Sustainability and the Built Environment: A Metric and Process for Prioritizing Improvement Opportunities

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SUSTAINABILITY AND THE BUILT ENVIRONMENT: A METRIC AND PROCESS FOR PRIORITIZING IMPROVEMENT OPPORTUNITIES

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1921 - 1997

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1933 - 1993

To the memory of those who did not survive to see this dissertation complete, and to the seventh generation, who may survive and prosper due in some small way to its impacts.

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SUMMARY

A quantitative model of built facility sustainability was proposed as a solution to the problem of prioritizing improvement options for increasing the sustainability of built facilities. Stakeholder Satisfaction, Resource Base Impacts, and Ecosystem Impacts were identified as a set of parameters to define the sustainability of systems on a technological scale. These parameters were corroborated via a content analysis of 83 definitions from the sustainability literature. The parameters were incorporated into a construct of system sustainability represented as a three-dimensional decision space. The three parameters of sustainability were operationalized in terms of built facility systems, resulting in a set of variables meaningful to facility decision makers that could be measured directly or estimated using available data. Logical relationships were specified among the variables to create a quantitative model with behavior matching constraints and objectives from the literature. A process for applying the model to prioritize facility improvement options was derived from classical decision theory, resulting in a vector-based representation for comparing options in terms of their improvement to the sustainability of a facility. A case study was used to demonstrate the model, and subsequent performance analysis of the model's behavior included comparison of expected results with model outputs, sensitivity analysis, and analysis of the mathematical properties of the vector representation. Findings from these analyses suggest that the model provides the capacity to discriminate among improvement options in terms of their relative sustainability. Implications for model refinement are discussed as areas for future research.

CHAPTER I

INTRODUCTION

Throughout recorded history, humans have constructed built facilities to shelter themselves and their possessions and to meet a variety of needs critical to human survival and prosperity. While the impacts of these facilities on their environment have not always been immediately apparent, their cumulative effects on our planet over time have become more evident. In response to these effects, sustainability has emerged as guiding paradigm to create a new kind of built environment: one that meets the needs of humans in the present without limiting the ability of future generations to meet their own needs.

Within this new paradigm, researchers and practitioners from many fields have begun to identify a variety of ways to improve the sustainability of the built environment. These improvement options span the entire scope of facility scales, types, and life cycle phases, ranging from siting facilities to maximize solar energy gain or increase transit accessibility, to installing water-saving fixtures, to careful deconstruction of facilities and recovery of their raw material components. Faced with more improvement options than available resources to implement them, decision-makers interested in increasing the sustainability of the built environment would like to choose the most suitable and effective opportunities to increase sustainability within their resource and contextual constraints. Prioritization based on sustainability is at best difficult, however, due to the apparent incommensurability of variables (e.g., use of renewable energy vs. water savings vs.

waste reduction and material recycling) affected by these diverse opportunities. The issue of context also presents a challenge, since cultural expectations, local resource abundance or scarcity, condition of local ecosystems, applicable laws and regulations, and other properties of a facility's surroundings influence the relative importance of solutions for that facility (e.g., saving water in arid regions, minimizing impact to ecosystems in areas with threatened or endangered species, creating a pleasing environment for a specific target market to maintain occupancy rates, etc.).

To address these challenges, this research proposes a model and systematic method to evaluate the sustainability of a facility from a holistic perspective within its specific context. This sustainability model and evaluation method provide the capability to prioritize improvement opportunities for increasing the sustainability of existing facilities, thus allowing facility decision makers to make informed choices of options that will most effectively increase the sustainability of their specific facilities while remaining within budget, resource, and other decision constraints. This dissertation describes the research that produced the sustainability model and evaluation method. To begin the dissertation, the purpose of this chapter is threefold: (1) to set up the research problem in the context of the built environment; (2) to introduce an overview of the whole research in terms of scope, objectives, and methodology; and (3) to provide a reader's guide to the total research. The next section describes the context of the research problem in terms of the built environment as it exists today.

1.1. Background and Context of the Research Problem

In the context of this research, the built environment is conceptualized as the set of all facilities constructed by humans to meet their needs and aspirations. Each facility, in conjunction with its users and site, can be considered as a system, defined as "a set of elements standing in interrelation" (von Bertalanffy 1968, Churchman 1979). Facility systems can then be defined as the set of physical elements (foundations, structure, enclosure, finishes, etc.) comprising a built facility, the site on which it stands, plus the stakeholders who impact or are impacted by the existence of the facility. So defined, facilities meet the definition of systems and exhibit the properties of (Zandi 1993, Zandi 1986): emergence (the system as a whole has properties which its parts by themselves do not); hierarchical organization (where the elements that comprise the system themselves are comprised of other sub-elements, each with different levels of emergent properties); communication (the transfer of matter, energy, or information among system elements that permit the system as a whole to function); and control (the ability of the system to perform and maintain its integrity under different conditions or demands).

This section describes the characteristics of the built environment, its impacts on humans and on the planet that are resulting in its evolution, and the role of sustainability in that evolution. These properties of the built environment comprise the context in which this research is grounded. The section concludes by describing the needs generated as a result of the evolution of sustainability in the built environment.

1.1.1 Characteristics of the Built Environment

Four sets of properties characterize the built environment: the roles it plays in meeting human needs and aspirations, the phases of its life cycle, the stakeholders affected by its existence, and its interfaces with technological and ecological systems.

Role of Built Facilities in Human Survival and Prosperity: In nearly all environmental contexts found on Earth, the built environment is an essential part of the infrastructure necessary for human survival. Buildings provide shelter from adverse climate conditions such as rain and snow, ambient temperature ranges outside human comfort levels, and threatening weather conditions. They also afford privacy and security from a variety of dangers, including predatory and pest animals and malevolent humans (Allen

1980). In addition to these roles which contribute to basic human survival, built facilities serve other purposes which help to expand the quality of human life beyond mere biotic survival, including their role as infrastructure for activities such as:

- Collection, treatment, and/or storage of solid, liquid, and gaseous waste
- Provision and distribution of pure water
- Processing and distribution of agricultural products into food
- Manufacturing and distribution of other products used by humans

Sectors of the Built Environment: The built environment can be divided into four primary types of construction, as shown in Figure 1.1 and Table 1.1. In 1997, the construction industry contributed an added value of over $600 billion dollars in new construction, additions, alternations or reconstruction of existing facility, and maintenance and repair (FMI Corporation 1998). The industry consisted of approximately 2 million business establishments in 1992 (U.S. Department of Commerce 1992), employing over 4.6 million people, and is growing annually (ibid.). Services provided by these companies included architectural, real estate development, construction management, and engineering services, in addition to general contracting, construction, and specialty construction work. In the United States, buildings represent more than 50% of the nation's wealth, and in 1993, new construction and renovation activities comprised approximately 13 percent of the Gross Domestic Product (Gottfried 1996).

Life Cycle of Built Facilities: Each of the facilities created by the construction industry has a life cycle, typically comprised of five sequential phases as shown in Figure 1.2. The life cycle of built facilities typically ranges from 30 to over 100 years (Yeang 1993). The facility life cycle starts with an idea or concept during the Planning/Pre-Design phase (Halliday 1994, Hendrickson & Au 1989), continuing with the development of aesthetic, functional, physical, economic/financial/time, psychological/social, legal/

regulatory, and technological parameters which must be taken into account during the design process (Vanegas 1987). The outcome of the planning phase is typically a program of requirements describing the intentions of the owner in seeking to construct the facility.

The second phase of the facility life cycle is Design, where the facility is transformed from concept to construction documents. Design is followed by Construction, in which the building is transformed from an idea on paper or in models to a real product in physical space (Vanegas et al. 1998).

