# Paper 96. Systems Integration for Sustainable Outcomes: A Proposed Curriculum

Gordon Thompson[1]

[1] Institute for Resource and Security Studies (Cambridge, Massachusetts, USA) and Clark University (Worcester, Massachusetts, USA)
*gthompson@irss-usa.org*

## Abstract

This paper outlines a proposed, master's-level degree program that would prepare its students to meet a growing demand. The demand is for engineers skilled in integrating three types of system – natural, human, and manufactured systems – to achieve sustainable outcomes. With those skills, engineers will be sought after to work on the design or appraisal of a wide variety of projects – including infrastructure (water, energy, transport, etc.), buildings, urban plans, and manufacturing centers – that will be needed in the 21st century. Achieving sustainable outcomes of these projects will require engineers who can engage with diverse stakeholders, employ new tools for decision support, conduct adaptive management, and find creative solutions by integrating natural, human, and manufactured systems in novel ways. The proposed degree program would have several features that nurture these skills. For example, the curriculum would engage students in practical, group tasks that run in parallel with theory courses. This experiential approach would connect theory to practice while enhancing capabilities in teamwork, communication, and creative problem solving. The program would begin operating as a two-year, full-time, face-to-face program leading to a master's degree. Later, it may spawn related programs employing online or blended delivery. The program would link students with employers, and would promote its own sustainability by practicing the skills that it teaches.

## 1. Introduction

There is growing recognition that aspects of modern economies must change substantially if our civilization is to be sustainable. Much intellectual work has been done to establish the conceptual, scientific, technical, and institutional basis for the needed changes. The new concepts have been applied in many practical projects. Thus, we are poised for a rapid, socio-technical transition to sustainability, waiting only upon general acknowledgment that the prevailing economic paradigm is inadequate. An important part of the transition will be the design or appraisal of a wide variety of engineering projects – including infrastructure (water, energy, transport, etc.), buildings, urban plans, and manufacturing centers – whose purpose is to yield sustainable outcomes. In that context, experience to date in the quest for sustainability has yielded a key lesson. Each project must integrate the functioning of three types of system – natural, human, and manufactured systems.

Engineers who are skilled in systems integration for sustainable outcomes are sought after today. Demand for their services is likely to grow, as the shift to a new paradigm of sustainability gains momentum. This paper outlines a proposed, master's-level degree program that would prepare engineers to meet the demand. The program would draw upon existing curricula. Many institutions of engineering education around the world now offer courses and programs that address sustainability. Yet, there is substantial variation in the themes and topics covered by the existing curricula. Also, a survey of sustainable engineering education at institutions in the USA found that courses tended to address systems with comparatively narrow boundaries, such as a firm or product, with less emphasis on larger or more complex systems (Allen et al, 2008). Thus, a degree program emphasizing systems integration would probably have to break some new ground in curriculum design.

Accordingly, this paper begins by discussing some essential background issues – the need for a new paradigm of sustainability, the practice of engineering in that paradigm, the role of systems integration, the challenges of implementing a systems-integration approach, and means for overcoming those challenges. That discussion identifies skills that the proposed degree program would nurture. The program is then outlined. Detailed design and implementation of the program would be a cooperative endeavor by diverse faculty. Also, systems integration for sustainable outcomes, as discussed here, is a comparatively new field. Thus, the proposed degree program would evolve in parallel with accumulating practical experience in the field, together with progress in research and the development of software tools and databases.

## 2. The Need for a New Paradigm of Sustainability

Science and direct observation provide ever more compelling evidence that we must change our practices if human civilization is to be sustainable. For example, a group of authors examining the "safe operating space for humanity" has said (Rockstrom et al, 2009):

> "The exponential growth of human activities is raising concern that further pressure on the Earth System could destabilize critical biophysical systems and trigger abrupt or irreversible environmental changes that would be deleterious or even catastrophic for human well-being. This is a profound dilemma because the predominant paradigm of social and economic development remains largely oblivious to the risk of human-induced environmental disasters at continental to planetary scales."

