainable as they will operate in a hostile atmosphere. The needs of these sustainable monitoring devices must be assessed in light of the differing scales of the built environment in both space and time.

The ability to continuously monitor structures of all types so that critical sustainability data can be collected is another key issue raised by workshop participants. Sensors must be integrated at all phases; pre, during, and post-construction. The sensors would function as part of a monitoring system that is required to identify a problem, determine the parameters, determine the magnitude, and input information into a decision-making process. Sensors need to automatically supply data for response systems of built structures to include materials and energy systems, structural condition assessment, environmental monitors, material handling and mixing, sedimentation and contamination, and storm-water.

The research should focus upon the technologies and underlying science that would support the adaptation of sensing systems to the built environment. These areas include biomechanical, isotope geochemistry, nano-sensors, and light sensor/optical materials. Additionally, the enabling technologies that must be included within sustainability research include power supply, data transmission, calibration, benchmarking, durability, and cost.

Novel or Improved Construction Materials

Throughout the workshop sessions the issue of novel and new (or improved) materials that would reduce the consumption rate of natural resources, maximize efficiency of construction, and have low environmental impact in their production, life and disposal was identified as a priority area. This would be accomplished by the design and synthesis of new, or newly rediscovered materials with environmentally benign impacts on bio-complex systems and maximizing efficient use of individual materials throughout their life cycles. Sustainability research related to materials must consider the material properties, the source of the raw materials, the process to produce the material, the installation process of the material, usage of the material, the material degradation process, the potential recovery and re-use, and ultimately final disposal of that material.

Novel areas of materials research includes the science behind the use, the development, the discovery or the adaptation of biomimetic materials, rapidly renewable materials, or abundant, public domain materials such as earth/soil construction. Possible avenues include biological alternatives or new materials that absorb contaminants produced during the life cycle of the built environment. There is a need for the development of smart materials. These materials may be embedded with sensors for quality control and maintenance or change colors or other properties in response to changing environmental conditions. Fundamental research is also required in substitutive materials for emission controls that will help to avoid the loss of soils, production of dust and pollutant migration from construction sites.

These ideas and goals are also in line with those expressed by the NSF area of bio-complexity in the environment in light of the fact that the interaction between the built environment must be considered as part of the overall analysis. Common themes include the development of new methods, models, theories and strategies for understanding complex environmental systems; new tools and infrastructure for interdisciplinary and collaborative research; and the fact that the integrity of ecosystems is inextricably linked to human well-being. Fundamental study of complex environmental systems is critical to the development of new ways to anticipate environmental conditions and improve decision-making in the use and development of new construction materials.

Large quantities of concrete are used within the built environment and this material received a high level of focus from the workshop participants. Identified research priorities relating to sustainability and concrete include minimization of the use of cement in concrete structures by increasing the use of naturally occurring cement materials such as rice husks and volcanic materials or discovery of other substitutes for Portland cement within concrete such as polymers.

Other areas identified during the workshop involve fundamental research into the categorization of materials, the improvement of material life cycles, the use of water as a construction material, the development of a product label that illustrates the sustainability level of the material and research that demonstrates use of novel materials in response to a hypothetical shortage of resources.

Finally, in order to facilitate materials research and optimize the information dissemination and research opportunities, participants would like to see a program to develop a sustainable materials clearinghouse at a national laboratory or collaboratively at several laboratories/research centers.

Decision Making Tools and Models

New mathematical tools are needed to understand the algorithms that provide decision-making tools for sustainable construction information systems and enhance understanding of environmental decision-making. These decision making tools must incorporate a component of data that considers human decision making needs when it comes to making sustainable decisions.

Workshop participants identified a need for the creation of models that incorporate all sectors and stakeholders relating to the built environment, institutional barriers associated with these sectors and stakeholders, and the development of transitional strategies to making fiscally sound decisions based upon a tightly coupled system between the built and natural environment. The models must focus on the process itself and highlight the consequences of decisions made early in the building design process. The models should be forecasting tools to optimize dollars and must incorporate the risks that are outside the field of view of the people who are making the decisions and bring them to their attention. The models must include an element related to risk and the human factors associated with such risks and the interactions between the built and the natural environment. Priorities in this area are strongly aligned with the human and social dynamics division of NSF to include the improving of decision-making in an uncertain world by studying risk perception and response to stimuli and enhanced research on decision-making and human environmental behaviors.

The research goals associated with the decision making tools required for a sustainable future are also tightly coupled with the goals set by the mathematics division of NSF. Both groups have identified as priority areas the development of new analytical, statistical, computational and experimental tools to tackle a broad range of scientific and technological challenges long considered intractable. The interaction between the natural and built environment is a complex nonlinear system with challenges posed by large data sets and varying data streams in which managing and modeling uncertainty is paramount for critical decision making that will impact the quality of human life.