Table 1.1: Examples of Built Facilities Classified by Sector (U.S. Department of Commerce 1992)

Residential Construction	Industrial Construction	Heavy Engineering Construction	Building Construction
• Single-Family Homes • Town Houses • Condominiums • High-rise Apartments	• Petroleum Refineries • Petrochemical Plants • Synthetic Fuel Plants • Nuclear Power Plants • Steel Mills • Heavy Mfg. Plants	• Urban Transit Systems • Communication Networks • Water Treatment Plants • Highways • Airports • Dams • Ports • Pipelines • Bridges • Tunnels	• Light Manufactur'g Plants • Government Buildings • Hospitals • Recreation Centers • Office Towers • Warehouses • Schools • Theaters • Universities • Commercial Malls

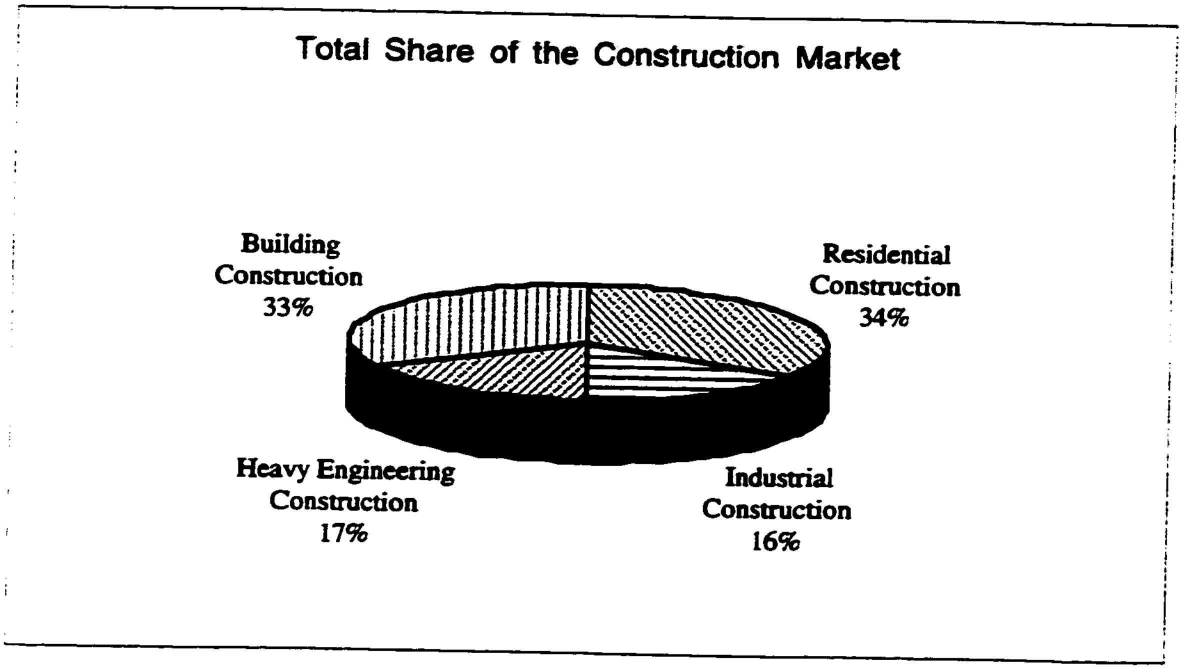


Figure 1.1: Sectors of the Built Environment (U.S. Department of Commerce 1992)

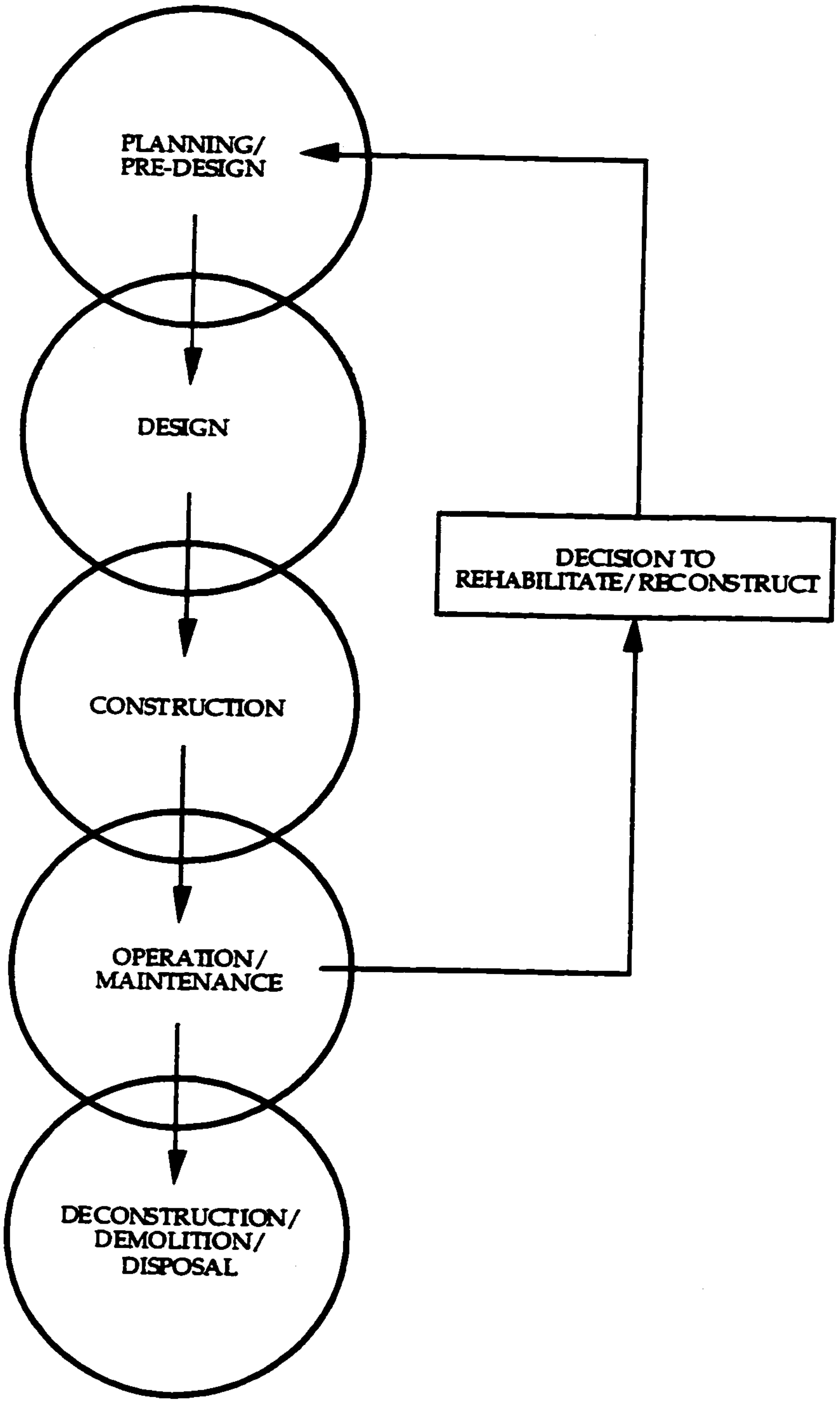


Figure 1.2: The Life Cycle of Built Facilities
(adapted from Vanegas 1987, Hendrickson & Au 1989, Halliday 1994)

After Construction, the Operation and Maintenance phase of the life cycle begins, during which the building is used to meet the needs for which it was designed. This phase is typically the longest phase of the life cycle. Operation is the process during which the facility performs its intended functions of use, while Maintenance consists of all non-operation-related activity performed on the facility necessary to keep it in proper condition to perform its intended function. Maintenance includes activities such as changing light bulbs as they burn out, cleaning the facility, and minor repairs to or replacement of building components with short life cycles compared to the facility itself (Vanegas et al. 1998).

When a facility exhibits a deficit in performance with respect to stakeholder requirements, one possible choice is to rehabilitate or reconstruct the facility to enable it to perform as required. A second possible fate of the facility is to end the life cycle of the facility. Deconstruction/Demolition/Disposal are three options for terminating the life cycle of a facility, ranging from planned, careful disassembly of the facility to destructive, less-careful processes and subsequent removal of materials from the site.

Facility Stakeholders: The next attribute of built environment systems is the set of entities who are affected by their existence: the stakeholders. Figure 1.3 shows typical stakeholders involved in each life cycle phase of built facilities. External stakeholders are those entities who are based external to the boundary of the facility system, such as contractors, designers, government agencies, and others. For these stakeholders, the built facility under consideration represents one of many systems in which they may be involved at any given time. For internal stakeholders, on the other hand, the system under consideration represents a major interest in which they are vested, and may be the only system affecting them at any point in time. These stakeholders, such as owners, tenants, users, and clients, have direct stake and involvement in the facility and the functions it serves: it is their needs which the facility is designed and constructed to meet.

External Stakeholders: Indirect	External Stakeholders: Direct	Phase	Internal Stakeholders: Direct	Internal Stakeholders: Indirect
Zoning Agencies Regulatory Agencies	Planners Developers	PLANNING/ PRE-DESIGN	Owners Land Developers	Investors
Financiers Code Enforcement Agencies Manufacturers Professional Institutions Surrounding Communities	Design Team: • Architects • Engineers • Interior Designers • Landscape Architects Project Managers	DESIGN	Owners Land Developers	Investors Users/Tenants Facility Managers/ Operators Clients/Product Consumers
Manufacturers Vendors/Suppliers Shippers Code Enforcement Agencies Regulatory Agencies	Construction Team: • Contractors • Consultants • Subs Utilities Financiers Project Managers Surrounding Communities	CONSTRUCTION	Owners	Investors Users/Tenants Facility Managers/ Operators Clients Product Consumers
Manufacturers Vendors/Suppliers Shippers Regulatory Agencies	Surrounding Communities Utilities Financiers	OPERATION/ MAINTENANCE	Owners Users/Tenants Facility Managers Operators Clients	Investors Product Consumers Users' Dependents
Waste Disposal Companies Recycling Companies Regulatory Agencies	Surrounding Communities Demolition Contractor Disposal Agent Salvage Agents Developers	DECONSTRUCTION/ DEMOLITION/ DISPOSAL	Owners	Future Users Investors

Figure 1.3: Typical Stakeholders for Built Environment Life Cycle Phases (synthesized from Jain et al. 1994; Halliday 1994; Raubacher 1992; Vanegas 1987; Hendrickson & Au 1987)

Direct stakeholders, either internal or external to the system, are those entities whose actions directly bear upon the facility system, who are directly impacted by the behavior of the facility system, or whose needs are met directly by virtue of their interaction with the facility. Direct stakeholders include users, constructors, designers, owners, and surrounding communities. Indirect stakeholders, on the other hand, have no direct impacts on the facility and may have no direct interaction with the facility at all, but nonetheless are indirectly impacted by the existence of the facility system. Indirect stakeholders include the entities who manufacture materials and supplies used to construct the facility, handle waste materials emitted by the facility, invest money in the potential of the facility, and create codes and regulations which must be observed by the facility system. In some phases of the facility life cycle, stakeholders who were indirectly represented by other stakeholders in earlier phases of the life cycle become direct stakeholders as their participation in the interactions of the system becomes integral. For example, future users and tenants of the facility system often do not participate directly in the planning and design process, but are represented by the owner and/or developer of the facility during those phases. After the facility reaches completion and begins operation, these parties become direct stakeholders due to their direct participation in the system operation.