Thus, a transition to a sustainable civilization requires a paradigm shift. Moreover, the shift must be rapid. In illustration, government leaders meeting in Copenhagen in 2009 committed their countries to holding the human-caused increase in average global temperature below 2°C. Analysis shows that we would have about a 50 percent chance of meeting that target if global emissions of greenhouse gases peak by 2020 and fall rapidly thereafter. Yet, although accumulating scientific knowledge indicates that a 2°C increase may be dangerously high, there is no plan to achieve the emissions reductions needed to meet that target (Anderson & Bows, 2011).

Even if climate change were not a problem, growth in consumption would be curbed by natural-resource limits. Experience shows that extraction of a unit of fossil fuel requires ever-increasing inputs such as energy and water, with increasing degradation of land and other natural resources. Farms and fisheries require increasing effort and materials inputs to achieve a unit of yield (Davidson & Andrews, 2013). Few government leaders recognize these diminishing returns, because they are not reflected in economic indicators such as GDP. Concepts such as "inclusive wealth" are being developed to correct this deficiency in accounting (UNU-IHDP & UNEP, 2012).

As natural-resource constraints tighten over the coming years, the choice facing humanity will become ever starker. Continued pursuit of the old paradigm would degrade our life-support systems, widen gaps between rich and poor, and promote conflict within and between nations, potentially leading to a retrograde civilization that has been dubbed "Fortress World". Alternatively, we could embrace a "New Sustainability Paradigm" that offers a bright future for humanity (Raskin et al, 2002). Pursuit of that future would create vast opportunity for engineers and related professionals with appropriate skills.

## 3. Engineering in the New Paradigm, and the Role of Systems Integration

During the past several decades, great progress has been made in establishing the conceptual, scientific, technical, and institutional basis for a sustainable civilization. This work has been done in overlapping spheres of intellectual and practical activity that include sustainability science (Kates, 2010), green engineering (Anastas & Zimmerman, 2003), ecological economics (Krishnan et al, 1995), industrial ecology (Jelinski et al, 1992), agro-ecology (De Schutter, 2010), the precautionary principle (European Environment Agency, 2013), renewable energy (Edenhofer et al, 2012), climate stabilization policy (Climate Policy Initiative, 2013), socio-technical transitions (Geels, 2005), sustainable operations management (Kleindorfer et al, 2005), and grassroots action (Hawken, 2007). Within the constraints of the prevailing economic paradigm, these new concepts have been applied in numerous practical projects.

A key lesson from experience to date is that each engineering project must integrate the functioning of three types of system – natural, human, and manufactured systems. With careful design, those systems can function synergistically, so that the outcomes of the project are sustainable. The systems within each type, added together, are collections of capital. Natural capital is the sum of the stocks and flows of pre-human planet Earth and its biosphere. Human capital is the sum of our knowledge, health, institutions, and similar assets. Manufactured capital is the sum of our artifacts. In a sustainable civilization, natural capital would be preserved. Human capital, on a per person basis, could grow without limit. The efficiency and sophistication of manufactured capital could also grow without limit.

Engineers will have key responsibilities in ensuring that natural capital is preserved, while human and manufactured capital grow appropriately. That growth must not only meet present needs, but also preserve and create options for future generations. Thus, projects must be designed to allow reversibility, adaptability, flexibility, and resilience. Designers must also conduct risk management, seeking to identify and prepare for unusual, adverse outcomes. Pursuit of these goals will create great opportunity for engineering entrepreneurs. Over time, our artifacts will use ever fewer material inputs to achieve a given result. Embodied materials will be reused or recycled at end of life. Designers will routinely apply concepts such as life-cycle assessment (SAIC, 2006) and energy return on investment (Gupta and Hall, 2011).

The energy sector is one arena where skills in systems integration are already sought after. Around the world, programs are under way to improve the efficiency of energy use and reduce the environmental impacts of energy production. As part of that trend, interactions among devices, stakeholders, and natural systems are becoming more complex and diverse. An approach known as energy systems integration is being developed to facilitate these interactions (Kroposki et al, 2012). Systems-integration skills are also increasingly important in the buildings sector (World Green Building Council, 2013) and other sectors.

