Resource Allocation and Problem Prioritization for Sustainable Facilities and Infrastructure

Annie R. Pearce, Ph.D.,[1] Associate Member, ASCE
Rita A. Gregory, Ph.D.,[2] Associate Member, ASCE
Jorge A. Vanegas, Ph.D.,[3] Associate Member, ASCE

Introduction

One of the most pressing problems in realizing sustainable facilities and infrastructure systems is deciding how to allocate economic and other resources to improve sustainability, within the constraints of limited budgets and organizational operating and decision environments. Decision makers responsible for the planning, design, construction, operation, maintenance, and decommissioning of facilities are beginning to feel increasing pressure to incorporate principles of sustainability into their decisions and actions regarding these facilities. Given these pressures, decision makers face the challenge of prioritizing already scarce resources to achieve the objective of sustainability in their facilities, while continuing to meet other objectives already in place such as occupant requirements, environmental compliance, and avoidance of risk.

This paper presents a hybrid process for prioritizing facility-related problems and allocating resources to solve those problems, based on the objective of increasing facility sustainability while meeting other goals and constraints faced by facility decision makers. The process is based on a model of built facility sustainability and incorporates aspects of resource allocation procedures used to identify and manage cost drivers for facility design

---

[1] Research Engineer, Sustainable Facilities & Infrastructure Program, Georgia Tech Research Institute, Atlanta, Georgia 30332-0837, (404) 894-8089, annie.pearce@gtri.gatech.edu

[2] Assistant Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0355, (404) 894-2242, rita.gregory@arch.gatech.edu

[3] Associate Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0355, (404) 894-9881, jvanegas@ce.gatech.edu

and construction. The paper includes a discussion of how sustainability relates to and incorporates existing facility-related objectives and constraints, and an overview of how the process can be applied to decision making for sustainability in residential facilities. The paper concludes with recommendations for incorporating sustainability as an objective in facility decision making.

Background

Increasing the sustainability of built facilities requires not only an understanding of what sustainability means in operational terms for built facilities, but also a way to measure the relative sustainability of various facility states. In the context of built facilities, sustainability can be defined as a state of the facility system marked by stability, both internal to the system as well as in terms of its context, into the foreseeable future (Pearce 1999). In terms of this definition, a sustainable facility is one that meets the needs and aspirations of present generations (both stakeholders and non-stakeholders alike), without compromising the ability of future generations to meet their own needs (adapted from Brundtland 1989; hereafter "Brundtland definition").

Measuring sustainability has traditionally posed a challenge to those who would use the concept as an objective for decision making. According to the systems-based definition of sustainability, measuring the state of sustainability of a given system requires knowledge not only of the behavior of the elements of the system itself, but also the ripple effects of the system due to its inputs from and outputs to the global Earth system. Rather than making a global account of all effects of a facility system, traditional approaches to measuring sustainability have typically relied upon monitoring indicators commonly believed to reflect system sustainability. For example, the Leadership in Energy and Environmental Design (LEED) system for evaluating facility sustainability is based on multiple categories of indicators that survived the rigor of a consensus process (USGBC 1998). Table 1 shows the LEED categories of indicators, along with the indicators from five other tools designed to evaluate the sustainability of built facilities and/or the materials from which they are constructed.

While indicator-based approaches to sustainability measurement have proven useful in many contexts, they suffer from two basic limitations. First, the outcome of a given tool is dependent upon the selection of indicators. The rationale for indicator selection may not be any more rigorous than the opinions of the tool developers, which differ significantly as evidenced by the variability of indicator categories from tool to tool (see Table 1). Second, indicators are usually incommensurable, i.e., their values cannot be directly combined to form a composite indicator of the sustainability of a facility, meaning that additional means for examining tradeoffs are necessary in order to use to the tools to support decision making. For example, values for thermal comfort cannot be validly added to values for water economy – the units of each indicator are different. Existing evaluation tools do not typically provide any method for normalizing indicators to permit direct comparison of different facilities or different states of the same facility. One exception is the point system adopted by the LEED system (USGBC 1998), but its coarse resolution provides relatively little guidance to a decision maker seeking to prioritize courses of action to increase facility sustainability, and its quantification of tradeoffs among different courses of action is linked to choices of best practices, not the *outcome* of those best practices in the context of specific facilities.