Interfaces with Technological and Ecological Systems: Built facilities are not independent of other systems; they could not exist without complementary technological and ecological systems to provide sources of matter and energy as inputs, and sinks, consumers, or storage for system outputs. As such, built facility systems are open systems, i.e., systems that exchange matter or energy with their environment (von Bertalanffy 1968, Churchman 1979). The primary links between built facility systems and other technological and ecological systems are via the flows of matter, information, and energy across the boundaries of the system. Figure 1.4 shows examples of flows into and out of a built facility, and how they relate to its technological and ecological context.

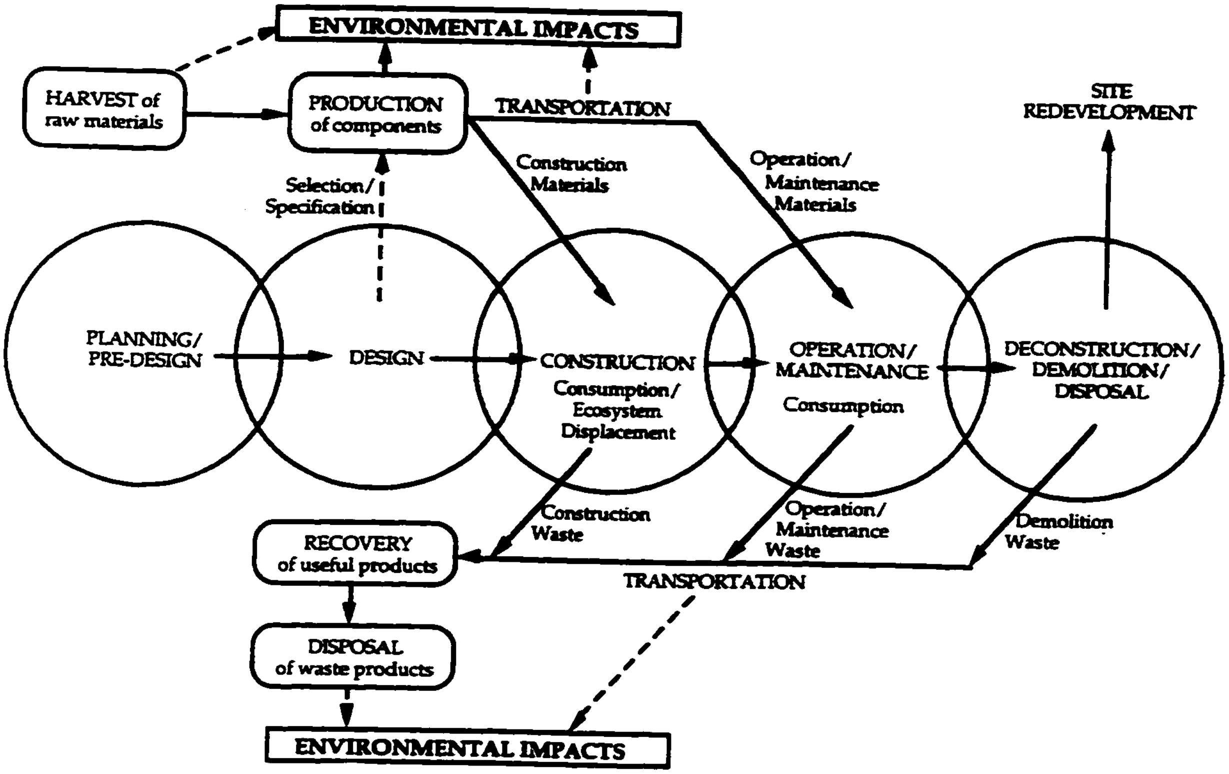


Figure 1.4: Interfaces of Built Facilities with External Systems
(adapted from Yeang 1995, Roberts 1994)

1.1.2 Reasons for this Research: Triggers for Evolution in the Built Environment

Built facilities are complex technological systems that meet critical human needs, persist over significant lengths of time, and involve multiple diverse stakeholders. Their interrelations with the technological and ecological systems that surround them have significant impacts on those systems. These impacts have not always been noticeable on the scale of individual facilities, but their cumulative effects on the planet over time have been increasingly well documented. For example:

- Buildings are responsible for over ten percent of the world's freshwater withdrawals, twenty-five percent of its wood harvest, and forty percent of its material and energy flows (Roodman & Lenessen 1996).
- 54% of U.S. energy consumption is directly or indirectly related to buildings and their construction (Loken et al. 1994).
- 30% of all new and remodeled buildings suffer from poor indoor environments caused by noxious emissions, off-gassing, and pathogens spawned from inadequate moisture protection and ventilation, resulting in $60 billion annually in lost white-collar productivity from Sick Building Syndrome (SBS) in the U.S. alone (Kibert et al. 1994)
- Nearly one-quarter of all ozone-depleting chlorofluorocarbons (CFCs) are emitted by building air conditioners and the processes used to manufacture building materials. (Energy Resource Center 1995)
- Approximately half of the CFCs produced around the world are used in buildings, refrigeration and air conditioning systems, fire extinguishing systems, and in certain insulation materials. In addition, half of the world's fossil fuel consumption is attributed to the servicing of buildings. (Zeiher 1996)
- The average household is annually responsible for the production of 3,500 pounds of garbage, 450,000 gallons of wastewater, and 25,000 pounds of CO_2 along with smaller amounts of SO_2, NO_X, and heavy metals. (Barnett and Browning 1995)
- Lighting accounts for 20-25% of the electricity used in the U.S. annually. Offices in the U.S. spend 30 to 40 cents of every dollar spent on energy for lighting, making it one of the most expensive and wasteful building features. (Energy Resource Center 1995)

- The construction industry is responsible for 8-20% of the total Municipal Solid Waste (MSW) Stream, 14% on average. (Tchobanoglous et al. 1993)

These cumulative impacts have resulted in increased attention to the role played by built facilities and infrastructure in the problems of natural resource depletion and degradation, waste generation and accumulation, and negative impacts to ecosystems. Since built facilities are a major direct and indirect contributor to these problems, they now face increasingly restrictive environmental conservation and protection laws and regulations, international standards to address environmental quality and performance, and substantial pressures from civic groups, environmental organizations, and citizens. As a result, facility stakeholders face new, complex and rapidly changing challenges imposed by these laws, regulations, standards, and pressures at all life cycle stages.

Environmental Impact: Negative impacts to natural ecosystems have begun to enter into decision-making in the construction industry. Forced by environmental legislation such as the National Environmental Policy Act of 1970, many U.S. projects now require an Environmental Impact Assessment of the project to be completed before construction can proceed. Still, however, many project planners, designers, and contractors see environmental considerations as an obstacle to be overcome rather than a way to achieve benefits for themselves and others (Kinlaw 1992). Many actions taken to mitigate environmental impact of projects are typically only applied as end-of-the-pipe measures, not changes to the environmentally damaging processes themselves (Liddle 1994). These traditional strategies of mere environmental regulatory compliance or reactive, corrective actions such as mitigation or remediation have proven to be consistently costly, inefficient, and many times ineffective (Vanegas 1997).

Resource Depletion and Degradation: Other triggers for change center around resource depletion and degradation. For example, many municipalities have adopted energy codes to promote energy efficiency in new facilities. While not widely enforced, these codes nonetheless represent an evolutionary step for the construction industry. In other cases, increased scarcity of resources such as dimensional lumber have forced the industry to seek alternatives to traditional materials, including engineered wood products, steel framing, recycled plastic lumber, and stress-skin panels. These products make use of materials formerly considered to be waste, including sawdust, post-consumer plastic, and wood pieces too small to be otherwise incorporated as structural members, and result in products that are structurally superior to the materials they replace. Alternative framing practices have also become more commonplace as constructors seek to minimize the use of raw materials. A positive side effect of some of these new trends is increased energy efficiency due to decreased thermal bridging and integrated insulation (BSC 1995).