Water management in China is an instructive test case for integrating natural, human, and manufactured systems. China faces a water crisis. Its per capita water availability from renewable sources is about one quarter of the world average, but its consumption per unit of GDP is three times the world average. Two-thirds of its cities have water shortages, 80 percent of its lakes suffer from eutrophication, more than 40 percent of its rivers are severely polluted, and about 300 million rural residents lack safe drinking water. The Chinese government is investing heavily in the water sector, but that investment has, until now, emphasized manufactured systems such as dams. If the water crisis is to be resolved, a more integrated approach will be required, with increased investment in natural and human systems (Liu and Wang, 2012). China's ability to implement an integrated-systems approach will be enhanced if more of its engineers acquire the necessary skills.

## 4. Challenges of Systems Integration, and Means for Overcoming those Challenges

Systems integration, as discussed here, will face substantial challenges. During design and implementation of a typical engineering project, three kinds of challenge can be expected. First, there will be the challenge of <u>technical complexity</u>. Pursuit of sustainable outcomes through integration of natural, human, and manufactured systems will increase the number of technical factors that must be considered in project design, and the range of interactions among system components will increase even more. The resulting complexity could overwhelm traditional processes of decision making. Second, there will be the challenge of stakeholder complexity. The number of stakeholders whose views must be accounted for will increase, as will the range of their perspectives and interests. Interactions among stakeholders will be multiplied. As a result, decision-making processes could become gridlocked. Third, there will be the challenge of paradigm mismatch. The concepts and values of sustainability could come into conflict with the traditional economic paradigm. For example, as a result of friction in the policy realm, monetary prices for project inputs might not correspond to the values dictated by sustainability. Also, centers of entrenched political power could impede appropriate actions. Such phenomena could hinder or warp decision making.

These challenges can be overcome through various means. To be effective, those means must operate within a comprehensive process of decision making for new projects. A suitable process is described here in the context of a larger project. A similar process could be applied to clusters of smaller projects. The process would typically have five phases. First, engagement with stakeholders determines the societal purposes of the project. Second, several design options for fulfilling the agreed societal purposes are identified, each option being an integrated combination of systems whose performance is known. Third, the design options are appraised against a matrix of sustainability indicators. Fourth, iterative engagement with stakeholders refines phases two and three, ultimately leading to agreement on a final design specification. That specification is handed off to specialists for detailed design and implementation. Fifth, the project's implementation and post-implementation performance are monitored, leading to appropriate project adjustments through an ongoing process of adaptive management.

Implicit in this decision-making process is the existence of databases on the performance of engineered projects and their component systems. Much of the performance data would come from the ongoing process of adaptive management that occurs during and after project implementation. The cost of that process would be attributed to the project. Thus, the resulting data could be a public resource, free for all to use. Other data could come from prototypical projects that test new systems. Underlying the databases would be a consensus-based framework of principles and indicators that measure the sustainability of a project's outcomes. That framework would be used for the design, appraisal, and monitoring of each project. The databases and underlying framework would be means that contribute substantially to overcoming the challenges described above.

Data on the performance of available systems would be a key asset for engineers engaged in design and appraisal of new projects. Another, complementary asset would be a suite of decision-support tools, typically expressed in software. Underlying those tools would be "good enough" models of relevant systems (Socolow & Lam, 2007), providing enough detail to assess systems-integration options while avoiding unnecessary complexity. Various decision-support tools are now available. For example, AECOM has created a proprietary tool, the Sustainable Systems Integration Model, which aids the design and appraisal of options for real-estate development (AECOM, 2013). Over time, the number and sophistication of such tools is likely to grow. Stakeholder engagement can become more productive as new tools allow alternative options to be explored interactively, with visual presentation of results. Video gaming technology may make an important contribution (Tucker, 2012).

In this paper the term "stakeholders" refers to all parties involved in, and affected by, a project. High-quality engagement with stakeholders is essential for at least two reasons. First, it can greatly reduce the risk of pitfalls during project implementation. Second, it can build a base of institutional and political support for a project, helping to overcome challenges such as paradigm mismatch. There is considerable experience with stakeholder engagement (Jeffery, 2009), and a corps of experts. Systems-integration engineers would need basic competence in this field, so that they can work productively with specialists.