Finally, existing indicator-based approaches to sustainability evaluation have yet to be embedded effectively within the process of decision making for built facilities. The LEED system, for example, is typically used as a means for establishing a rating for a given facility rather than as a tool for maximizing sustainability over the facility life cycle. It does not incorporate other typical constraints and considerations such as cost or availability of resources within the context of a specific facility that are critical for meaningful decision making. The next section explores the process of decision making and resource allocation in the context of capital facilities, in which any system of sustainability evaluation must be embedded in order to be useful.

Table 1. Assessment and Evaluation Tools for Built Environment Sustainability

		Sustainability Variables	Built Environment Variables
Individual Material	**Lawson (1996)** "Built Environment Sustainability (BES) Index"	Ecological impacts/pollution Cyclic processes Waste minimization Resource depletion Energy consumption	Resource depletion: *Raw material extraction damage* *Extraction efficiency* *Resource supply status* *Recycled content* *Required maintenance* *Product recyclability* Inherent Pollution: *Embodied solid waste* *Embodied liquid waste* *Embodied greenhouse gases* *Embodied toxics/particulates* Embodied Energy: *Process energy requirements* *Transport energy* *Construction energy*
	Lippiatt & Norris (1995) "BEES - Building for Economic & Environm'tl Sustainability"	Environmental Performance Economic Performance	Building Materials Material Life Cycle
Whole Facility	**Building Research Establishment (1993)** "BREEAM - Building Research Establishment Environmental Assessment Method"	Global Issues: *CO2 emissions* *Acid rain* *Ozone depletion* *Recycled materials* Resource Use	Local Issues: *Legionnaires' Disease* *Wind Effects* *Noise* *Overshadowing* *Water economy* *Ecological value of site* *Cyclists' facilities* Indoor Issues: *Legionnaires' Disease* *Ventilation/smoke/humidity* *Hazardous materials* *Lighting* *Thermal comfort* *Indoor noise*
	USGBC (1998) "LEED - Leadership in Energy and Environmental Design"	Prerequisites *Ozone-depleting chemicals* *Recyclables storage/collection* *Water conservation stds.* *Water quality stds.* Energy Ozone Depletion/CFCs Water Conservation Water Quality	Prerequisites *Asbestos-free* *Commissioning* *Energy codes* *Smoke-free* *Thermal Comfort* Building Materials Construction Waste Management Existing Building Rehabilitation Indoor Air Quality Landscaping/Exterior Design Using a LEED-certified Designer Occupant Recycling Equipment Operations & Maintenance Facilities Siting Transportation
Facility + Processes	**DuBose & Pearce (1997)** "The Natural Step"	Material accumulation: *Lithospheric* *Synthetic* Ecosystem damage Resource efficiency/fairness	Facility Life Cycle Resource Flows into/out of facility Environmental Impact: *On site* *Embodied in resources* *Resulting from waste disposal* Facility efficiency
	Graedel & Allenby (1995) "Industrial Ecology"	Ecology impacts/biodiversity Energy use Solid residues Liquid residues Gaseous residues	Site selection, dev't, and infrstrc. Business products Business processes Facility operations Refurbishment/transfer/closure

Decision Making and Resource Allocation for Capital Facilities

For many types of facilities, the process of allocating resources follows an annual cycle in concert with fiscal budget cycles (Gregory & Pearce 1999). Figure 1 shows a typical resource allocation cycle that begins with consideration of the needs and objectives of stakeholders, followed by identification of actions, i.e., projects, that may meet those needs and objectives. With limited resources as are typical of most decision situations, these potential projects are subjected to some sort of evaluation filter or criteria that may be derived from stakeholder needs and objectives, resulting in a prioritization of projects. The top-ranking project or combination of projects are selected based on resource availability, and allocations of resources are made for the implementation of those projects over the period covered by the budget cycle. At the end of the cycle, any new or unmet needs and objectives feed back into the next iteration of the cycle to serve as a basis for identification of new projects.