Human Health: A third trigger for change is the increasingly noticeable impacts of the built environment on human health. Many humans spend most of their time indoors, nearly 90% of an average day (Kibert et al. 1994). Building-related threats to human health include the carcinogenic properties of asbestos and the neurologically damaging effects of lead-based paint. Yet these products were common components of buildings during the period between 1950 and 1970. More recent evidence supports the carcinogenic effect of low-level electromagnetic radiation, which is generated by all electrical appliances (Rousseau & Wasley 1997). Some individuals are highly sensitive to irritants and/or toxins such as off-gassed volatile organic compounds (VOCs), formaldehyde from adhesives and fabrics, and molds, bacteria, and dust accumulating in and resulting from building products (ibid.). The cleaning and maintenance products used during facility operation, including pesticides, solvents, and chlorine, present another set of irritants that cause reactions in an increasingly large portion of the population. Rousseau and Wasley describe the trend:

> The body absorbs an alarming number of these agents, and some accumulate for long periods causing toxic or immune-like reactions. Others mimic chemicals which regulate body functions, causing 'error responses.' Testing requirements for new chemicals may be rigorous, but it is impossible to anticipate all of their potential long-term effects...The financial gain from successful new products makes them very attractive to develop, and creates political pressure to approve them for sale. It is sobering to think that chlorofluorocarbons, DDR and PCBs were all considered 'miracle chemicals' when they were introduced. (1997, p. 14)

Given the complex combinations of materials and chemical products being incorporated into built facilities, the potential of buildings to have negative impacts on human health is significant. The number of potential irritants and toxins is growing rapidly with the proliferation of synthetic chemicals present in almost every product used by humans. Thus, threat to human health is a third significant category of triggers that reflects the need for change in the way built facilities are created and operated, along with the building technologies, systems, products, and materials used within them.

1.1.3 Sustainability as a Response to the Need for Change

In response to these drivers of evolution, sustainability has emerged as guiding paradigm to create a new kind of built facility: one that meets the needs of humans in the present without limiting the ability of future generations to meet their own needs (after WCED 1987). At present, the industries responsible for the built environment are cost-driven, with minimization of first cost and implementation time as primary objectives, meeting quality and performance goals as secondary objectives, and minimizing negative impacts as a tertiary objective. The shift to a sustainable built environment does not necessarily eliminate these objectives of traditional construction, but rather embeds them in a larger context of sustainability-related life cycle objectives (Figure 1.5).

Benefits of Sustainable Construction: Sustainable construction is an approach to creating facilities with the goal of meeting the needs and aspirations of humans while minimizing negative impacts to the resource bases that provide goods and ecosystems that provide services to meet those needs. From a life cycle perspective, sustainable construction may yield economic benefits to decision makers while at the same time protecting the environment and moving toward a higher level of quality of life for stakeholders and non-stakeholders alike (Kinlaw 1992). For example, Schmidheiny (1992) writes:

> ...environmental concerns become not just a cost of doing business, but a potent source of competitive advantage. Enterprises that embrace [sustainable development] can effectively realize the advantages: more efficient processes, improvements in productivity, lower costs of compliance, and new strategic market opportunities.

Liddle (1994) echoes this sentiment:

> Sustainability will impact the construction industry in a number of ways: polluting processes and materials used in construction will become more expensive, new markets will be created for energy efficient buildings, for manufacturing firms looking to reduce their pollution, and for satisfying increasingly environmentally concerned clients and public; new sources of funding for projects with environmental benefits will become available; finally, there will be increased traditional (infrastructure) projects owing to an emphasis on investment.

While the differences between traditional and sustainable construction can be radical, the forces of social and economic change are increasingly eliminating the differences. Whereas traditional construction focuses on cost, performance, and quality objectives, sustainable construction will add to these criteria minimization of resource depletion and environmental degradation, and creating a healthy built environment (Kibert 1994). Sustainable construction approaches each project with the entire life cycle of the facility in mind, not just the initial capital investment. Accordingly, decision makers must evaluate the long-term as well as short-term impacts of their decisions on both local and global environments. Project stakeholders who take a sustainability approach to construction will be rewarded with reduced liability, new markets, and an Earth-friendlier construction process, which will help future and current generations to achieve a better quality of life (Kinlaw 1992, Liddle 1994).

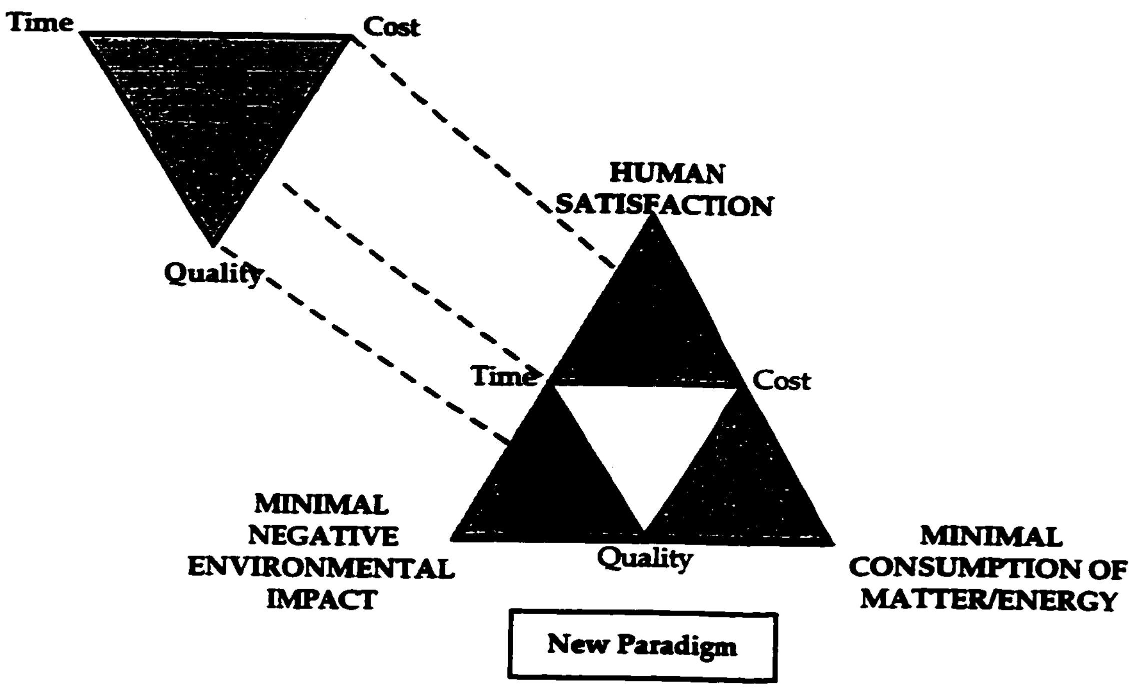


Figure 1.5: A Paradigm Shift to Sustainable Construction

Increasing Built Environment Sustainability: To realize the potential benefits offered by the new paradigm of sustainability, researchers and practitioners have begun to identify a variety of strategies and actions for improving the sustainability of the built environment. A recent study identified over 4000 different rules of thumb or heuristics in the published literature for increasing built environment sustainability (Jones-Crabtree et al. 1998). These heuristics span the entire scope of facility scales, types, and life cycle phases, ranging from purchasing energy efficient appliances, to installing water-saving fixtures, to using finish materials that improve indoor air quality. Most of this knowledge is in a non-quantitative form such as "Install low flow fixtures" or "Use low-VOC paints", with no way to predict which of the many possible actions will have the most significant impact on facility sustainability.

These heuristics represent a fragmented approach to improving sustainability, offering little guidance as to the appropriate context in which to apply them and focusing primarily on specific issues or problems rather than ways to improve facility sustainability holistically. As described further in Chapter 2, a limited number of tools and techniques exist today to compare the environmental, energy, or economic life cycle performance of individual materials, components, or systems within a facility. However, systematic mechanisms to evaluate the sustainability of a facility from an integral perspective and within its specific context, particularly in terms of selecting improvement options, currently do not exist.

1.1.4 Research Need

Given the current state of sustainability knowledge for the built environment, there is a very strong need to find a method to evaluate and prioritize improvement options for specific facilities. Thanks to the continually evolving body of heuristic knowledge (see Section 2.2.1), decision makers have a large set of alternatives to consider when seeking to improve the sustainability of a facility. Each of these alternatives has a set of outcomes that may result upon implementation, and each of the outcomes will be associated with some change to the overall sustainability of the facility. Yet without knowing how possible actions influence the sustainability of their facilities, decision makers seeking to improve sustainability have no way to systematically prioritize potential actions.

Filling this void requires knowing how to measure the sustainability of a facility, and being able to evaluate how changes in the facility affect its sustainability. Until stakeholders know what data is important for evaluating sustainability and how to use that data to assess facility sustainability, they will be unable to comparatively assess potential alternatives to increase sustainability.