## 5. Outline of the Proposed Degree Program

The program would begin operating as a two-year, full-time, face-to-face program leading to a master's degree. Later, it may spawn related programs employing online or blended delivery. Throughout the two years, the curriculum would engage students in practical, group tasks that connect theory to practice while enhancing skills in teamwork, communication, and creative problem solving. Theory courses would run in parallel with practical tasks. This experiential approach has been recommended as a model for engineering education (Olson, 2013). It has been used successfully since 2000 in the "Solving Complex Problems" class for undergraduates at MIT (Hodges, 2012).

One of the skills to be nurtured by the program is adaptive management, which involves monitoring each project's performance and adjusting the project accordingly. The program itself would operate on this principle. It would devote effort to placing students in short-term internships and post-program employment. Former students would be encouraged to provide feedback and to help the program adjust so as to improve its performance. Employers would be encouraged to assist the adaptive-management process in a similar manner. One of the indicators of program effectiveness would be the value added to employers' operations by the program's graduates. Where high added value is demonstrated, employers would be encouraged to contribute to scholarship funds, thus enhancing the sustainability of the program.

Pre-requisites for entry into the program would be typical of the skills possessed by many recent graduates in engineering or related fields such as environmental science, with the proviso that some experience with humanities and social sciences would be expected. In theory, the ideal candidate would enter with basic knowledge of mathematics, natural and life sciences, ecological principles, technologies, humanities, social sciences, engineering design, and communication, together with a demonstrated interest in sustainability and the pursuit of practical outcomes. In practice, admission requirements would be flexible, with emphases on motivation, critical thinking, and the ability to learn independently.

The subjects covered in theory courses and practical tasks would cross the boundaries of a number of traditional disciplines. Therefore, the program should be tested first in a comparatively large institution, so that faculty from a range of disciplines would be readily available to provide specialist knowledge. Interactions with diverse faculty would be valuable experience for the students, because engineers practicing systems integration will often need advice from specialists. Faculty could also benefit from these interactions. The subjects to be covered would include:

- Sustainability overview (understanding principles, trends, challenges, & opportunities)
- Defining and characterizing a system (drawing system boundaries; identifying key connections and dynamics)
- Understanding socio-technical transitions (mapping interactions among social and technical systems; identifying factors that promote regime stability or transition)
- Framework for project design and appraisal (understanding principles and indicators that are used to assess sustainability of outcomes)
- Development of design options (accessing a wide experience base; participating in creative problem-solving)
- Accommodating risk & uncertainty (mapping factors that influence risk & uncertainty; characterizing potential outcomes; designing for risk & uncertainty)
- Stakeholder engagement (identifying stakeholders and their relationships to a project; ensuring appropriate engagement)
- Use of decision-support tools (assessing strengths and limitations of tools; modifying or creating tools)

- Project planning and adaptive management (preparing design specifications, schedule, and budget; establishing metrics and process for follow-up during and after implementation)

## 6. Conclusions and Recommendations

There is demand now for the services of engineers who are skilled in integrating natural, human, and manufactured systems to achieve sustainable outcomes. That demand is likely to grow. Thus, there is likely to be a useful role for a two-year, full-time, master's degree program that nurtures systems-integration skills at a high level. Such a program would draw upon existing curricula in sustainable engineering, but would probably have to break some new ground in curriculum design.

The skills needed for systems integration are diverse, and extend beyond the boundaries of a traditional engineering education. Nurturing of these skills could be accomplished by using an experiential approach and by involving diverse faculty in the program. This paper outlines a proposed program and its curriculum. Detailed design and implementation of the program would require cooperative effort by diverse faculty. That effort is recommended, to be based at a comparatively large institution. The effort should be informed by worldwide experience with sustainable engineering education. Once implemented, the proposed degree program would evolve over time, in parallel with accumulating experience and capability in systems integration.

## 7. References

AECOM. 2013. Sustainable Systems Integration Model (Worldwide). http://www.aecom.com/News/Innovation/_projectsList/Sustainable+Systems+Integration+Model+(Worldwide), accessed 18 April 2013.

Allen, D., & eight others. 2008. *Benchmarking Sustainable Engineering Education: Final Report*. December 2008. Center for Sustainable Engineering, Syracuse, New York. http://www.csengin.org/csengine/sub.html?skuvar=147, accessed 13 July 2013.

Anastas, P.T., & Zimmerman, J.B. 2003. Design Through the 12 Principles of Green Engineering. *Environmental Science and Technology*, 1 March 2003, pp 95-101.