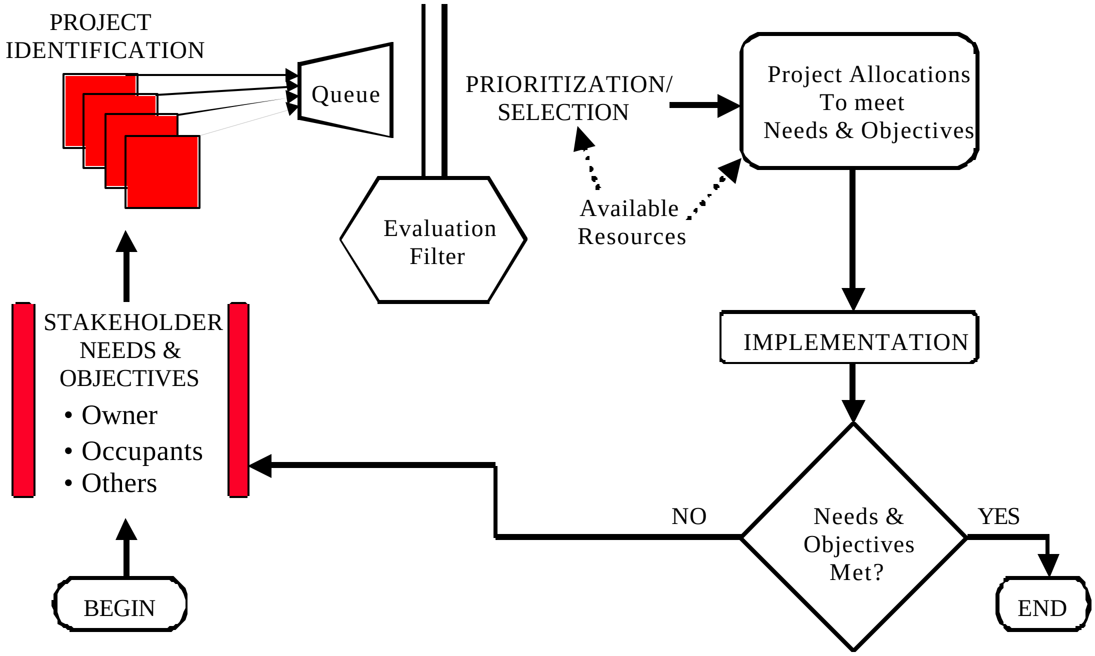


Figure 1. Cyclic Resource Allocation Process (after Gregory & Pearce 1999)

In the context of this process, sustainability can enter at various points in the cycle, including: a) as an explicitly stated stakeholder objective; b) as a search criterion for the identification of candidate projects; c) as a filter criterion for evaluating, prioritizing, and/or selecting candidate projects; or d) as a guiding principle for project implementation (Vanegas & Pearce 2000). In terms of allocating resources, the most critical point at which sustainability can be incorporated into the process is as an evaluation filter to support prioritization of candidate projects. The next section describes a method for incorporating sustainability as a criterion for evaluating candidate projects, prioritizing those projects, and selecting projects to which resources should be allocated to meet the objective of increasing facility sustainability.

A Method to Support Resource Allocation for Sustainability of Capital Facilities

A key element of resource allocation for capital projects is prioritization of candidate projects according to how well their realization will meet the objectives of the decision process. In the case of sustainability, prioritization requires an understanding of what sustainability means, and the ability to operationalize and quantify it in terms of candidate facility projects. A solution to these requirements is discussed next.

Defining Sustainability

The first step in prioritizing projects for resource allocation is to understand and define the objective of increasing sustainability. Based on a search for constraints and a content analysis of 83 definitions of sustainability from the literature, three main constraints define the concept of sustainability as it applies to systems (Pearce 1999):

1) Stakeholder Satisfaction Basic needs met
2) Resource Base Impact No or neutral impacts
3) Ecosystem Impact No or neutral impacts

The first constraint provides a basic threshold to ensure that the interests of the decision maker are met in the present, thus meeting the first condition of the Brundtland definition of sustainability. The second two conditions address the needs of non-stakeholders in present and future generations that might otherwise be impacted by direct or ripple effects of facility decisions and actions, thus meeting the second condition of the Brundtland definition. Using these three parameters and associated constraints, a sustainability decision space can be constructed to represent various states of sustainability of a system, with the origin of the axial system representing the equality states of the constraint equations (Figure 2).