1.2. Overview of the Research

This research addresses the need for a way to measure facility sustainability by developing a model of built facility sustainability and a systematic process for using it to evaluate the relative sustainability of improvement options on a holistic facility scale. This section provides a description of the research, including the research problem, objectives, scope, approach, and contributions of the work.

1.2.1 Research Problem, Objective, and Hypothesis

One primary question has served as the driver for this research effort: how can decision makers tell how sustainable a built facility is? Despite many efforts by theoreticians and practitioners to develop strategies and tools to make buildings more sustainable, no one has as yet satisfactorily answered the question of how to evaluate their outcomes in terms of the original objective of sustainability. This inability is due to the lack of an operational method to define and measure the sustainability of built facilities. Thus, the problem addressed in this research has been to develop such a measure or model of sustainability for built facilities, along with a process for applying the model to the task of prioritizing improvement options. Using the model and process, decision makers can systematically prioritize potential improvement options according to their relative effects on the sustainability of the facility system as a whole, subject to decision constraints such as economic feasibility, regulatory requirements, etc.

Research Problem Characterization: In order to develop a model of facility sustainability, the following issues were considered:

1. Existing knowledge about built environment sustainability is based on divergent implicit theories about the concept (described further in Chapters 2 and 4)
2. No metrics of facility sustainability exist which can compare or prioritize improvement options with different primary effects, e.g., water-saving vs. energy efficiency vs. improved indoor air quality (described in Chapter 2)
3. Built facilities do not exist in isolation, and therefore cannot be evaluated in terms of sustainability without consideration of contextual interdependencies with other systems, at a potentially global scale (described in Chapter 5)
4. Built facility decision-makers operate within a context of constraints, e.g., economic feasibility, regulatory requirements, etc., that must be considered in prioritizing improvement options (described in Chapter 6)

These issues characterize the problem addressed by the contributions of this research.

Research Objective: The objective of this research is to create a method for prioritizing improvement options to existing, operational facilities in terms of their relative improvement to the sustainability of those facilities. The method consists of a model of the sustainability of built facilities, along with a process for applying the model to the task of prioritizing improvement options within given decision constraints.

Research Hypothesis: The hypothesis of the dissertation is that it is possible to develop a model of built facility sustainability that allows decision makers to prioritize facility improvement options according to their relative influence on facility sustainability. This hypothesis was tested in the research by constructing such a model, demonstrating its application on a single-family detached residential facility, analyzing its performance via comparison of expected with actual model outputs, sensitivity analysis, and analysis of the mathematical properties of the model, followed by supporting the validity of the model in terms of conclusion, internal, construct, and external validity (Chapter 6). Chapter 7 describes the conclusions resulting from testing the hypothesis.

1.2.2 Research Scope

This research draws from and synthesizes three domains of knowledge: knowledge about the built environment, knowledge about decision making, and knowledge about sustainability. The contribution of this research lies in the intersection of all three domains in that it provides an innovative way to make decisions about the sustainability of the built environment (Figure 1.6). Within the intersection of the three domains of knowledge shown in Figure 1.6, additional scoping decisions for each domain guided the research.

Built Environment Knowledge: Within the domain of built environment knowledge, the research was limited to an examination of improvement options to existing, operating facilities. This scope was selected because it permits meaningful baseline values to be established for the initial state of a facility, based on actual measurements of the facility's characteristics. By focusing on existing, operating facilities, only future states of the facility require estimation, whereas the initial state can be measured directly (as described further in Chapter 6).

The scope of this research included demonstrating the option prioritization method in the context of a single-family detached residential facility. This demonstration case was selected for two primary reasons. First, according to a recent study, construction of single-family residences are projected to comprise 26.1% of all construction in 1999, making them the largest single category of facilities built in the United States (FMI Corporation 1998). The total number of single-family detached homes existing in the United States was over 62 million in 1993, and was estimated to be growing by 18 million per year (U.S.

Department of Commerce 1993), making this type of facility a very significant component of the residential sector. Additionally, over $73 billion were spent on residential improvements in 1998, a figure representing approximately 13% of all construction volume in terms of current dollar expenditures (FMI Corporation 1998). Thus, single-family detached residences and improvements thereto comprise a significant portion of all facilities being constructed in the U.S., and any changes or improvements to the state of the art in this segment of the industry have potentially widespread and cumulatively significant impacts.

Second, the set of all stakeholders for a single-family detached residence in the operations phase of its life cycle is considerably simpler than the set of stakeholders for other facility types or life cycle phases. Given the designated scope, the only direct internal stakeholder relevant for a typical single-family detached residence during operation is the homeowner, who is also the user/tenant, facility manager, and operator of the facility. In many cases, the indirect internal stakeholders (investors, users' dependents, etc.) are also equivalent to or represented by the homeowner. By scoping the demonstration case to this kind of facility, the requirements for assessing stakeholder-related variables in measuring sustainability are considerably simplified. Successful demonstration of the model and process in this context provides a solid basis for future research to extend the scope of applicability to other sectors and life cycle phases of the built environment.

Decision Making Knowledge: Within the second domain, decision making, this research was limited to rank-ordering improvement options, with equal or uniform weighting of each attribute considered in the ranking. Scoping the research to ranking was chosen because it meets the needs of built environment decision makers who are seeking to prioritize potential options within the context of a specific facility—the objective of this research. Calculation of intervals between options on a scale, establishing an absolute zero for the model developed herein, or incorporating non-uniform weighting of attributes are outside the scope of this work and are left to future research.

Sustainability Knowledge: Finally, within the third domain—sustainability knowledge—the research focused on three primary considerations: humans, the resource bases that provide goods to meet human needs and aspirations, and the ecosystems that provide services to meet human needs and aspirations. The reasons for selecting these three considerations are based on findings documented extensively in Section 4.1, Section 4.2, and Appendix B of the dissertation. Additionally, the scope of humans considered in this research is limited to intra-system stakeholders for reasons described in Section 5.1.2, which consists of the homeowner for the built environment scope described previously.

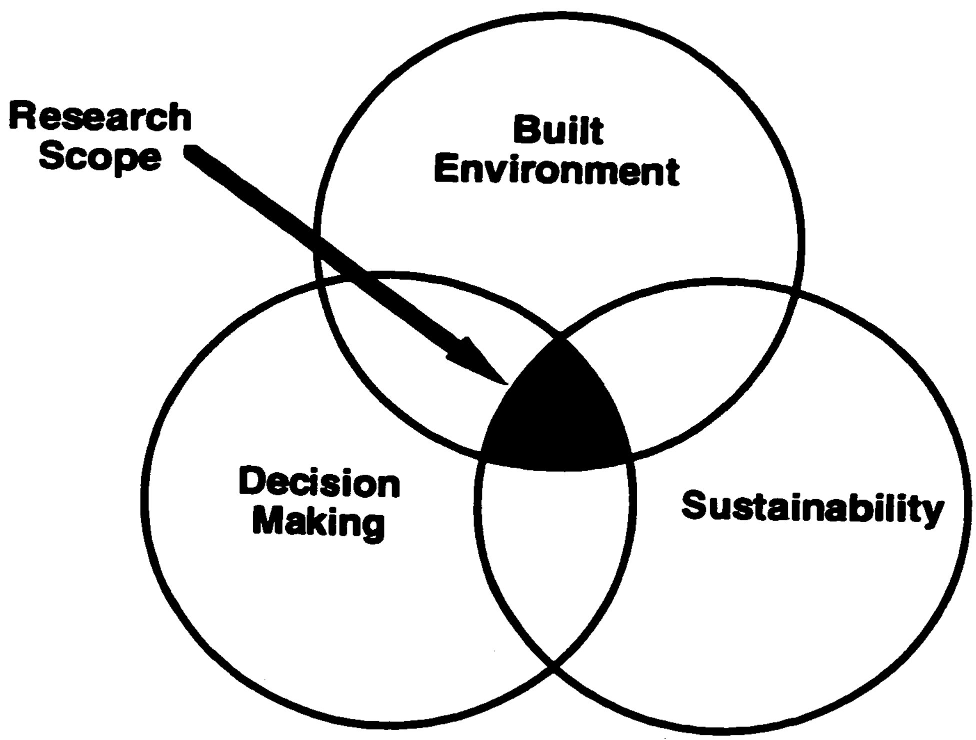


Figure 1.6: Scope of the Research

1.2.3 Research Approach, Expected Outcome, and Benefits

The goal of this research is to enable decision makers to systematically prioritize improvement options based on the goal of increasing facility sustainability. To accomplish this goal, a measure of the sustainability of facilities is needed. This measure must be based on a sound theoretical construct of the concept of sustainability, followed by a valid operationalization of the construct into observable or measurable terms relevant to built facilities. It must also be embedded within a process for application or use, so that it can be useful for prioritizing options. Finally, the resulting model and process must take into account not only the constraints existing within built facility decision-making processes, but also it must incorporate the specific context of the facility in question. Together, these requirements specify a means of comparatively evaluating the variety of sustainability improvement options for built facilities in the context of their use.