In order to make these models robust, data is required. A dynamic mechanism that accomplishes identification, acquisition, generation, filtering, processing, storing, retrieving, implementing, and updating of data, sustainable product information, best practices, and lessons learned must be developed to capture the data necessary to populate the desired models.

In addition, these decision making tools and models must include human factors. Viewing the sustainability question in light of construction and the impact it has upon the environment, there must be an advancement in the understanding of human and social changes that cross cultural, political, environmental, economic, and technological boundaries. This will enable us to better understand and anticipate many aspects of change, including its consequences, its human causes and responses, and how human and social behavior changes over time, thus helping us to better manage profound or rapid changes in the environment. The world faces significant scientific and societal challenges, including the prospect of rapid environmental and climatic change and the complicated question of long-term impact upon the environment based human decisions. Applying state-of-the-art methods and cross-disciplinary approaches to better understand the dynamics that influence human behavior and action when it comes to selection of materials to build with, land to develop, and facilities to purchase is paramount to any research effort.

Education

Research must be completed to develop an appropriate pedagogy and curricula that includes accreditation for enabling teaching and learning in sustainable communities, facilities, and civil infrastructure systems within the total education pipeline. This includes formal education at the following levels, K-12, Undergraduate, Masters, Doctorate, and profession education and informal education of the public through seminars, workshops, discussions, and readily accessible web-based materials.

There must be an integrated environment for education, research, and practice within related disciplines in which we teach what is practiced and what is researched; we research what is practiced and what is taught; and we practice what is taught and what is researched. By developing education methods and tools for this purpose, we ensure that sustainability issues are addressed at all levels of learning.

Curricula must also be developed that fosters teaching and learning environments that enable students to experience not only a discipline-focused education, but one that embraces multidisciplinary, interdisciplinary and trans-disciplinary viewpoints. This is critical in developing a workforce for the future that embraces all aspects of problems and issues in attempts to solve global issues.

Collaborative Research

In addition to these general research themes, it became quite clear that the research efforts must be completed within an interdisciplinary framework due to the nature of the issues and the depth to which they impact society. This type of research is not traditional in nature, for although some engineering disciplines are forced to collaborate with other sciences on issues, the topic of sustainability spans a vast variety of the social, physical, and applied sciences as well as engineering, business, and legal disciplines. The research must also include regulatory agencies and industry users in order to successfully implement any changes, innovations, or developments resulting from the research. This conclusion is nothing new and innovative, but it further reinforces the concepts and ideas that have been developed at other workshops, intellectual forums, and previous studies (NSF 2003).

The workshop participants all agreed that any research completed in the sustainability area must be addressed in an interdisciplinary way: civil, mechanical, electrical, computational science, as well as bio, medical, and social sciences must work together. Information must be used more effectively to reduce the need for a “one size fits all” solution for local problems and the focus must be on a global scale. This focus meshes extremely well with the human and social dynamics and bio-complexity in the environment research areas within NSF. Both areas recognize that new knowledge develops concurrently with its human and social applications, so the knowledge and its application must be studied as interdependent pieces of a whole. A research agenda for sustainability must be built upon new methods, data, and technologies that span a multitude of disciplines. This includes the adaptation of technologies already in use within other disciplines to help solve built environment issues. Other possible alignments within NSF priority areas include mathematics, the physical and social sciences, and engineering. These integrations are critical to the success of the new research agenda.

Recommendations

In order to facilitate a more sustainable future for construction, it is recommended that the NSF focus research into three specific areas:

1. Data collection and monitoring of the impact and effectiveness of sustainable construction with the development of ubiquitous sensors and monitoring devices.
2. Development of improved or novel construction materials with a focus on the full life-cycle of these materials. Included with this would be a national program for information collection and dissemination.
3. Development of decision making tools and models. These models should include both sustainable designs incorporating human factors and also models representing the interactions between the natural and built environment. The intention is to develop methods that reduce negative interactions and promote positive ones.

All these research foci must include a large and widespread educational component. Included would be efforts at K-12, higher education, and public education. Also, because of the nature of the topic, each research area should embrace substantial collaborative efforts, even across fields that do not traditionally do collaborative research.

Therefore, in order to move forward with this research agenda, it is recommended that NSF fund a second, more focused workshop on Construction and the Environment. This workshop would concentrate specifically on these three topic areas. The workshop would engage and unite the construction and environmental research communities. The result of this focused workshop would be to establish specific research thrusts, set priorities, establish timelines, and recommend funding levels. Target benefits and outcomes from this research initiative would be discussed. Ideally, a specific set of RFPs would be produced.

Without this research, land development and construction will continue to press forward in haphazard bounds. Population increases and growth stresses have never been greater. With advances in analytical technologies, we continue to learn of negative impacts on the environment from anthropogenic activities. Without moving forward with a focused research agenda, we can only expect greater deleterious social, economic, and environmental impacts.

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