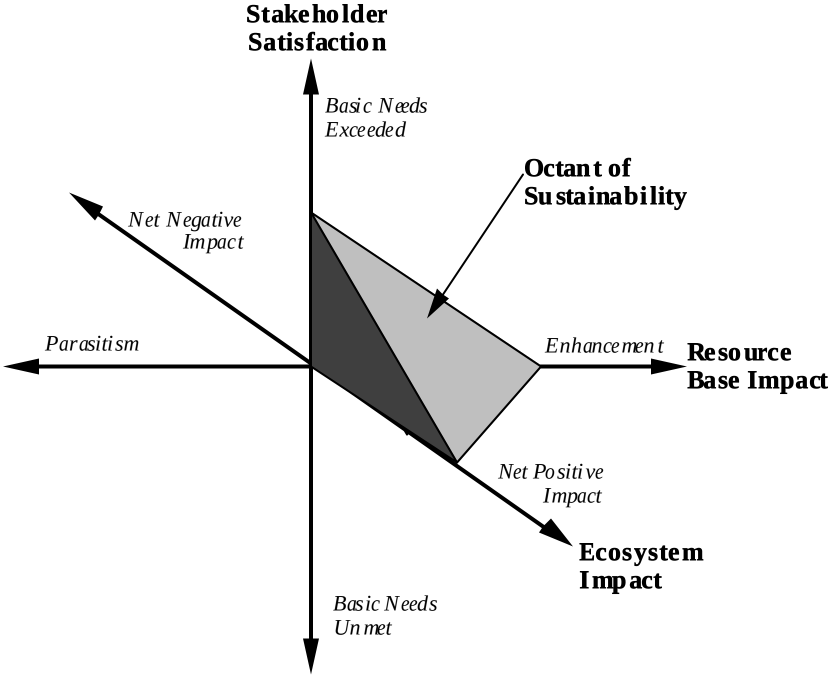


Figure 2. Three Dimensional Sustainability Decision Space (Pearce 1999)

Operationalizing and Quantifying the Sustainability of Built Facility Systems

With a construct of the concept of sustainability developed in the previous section, the next step is to operationalize the theoretical concept in terms of variables that are meaningful for built facilities and that completely define each of the three axial parameters. To operationalize the three parameters of sustainability for built facilities, two criteria were used to establish meaningful, measurable variables for built facility sustainability. First, the set of operational variables had to completely define each parameter in a mutually exclusive, collectively exhaustive fashion for a facility system. Second, each individual variable had to be measurable or estimatable using data available to or easily collected by facility decision makers. Any variables that could not be easily calculated by facility decision makers had to be provided as a default appropriate for the facility type and context being analyzed. The set of variables describing each parameter of sustainability was developed using a systems model of built facilities, shown in Figure 3. This model enables the systematic accounting of impacts in a mutually exclusive, collectively exhaustive way by dividing the world into two categories: everything *inside* the system boundary, and everything *outside* the system boundary. Table 2 shows the categories identified using the systems model.

After the operational variables were identified using the systems model, they were combined mathematically into equations that could be used to calculate values for the three parameters of sustainability (Stakeholder Satisfaction, Ecosystem Impact, and Resource Base Impact) using a pairwise deductive technique for selecting appropriate mathematical functions (Pearce 1999). Table 3 shows the derived equations that describe the sustainability of built facility systems in terms of the three parameters of sustainability. The reader is referred to (Pearce 1999) for a detailed discussion of the derivation of these equations. Using these equations, a decision maker can calculate variables for the three parameters defining sustainability for built facilities, resulting in a point in three-dimensional sustainability decision space that represents the sustainability of the built facility for the system state being analyzed.