To align the divergent perspectives reflected in current models of built environment sustainability, the methodology used in this research included examination of various perspectives on theoretical sustainability from the general literature. By expanding the lens of examination to include general sustainability, the research was able to frame existing perspectives in terms of the general sustainability principles from which they stem. This process of construct development is contained in Chapter 4, and includes two parallel approaches to determining the main parameters that define sustainability: identification of parameters based on thermodynamic, biological, and anthropocentric constraints (Section 4.1) and content analysis of definitions of sustainability from the literature (Section 4.2). These two corroborating methods resulted in a unified construct of sustainability, described in Section 4.3, to serve as input to the process of operationalization for built facilities in Chapter 5.

Since the objective was to develop a method for prioritizing built facility improvement options, the research went beyond simply developing a unified theoretical construct of sustainability. To meet the research goal, a model of built facility sustainability was built by establishing a construct of sustainability for built facilities and specifying operational, measurable variables needed to prioritize alternatives to improve sustainability in the built environment. The operational variables of built environment sustainability were then combined by specifying mathematical relationships that result in model behavior congruent with the thermodynamic, biological, and anthropocentric constraints of sustainability described in Chapter 4. Chapter 5 presents the process and outcome of this model building process.

Having built a model of built facility sustainability, the last step was to specify a process for its use that would result in the ability to prioritize facility improvement opportunities. This prioritization process was developed from classical decision theory and benchmarking methods as described in Chapter 6. The process was demonstrated with a case study in Section 6.2 to illustrate how the model can be applied to prioritize improvement options. Finally, the performance of the model was analyzed using comparison of model outputs with expected outcomes (Section 6.3.2), sensitivity analysis (Section 6.3.3), and proof of arithmetic properties of the model and prioritization process (Section 6.3.4).

Expected Outcome and Impacts: The outcome of the research approach is a new model and process for measuring built environment sustainability, including (a) a theoretical construct of sustainability generated by aligning perspectives from the literature; (b) a set of measurable variables that define the sustainability of built facilities, based on the theoretical construct; (c) an operational model for benchmarking the level of sustainability of a built facility, using the variables; and (d) a process for applying the model to prioritize facility improvement options from a sustainability perspective. These four research products come together as a systematic mechanism that, at an individual facility level, will enable decision-makers to evaluate improvement options in terms of their relative contribution to the sustainability of a facility. This methodology is an advancement beyond the existing state of knowledge in three ways:

1. It enables decision makers to compare and prioritize the multitude of potential solutions suggested by the body of heuristic knowledge
2. It provides a construct of sustainability for the built environment that envelops and unifies existing theories of built environment sustainability
3. It provides an explicit quantitative model and process for evaluating the relative sustainability of improvement options.

The contribution provides a solution to the research problem of prioritizing improvement options for built facilities, since it has the capacity to evaluate the baseline state of sustainability for a facility system, and to estimate changes in future states of sustainability due to implementing facility improvement options. Using the model, decision-makers can prioritize improvement options according to their relative changes to the sustainability of the facility, within the specific constraints of the decision environment. Thus, the sustainability model and evaluation method allow facility decision makers to make informed choices of options that will most effectively increase the sustainability of their facilities while remaining within budget, resource, and other decision constraints.

1.3. Reader's Guide to the Dissertation

This research seeks to provide an impetus for increasing the sustainability of existing built facilities by building a model and process that facility decision-makers can use to prioritize potential changes to their facilities based on how those changes impact facility sustainability. The rest of the dissertation describes the research that resulted in the model and process, and this section provides a chapter by chapter summary to guide the reader through the remainder of the document.

1.3.1 Literature Review

In the domain of built facilities, some work has been done that addresses the concept of sustainability. Chapter 2 provides a critical review of this existing literature of sustainability for the built environment, to establish the point of departure for the research. The sustainable building literature is divided into four categories of work: heuristics and guidelines, resource guides, models and frameworks, and assessment and evaluation tools, each of which is addressed in turn. The chapter concludes with an overview of the literature, identifying trends, weaknesses, and opportunities for improvement.

1.3.2 Research Approach

Chapter 3 provides an overview of the three-phase approach used for this research: aligning existing perspectives to develop a unified construct of sustainability, operationalizing that construct into a model of sustainability for built facility systems, and developing a process to apply the model to the task of prioritizing facility improvement options. The research approach is geared toward developing a method for facility owners to understand how specific improvement actions affect the sustainability of their facilities. Chapter 3 concludes with a discussion of validity issues to be addressed in the research.

1.3.3 Defining Sustainability for Systems

Chapter 4 presents the first major methodological step of the research: developing a unified construct of sustainability to align existing perspectives on the topic. Based on the seminal literature of theoretical sustainability, Chapter 4 develops a systems-based construct of three operational parameters: resource base impact, ecosystem impact, and stakeholder satisfaction. Examining patterns in published definitions of sustainability using the linguistic technique of content analysis corroborates this construct. The resulting construct of sustainability comprises one of four primary products of this research.

1.3.4 Operationalizing Built Facility Sustainability

Chapter 5 establishes the second and third contributions of the research: a set of measurable variables that define built environment sustainability, combined into a quantitative model for evaluating the sustainability of built facilities. In this chapter, a systems-based representation of built facility systems is used to classify the set of possible impacts built facilities can have on the three parameters of sustainability identified in Chapter 4. Each parameter is expanded into variables that are meaningful to and can be evaluated by decision makers in the built environment. Chapter 5 also describes how mathematical relationships among the variables were established to form the model's parameter functions. The chapter concludes with an overview of the model of sustainability for built facilities and a description of data sources that can be used to evaluate the parameter functions of the model.

1.3.5 Applying the Model of Built Facility Sustainability

Chapter 6 develops and presents the method for using the model of facility sustainability to prioritize improvement opportunities. This prioritization process links the parameter functions developed in Chapter 5 to the three-dimensional sustainability construct developed in Chapter 4 to provide a means for comparing the relative sustainability of improvement options, thus yielding the fourth major contribution of the research. The process is demonstrated using a case study of a single family detached residence in which the homeowner would like to select the improvement options that are likely to have the greatest impact on the sustainability of the home, while avoiding any negative ramifications for the home's occupants and remaining within budgetary constraints. An expected prioritization based on estimates of relative impacts is used to test the model's behavior, and a sensitivity analysis and examination of the mathematical properties of the model elucidate the major findings of the research. Chapter 6 also includes an evaluation of the research in terms of the validity questions from Chapter 3.

1.3.6 Contributions, Conclusions, and Future Research

The final chapter of the work recapitulates the major issues addressed in the research and describes the contributions to and impacts on basic theory and applied practice resulting from the research. Chapter 7 also includes a discussion of seven notable lessons learned from the research. The dissertation concludes with a summary of the research findings and an examination of areas for future research. The ultimate contribution of this research is a model of built facility sustainability based on an aligned construct of sustainability, along with a process for applying that model to the task of prioritizing improvement opportunities to increase the sustainability of the built environment.

CHAPTER II

LITERATURE REVIEW

Chapter 1 established the problem of evaluating the sustainability of built facilities to prioritize options for sustainability improvement. With respect to the nature and context of the problem as discussed in Chapter 1, the body of existing literature on built facility sustainability can be categorized into multiple types of knowledge: heuristic or rule-of-thumb knowledge and guidelines that support decision making in ill-defined situations, and more generalized theory in the form of models, frameworks, or evaluation/assessment tools that provide the capability to predict, control, or optimize human actions in the context of the world. A total of four categories comprise the breakdown of literature reviewed in this chapter: heuristics and guidelines, resource guides, models and frameworks, and assessment and evaluation tools. This chapter also describes other ways of analyzing existing knowledge about built environment sustainability, including identifying the variables in the implicit theories of sustainability that underlie the literature. The purpose of the chapter is to establish a point of departure for the research by illustrating the diversity and divergence among implicit theories of built facility sustainability represented in existing work.

2.1. Strategy for Analyzing the Literature

The primary issue considered in analyzing the literature was how the authors defined the subject of sustainability, reflected by the choice of variables or parameters included or used to classify elements in their work. A secondary issue was how the authors conceptualized the built environment in terms of included variables. Each source was reviewed to identify variables in two main classes: sustainability variables, and built environment variables. The reason for identifying these variables was to permit comparison of the subjects each author explicitly or implicitly used to define both sustainability and the built environment. Identifying the variables also permits inferences about what each author felt were the critical facility drivers of sustainability, and illustrates the divergence among authors with respect to their implicit theories of built facility sustainability.

The literature on built environment sustainability can be broken down into four distinct categories: heuristics and guidelines, resource guides, models and frameworks, and assessment and evaluation tools. The next four sections of the chapter provide an overview of significant works in the built facility sustainability literature within each of these classes, highlight the sustainability and built environment variables considered to be important by each source, and discuss the limitations and opportunities present within each class of literature.