Anderson, K., & Bows, A. 2011. Beyond 'dangerous' climate change: emission scenarios for a new world. *Phil. Trans. Roy. Soc. A*, Vol. 369, 2011, pp 20-44.

Climate Policy Initiative. 2013. *The Policy Climate*. Climate Policy Initiative, San Francisco, California.

Davidson, D., & Andrews, J. 2013. Not All About Consumption. *Science*, Vol. 339, 15 March 2013, pp 1286-1287.

Edenhofer, O., & ten others, (editors). 2012. *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, New York.

European Environment Agency. 2013. *Late lessons from early warnings: science, precaution, innovation*. European Environment Agency, Copenhagen.

Geels, F.W. 2005. The Dynamics of Transitions in Socio-technical Systems: A Multi-level Analysis of the Transition Pathway from Horse-drawn Carriages to Automobiles (1860-1930). *Technology Analysis & Strategic Management*, Vol. 17, No. 4, December 2005, pp 445-476.

Gupta, A.K., & Hall, C.A.S. 2011. A Review of the Past and Current State of EROI Data. *Sustainability*, 2011, 3, pp 1796-1809; doi:10.3390/su3101796.

Hawken, P. 2007. *Blessed Unrest*. Viking Penguin, New York.

Hodges, K.V. 2012. Solving Complex Problems. *Science*, Vol. 338, 30 November 2012, pp 1164-1165.

Jeffery, N. 2009. *Stakeholder Engagement: A Road Map to Meaningful Engagement*. July 2009. Cranfield School of Management, Cranfield, UK.

Jelinski, L.W., Graedel, T.E., Laudise, R.A., McCall, D.W., & Patel, C.K.N. 1992. Industrial ecology: Concepts and approaches. *Proc. Natl. Acad. Sci. USA*, Vol. 89, February 1992, pp 793-797.

Kates, R.W., (editor). 2010. *Readings in Sustainability Science and Technology*. CID Working Paper No. 213. December 2010. Center for International Development, Harvard University, Cambridge, Massachusetts.

Kleindorfer, P.R., Singhal, K., & Van Wassenhove, L.N. 2005. Sustainable Operations Management. *Production and Operations Management*, Vol. 14, No. 4, Winter 2005, pp 482-492.

Krishnan, R., Harris, J.M., & Goodwin, N.R., (editors). 1995. *A Survey of Ecological Economics*. Island Press, Washington, DC.

Kroposki, B., & six others. 2012. *Energy Systems Integration: A Convergence of Ideas*. July 2012. National Renewable Energy Laboratory, Golden, Colorado.

Liu, J., & Yang, W. 2012. Water Sustainability for China and Beyond. *Science*, Vol. 337, 10 August 2012, pp 649-650.

Olson, S, (editor). 2013. *Educating Engineers: Preparing 21st Century Leaders in the Context of New Modes of Learning*. National Academies Press, Washington, DC.

Raskin, P., & six others. 2002. *Great Transition: The Promise and Lure of the Times Ahead*. Stockholm Environment Institute, Boston, Massachusetts.

Rockstrom, J., & twenty-eight others. 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, Vol. 14, No. 2, Article 32.

SAIC (Scientific Applications International Corporation). 2006. *Life Cycle Assessment: Principles and Practice*. May 2006. National Risk Management Research Laboratory, US Environmental Protection Agency, Cincinnati, Ohio.

De Schutter, O. 2010. *Report submitted by the Special Rapporteur on the right to food, Olivier De Schutter*. 20 December 2010. Human Rights Council, UN General Assembly.

Socolow, R.H., & Lam, S.H. 2007. Good enough tools for global warming policy making. *Phil. Trans. Roy. Soc. A*, Vol. 365, pp 897-934.

Tucker, D. 2012. *Gaming Our Way to a Better Future*. Policy Brief. December 2012. Wilson Center, Washington, DC.

UNU-IHDP & UNEP. 2012. *Inclusive Wealth Report 2012: Measuring progress toward sustainability*. Cambridge University Press, Cambridge, UK.

World Green Building Council. 2013. *The Business Case for Green Building*. World Green Building Council, http://www.worldgbc.org/.