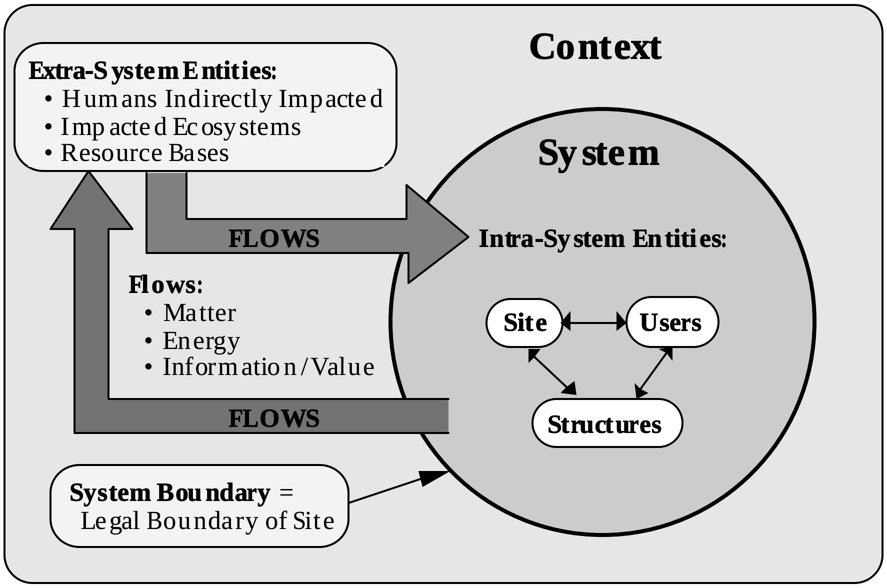


Figure 2. Systems Model of Built Facilities (Pearce 1999)

Table 2. Classification of Key Variables Defining Facility Sustainability (Pearce 1999)

	Intra-System Impacts	**Extra-System Impacts**
Stakeholder Satisfaction	• Stakeholder expectations met • Relative importance of stakeholder expectations	Determined by System Impacts on Ecosystems and Resource Bases
Resource Base Impacts	• Change in intra-system resource bases • Significance of change	• Resource flow into/out of facility system • Unit impact exerted by flow on source/sink system • Significance of unit impact
Ecosystem Impacts	• Change in intra-system ecosystems • Significance of change	• Resource flows into/out of facility system • Unit impact exerted by flow on source/sink system • Significance of unit impact

Table 3. Sustainability Equations for Built Facilities (Pearce 1999)

Parameters/Variables	Description	Range
SS = $(E_E - E_{NM}) / E_T$	**Stakeholder Satisfaction Parameter**	**[-1, 1]**
E_M	Number of Stakeholder Expectations Met	$[0,\infty]$
E_{NM}	Number of Stakeholder Expectations Not Met	$[0,\infty]$
E_E	Number of Stakeholder Expectations Exceeded	$[0,\infty]$
$E_T = E_M + E_{NM} + E_E$	Total Number of Stakeholder Expectations	$[0,\infty]$
RBI = $\tanh(RBI_I + RBI_E)$	**Resource Base Impact Parameter**	**[-1, 1]**
$RBI_I = \Delta RB_I * \omega_{\Delta RB}$	Intra-system Resource Base Impact	[-1, 1]
ΔRB_I	Change in Intra-system Resource Base for unit time	[-1, 1]
$\omega_{\Delta RB}$	Significance of Change in Intra-system Resource Base	[-1, 1]
$RBI_E = Q * RBI_S/Q_T$	Extra-system Resource Base Impact	[-1, 1]
Q	Quantity of Flow between System & Source/Sink System	$[0, \infty]$
RBI_S	Resource Base Impact of Source/Sink System	[-1, 1]
Q_T	Total Quantity of Flow Served by Source/Sink System	$[0, \infty]$
EI = $\tanh(EI_I + EI_E)$	**Ecosystem Impact Parameter**	**[-1, 1]**
$EI_I = \Delta EI_I * \omega_{\Delta EI}$	Intra-system Ecosystem Impact	[-1, 1]
ΔEI_I	Change in Intra-system Ecosystems for unit time	[-1, 1]
$\omega_{\Delta E}$	Significance of Change in Intra-system Ecosystems	[-1, 1]
$EI_E = Q * EI_S/Q_T$	Extra-system Ecosystem Impact	[-1, 1]
Q	Quantity of Flow between System & Source/Sink System	$[0, \infty]$
EI_S	Ecosystem Impact of Source/Sink System	[-1, 1]
Q_T	Total Quantity of Flow served by Source/Sink System	$[0, \infty]$