2.2. Existing Guidelines and Heuristics

The first category of literature relating to built environment sustainability is the body of work comprised of heuristics or guidelines for planning, designing, constructing, operating, maintaining, and ending the life cycle of built facilities. Literature in this category represents the body of knowledge created and tapped by building practitioners in striving to achieve sustainability in professional practice. As such, it is the most practical sector of knowledge in the sustainability-related building literature, and is a starting point for evolution of knowledge.

2.2.1 Attributes of Knowledge Statements

The growing body of practical knowledge statements about sustainable design and construction can be represented on three parallel levels of specificity: principles, heuristics, and specifications (Figure 2.1). Principles are the most general type of knowledge, and are defined as inoperative statements that together form a global set of objectives to define sustainability. These first principles comprise the fundamental axioms of sustainability theory and are therefore not limited to use only in the domain of the built environment, but rather apply to all domains of human activity. An example of a sustainability principle is "Conserve energy". There are a relatively small number of principles compared to the other class categorizations of heuristic and specification. Table 2.1 shows other examples of principles from the reviewed sources.

Heuristics, the second class categorization, are less general than principles because they address a specific domain, in this case the built environment. Heuristics are often referred to as 'rules-of-thumb'. They represent a set of operable and qualitative but often unquantitative rules that can be applied under the guidance of experts in the domain, based on training or past experience.

In the realm of sustainability, many heuristics have been derived directly from sustainability principles rather than from trial and error. Heuristics often serve a useful purpose in assessment and diagnosis (Dym & Levitt 1991) but since they are typically suggestive rather than axiomatic, they are generally not specific enough to aid non-experts in decision-making. An example of a heuristic correlating to the "Conserve energy" principle is "Minimize air leakage through building envelopes". This heuristic provides enough information to guide a building professional in improving the sustainability of a building, but would not be of much use to someone who was unfamiliar with techniques used to manage air leakage through building components. In addition, measuring compliance with this statement might be difficult - while one can take quantitative measures of air leakage in a building, one may never know if minimal leakage has been achieved. No specific threshold of acceptable performance is specified. Table 2.2 shows other examples of heuristics from the reviewed sources.

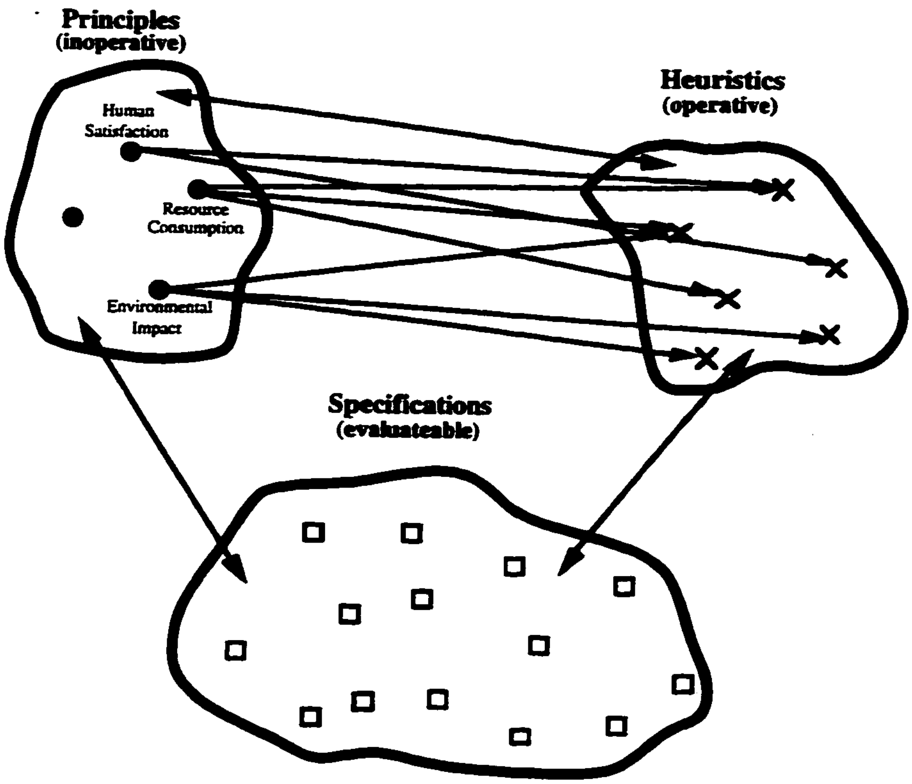


Figure 2.1: Classes of Knowledge Representation (Realff 1996)

Table 2.1: Examples of Principles from Selected Sources

Principle	Source
Practice pollution prevention.	(HOK 1995)
Reduce life cycle energy consumption	(Ander 1994)
Reduce, reuse, or recycle waste.	(Roberts 1994)

Table 2.2: Examples of Heuristics from Selected Sources

Heuristic	Source
Provide ecologically sound and healthy building materials.	(HOK 1995)
Assess external microclimate including sun paths, seasonal temperatures, local wind and rainfall patterns.	(Halliday 1994)
Integrate passive solar heating with daylighting design.	(PTI 1996)
Study regional impacts of proposed development, such as transportation, water quality and flooding, ecosystems, and wildlife habitats.	(HOK 1995)
Select low-emitting, environmentally friendly cleaning agents for use in regular maintenance.	(PTI 1996)
Increase efficiency of irrigation with controllers and sensors.	(PTI 1996)
Avoid on-site chemical treatment.	(Halliday 1994)

The third class of sustainability guidelines is the most detailed level of knowledge - the specification. Statements can be classified as specifications in cases where the statement is both operable and quantifiable within the domain of the built environment. Specifications are prescriptive and measurable, and often serve as instructions for implementation of sustainability. An example of a specification following from the previous examples is "Use weather-stripping around all doors and windows". This statement is both operable (it provides specific instructions which could be understood by non-experts) and quantifiable (measuring compliance with this statement is as easy as checking to see that all building openings have been weather-stripped). Table 2.3 shows additional examples of specifications from the reviewed sources.

Table 2.4 summarizes the factors used for categorization of statements into the classes of principle, heuristic or specification. Domain specificity is dependent upon the statement's relevance to the built environment. If compliance with the statement can be measured, then the statement can be deemed to have evaluability. The final factor is operability, determined by answering the following question: can a non-specialist implement the statement?

Table 2.3: Examples of Specifications from Selected Sources

Specification	Source
Exceed ASHRAE/IES standard 90.1-1989 by 30%.	(HOK 1995)
Use graywater for irrigation.	(PTI 1996)
Use life cycle costing with 25-year life cycle to evaluate cost beneficial options.	(HOK 1995)
Clearly identify the actual purpose of lighting to determine minimum acceptable levels.	(PTI 1996)
Increase average building durability from 40 to 100 years.	(HOK 1995)
Use not more than two incandescent luminaires in any one interior.	(Halliday 1994)
The maximum distance, in plan, between a luminaire and its switch should not exceed three times the height of the luminaire above the floor.	(Halliday 1994)
Recommend nonsmoking buildings.	(HOK 1995)
Amend soil in planting areas according to professional advice.	(PTI 1996)

Table 2.4: Class Categorization Factors for Sustainability Guidelines (Jones-Crabtree et al. 1998

	Domain Specificity	Evaluability	Operability by Non-experts
Principle	No	No	No
Heuristic	Yes	No/Yes	No
Specification	Yes	Yes	Yes

2.2.2 Synthesis of Existing Heuristics and Guidelines

From the many available sets of heuristics and guidelines developed for built environment sustainability, seven sets were analyzed in detail in this analysis. The seven sets of heuristics and guidelines were selected to address multiple phases of the facility life cycle: two of the sets of guidelines were developed to assist in designing sustainable facilities (U.S. National Park Service 1993, NC Recycling 1994); two were developed to facilitate sustainable construction (Vanegas et al. 1995, Environmental Building News 1994); and three provide guidance over multiple phases of the facility life cycle (HOK 1994, Halliday 1994, PTI 1996).

2.2.3 Limitations and Opportunities

The review of guidelines for built environment sustainability from the literature shows that significant disparities exist in terms of the variables included for consideration, as well as with respect to the nonuniform emphasis on the design phase of the built environment life cycle. In Figure 2.2 (Jones-Crabtree et al. 1998), the phase designations

2-6 correspond to facility life cycle phases of Planning, Design, Construction, Operation/Maintenance, and Deconstruction/Rehabilitation. Phase 1 represents heuristics that were applicable to all life cycle phases. The majority of heuristic knowledge at the time of this study exists on a project scale with reference to the design phase of the project life cycle.