Prioritizing Actions and Allocating Resources for Built Facility Sustainability

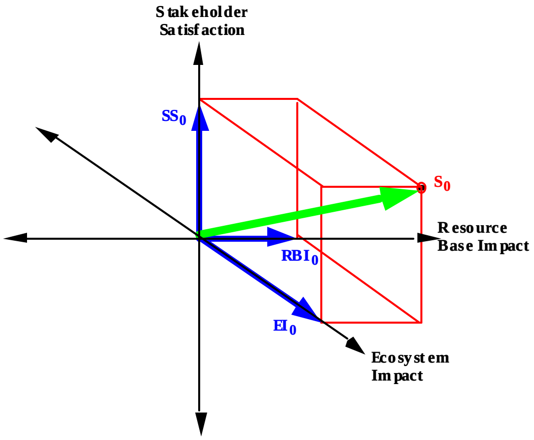
By combining the three-dimensional sustainability decision space with the operational parameter equations for built facilities, various states of a built facility system can be calculated, plotted, and used to compare the relative sustainability of the facility as it changes due to implementation of project actions. Referencing the change in sustainability to a common baseline state of the facility's initial sustainability provides a basis for comparison of how various candidate projects will influence the sustainability of the system during and following implementation of each project. Note that the parameter equations all reference changes caused by actions over a discrete unit of time, typically selected to be one year to correspond to fiscal resource allocation cycles. Figure 3 illustrates the complete method for comparing and prioritizing candidate projects to increase facility sustainability.

Conclusions and Future Research

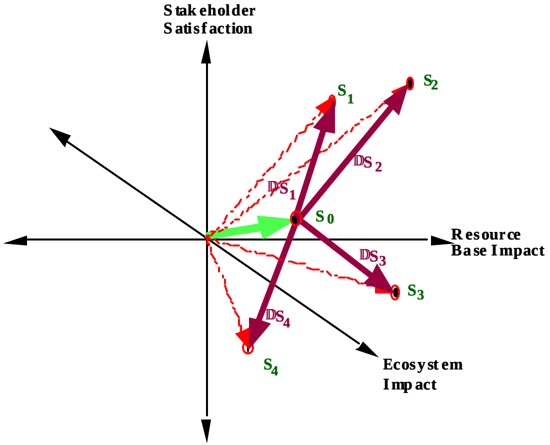
With increasing attention to built environment sustainability, the need for an objective and quantitative method to measure progress toward that goal is apparent. While existing indicator-based tools provide one approach to assess facility sustainability, they are limited in their precision, context-specificity, and generalizability. This paper describes an alternative to indicator-based approaches for measuring built facility sustainability, embedded within a systematic method for supporting the prioritization and selection of solutions to increase facility sustainability. The method provides the capability to incorporate realistic constraints on facility decision making such as economic feasibility and available resources. These constraints can be imposed during the project identification stage to prune infeasible options, or integrated within the prioritization process as feasibility “regions” within the three-dimensional decision space.

The prioritization method and the model on which it is based addresses the limitations of indicator-based approaches. The process for project prioritization and resource allocation provides an integrated approach for monitoring incremental changes in the sustainability of a facility system due to both its normal operating state and changes due to project implementation. This process is particularly useful for monitoring and comparing changes to existing facility systems, although it can also be applied to facilities in the design or construction phase of their life cycle. When examining a facility in operation, the sustainability impacts of earlier life cycle phases are considered to be sunk costs, and are not reflected in the baseline state of system sustainability. Additional investigation may produce better ways of amortizing these initial impacts over the life cycle of the facility. Nonetheless, the method provides a useful way to examine the impacts of changes due to specific project actions. The method may be applied to compare actions within a single facility system, or across multiple facilities if desired. However, to provide valid comparison in multiple facility systems, all candidate projects must be analyzed over the whole multiple facility system, not in terms of the individual facilities in which they may be implemented.

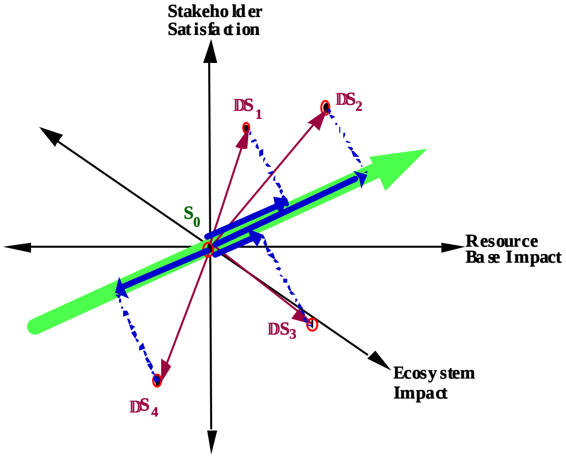
Future research to extend the model’s capabilities includes aggressive monitoring and archiving of data required to support the model’s application in multiple contexts, research to develop life cycle analysis methods for combining and amortizing discrete unit time sustainability changes reflected in a single iteration of the model, and development of a web-based implementation of the model to obtain feedback and data from more widespread application of the prioritization method.



a)Establish baseline sustainability state



b) Calculate sustainability change
for candidate projects



c) Normalize projects with respect to baseline stateand
compare via projection onto most positive unit vector

Figure 3. Prioritizing Candidate Projects according to Sustainability Increase

Acknowledgments

The authors are grateful for intellectual support and other resources provided by the National Science Foundation, Georgia Tech's School of Civil & Environmental Engineering, the Georgia Tech Research Institute, and the Institute for Sustainable Technology and Development (formerly the Center for Sustainable Technology).

References

Brundtland, G.H. (1989). "Protecting the Global Commons," *Earth Ethics,* Fall, 12.

Building Research Establishment. (1993). *An Environmental Assessment for New Office Designs*. BREEAM/New Offices, Version 1/93. Building Research Establishment, Garston, Watford, UK.

DuBose, J.R. and Pearce, A.R. (1997). "The Natural Step as an Assessment Tool for the Built Environment." *Proceedings, 1997 CIB Conference on Green Building*, Paris, June.

Graedel, T.E. and Allenby, B.R. (1995). "Matrix Approaches to Green Facility Assessment", *Proceedings, Second International Green Buildings Conference, Special Publication 888*, National Institute of Standards and Technology, Gaithersburg, MD, 84-102.

Gregory, R.A. and Pearce, A.R. (1999). "Cost Effective Allocation of Research Funds for the Development of Emerging Technologies," *Journal of Professional Issues in Engineering Education and Practice.*

Lawson, W.R. (1996). "Appraisal System for Ecologically Sustainable Building." *Proceedings, 2nd National Energy Efficiency in Buildings Conference*, Wollongong, New South Wales, Australia, June.

Lippiatt, B.C. and Norris, G.A. (1995). "Selecting Environmentally and Economically Balanced Building Materials," *Proceedings, 2nd International Green Building Conference and Exposition - 1995, NIST SP 888*. Fanney, A.H., Whitter, K.M., and Cohn, T.B., eds. National Institute of Standards and Technology, Gaithersburg, MD, 38-46.

Pearce, A.R. (1999). *Increasing the Sustainability of the Built Environment: A Metric and Process for Prioritizing Improvement Opportunities.* Ph.D. Dissertation, School of Civil & Environmental Engineering, Georgia Institute of Technology, Atlanta, GA.

Pearce, A.R., Estrada, S.M., and Augenbroe, G.L.M. (2000). "Sustainable Construction in the U.S.: A Perspective to the Year 2010." *Proceedings, Construction Congress VI,* February 20-22, Orlando, FL.

USGBC – United States Green Building Council. (1998). "Leadership in Energy and Environmental Design: The LEED Building Rating System." 3rd Draft, http://www.usgbc.org.

Vanegas, J.A. and Pearce, A.R. (2000). “Drivers for Change: An Organizational Perspective on Sustainable Construction.” *Proceedings, Construction Congress VI*, February 20-22, Orlando, FL.