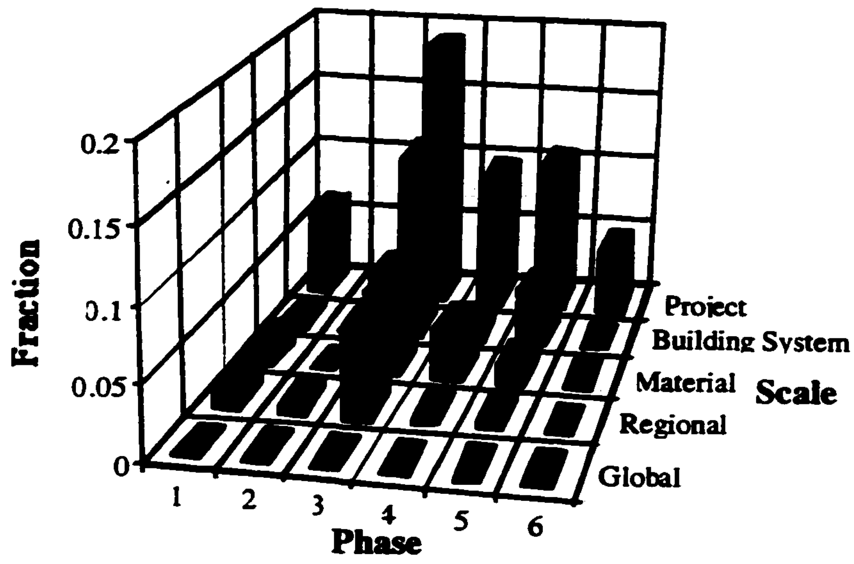


Figure 2.2: Relative Frequency Distribution of Heuristics (Jones-Crabtree et al. 1998)

Table 2.5 provides a summary of the information unearthed in the analysis of the heuristics and guidelines for sustainability. One significant problem apparent from examination of Table 2.5 is the wide variability in levels of specificity for what variables are considered to be important in defining sustainability. Since rules of thumb are by nature guidance evolved from learning what works in specific situations, variables included for the built environment may legitimately vary based on the phase of problem solving being addressed and the scale and type of facility being analyzed. However, over sets purporting to address all phases of the facility life cycle, the diversity in variables considered is reflective of the fact that sustainability is still a relatively evolving field.

2.3. Existing Resource Guides

The next category of literature reviewed was resource guides, defined as compilations of information about specific materials and building technologies to assist building decision-makers in generating alternatives for specific solutions to facility problems. This section reviews a total of three references in the Resource Guide category of the built environment sustainability literature.

2.3.1 Synthesis of Existing Resource Guides

The whole population of resource guides is rapidly growing, although many of the guides focus on very limited criteria due to the difficulty of obtaining data. Table 2.6 shows a sample of many of the resource guides available today. Of the total set, two guides specifically claiming to represent sustainability were selected for detailed analysis – one providing guidance on selecting sustainable materials (St. John 1992), and the other providing guidance on materials, technologies, and business strategies for sustainable design and construction (O'Brien & Palermini 1993). The third guide (Loken et al. 1994) was selected since it is one of the most widely used and easily available guides of its kind.

Table 2.5: Heuristics and Guidelines for Creating a Sustainable Built Environment

Category	Source	Sustainability Variables	Built Environment Variables
Design Guidelines	U.S. National Park Service (1993)	Natural resources Cultural resources Energy management Water supply Waste prevention	Site design Building design Facility maintenance/operations Energy conservation Energy efficiency
Design Guidelines	NC Recycling (1994)	Energy Resource consumption Healthy environments	Site Building codes and inspection Energy systems Mechanical systems Materials/finishes/fixtures/furniture Waste management/recycling Operations/maintenance/procurement
Construction Guidelines	Vanegas et al. (1995)	Resource consumption Environmental impact Human Satisfaction	Time Cost Quality
Construction Guidelines	Environmental Building News (1994)	Resource use: *Materials* *Energy* *Efficiency* Environmental Impacts: *Toxics* *Sensitive ecosystems*	Design Siting Materials Equipment Job Site
Comprehensive Guidelines	HOK (1994)	Site development impacts Pollution prevention Building durability Efficiency: *Energy* *Resources* Materials: *Ecologically sound* *Healthy* Stakeholder partnerships Public dialog and education	Site Energy Materials Indoor air quality Water conservation Recycling and waste management
Comprehensive Guidelines	Halliday (1994)	Environmental performance: *Human health and safety* *Environmental damage* *Energy consumption* *Materials from threatened species or environments* *Human satisfaction* *Waste generation* *Renewable resources*	Facility Life Cycle: *Pre-design* *Design* *Preparing to Build* *Construction* *Occupation* *Refurbishment* *Demolition*
Comprehensive Guidelines	PTI (1996)	Energy efficiency Water efficiency Waste reduction Construction costs Building maintenance & management savings Insurance & liability User health/productivity Building value	Pre-Design Site Issues Building Design: *Passive solar design* *Indoor Environmental Quality* *Materials and specifications* *Local Government* Construction Operations and Maintenance

Table 2.6: Commonly Available National Sustainable Building Material Guides

Resource Guide	Reference	Criteria
Sustainable Design Guide	St. John (1992)	Environmentally responsible manufacturing process; Benign substitute for a known "bad actor"; "More than token" recycled content
The Natural House Catalog	Pearson (1996)	100% natural materials Non-toxic alternative to traditional materials
Consumer Guide to Home Energy Savings	Wilson & Morrill (1996)	Energy efficient alternative to traditional product; Contributes to thermal efficiency
Guide to Resource Efficient Building Elements	Loken et al. (1994)	Resource-efficiency Recycled content
The Green Pages	Bennett (1990)	Non-toxic 100% natural materials
Sustaining the Earth	Dadd-Redalia (1994)	Renewable or natural; Organic; Reused/Reusable; Recycled/Recyclable; Sustainably harvested; Energy- or Resource-efficient; Nontoxic; Ozone-friendly; Biodegradable; Socially Responsible
The Official Recycled Products Guide	American Recycling Market (1997)	Recycled content
The Harris Directory	Harris (1993).	Recycled content
The REDI (Resources for Environmental Design Index) Guide	Iris Communications (1994)	Recycled content Resource efficiency Sustainably managed wood sources
Environmental by Design	Leclair & Rosseau (1994)	Interior products, including thermal insulation

Table 2.7: Resource Guides to Support Sustainable Building

	Sustainability Variables	Built Environment Variables
St. John (1994) "Sustainable Design Guide"	Consensus of endorsement Environmental responsibility Benign substitution Recycled content	CSI Masterformat Divisions
Loken et al. (1994) "GREBE"	Resource efficiency Use of recycled materials Energy savings in mfg. Durability Dimensional lumber alts.	Foundations Framing and Panel Systems Enclosures: *Sheathing & Wallboard* *Roofing* *Exterior Siding & Trim* *Insulation* *Windows & Doors* Interior Finishes: *Floor Coverings* Landscaping Job Site Recycling
O'Brien & Palermini (1993) "Guide to Resource Efficient Building"	Energy Efficiency Embodied Energy Efficiency Environment Protection Material Efficiency Health and Safety Affordability Competitiveness	Site Design Building Size and Shape Structure and Construction Safety and Health Systems Selling

2.3.2 Limitations and Opportunities

The review of resource guides for built environment sustainability shows that significant disparities exist in terms of the variables included for consideration. Table 2.7 summarizes the sustainability and built environment variables each of the three sources implicitly or explicitly considered important to define built environment sustainability.

One significant problem apparent from examination of the table is the wide variability in levels of specificity for what variables are considered to be important in defining sustainability. This differing level of specificity among guides is likely due to the difficulty of obtaining building product data, since no common standard exists to specify what data should be monitored by the manufacturer. Nonetheless, even the guides that claim to be about sustainability show an extremely sparse coverage of potential variables, particularly when compared to the broad coverage provided by the other types of literature. None of the guides included in the detailed analysis explicitly discusses the selection of indicators, although other resource guides not specific to the built environment attempt to do so (e.g., Dadd-Redalia 1994).

2.4. Existing Models and Frameworks

Moving to the theory-based segment of the literature, the next category includes existing models and frameworks of built environment sustainability. In the context of this analysis, models are defined as abstract representations of the real world, specifically of built environment sustainability. Each of the models analyzed represents various parameters and objectives of sustainability, along with different sets of built environment variables considered important by the authors for sustainability. The term framework in this context refers to prescriptive or process models, specifically those abstract or simplified representations of real world processes that illustrate how sustainability should be achieved for the built environment.

2.4.1 Synthesis of Existing Models and Frameworks

Five sources from the literature were selected to represent a cross-section of existing models and frameworks. The model and framework literature is characterized by a split between reductionist approaches vs. holistic, systems approaches, and the first four sources were selected to equally represent each side. The fifth framework (Hill et al. 1994) was included since it addresses sustainability from an organizational, rather than physical facility, point of view, and is prescriptive rather than evaluative in nature.

With one exception, these models and frameworks were developed independently of one another, representing the fragmentation that is characteristic of applied research in sustainability to date. The first two sources (Kibert 1994; Vanegas & Pearce 1997) are sequential first approaches to operationalizing sustainability in the context of facility construction, and represent a reductionist view of sustainability in their checklist approach to selecting indicators. Neither of these conceptual frameworks was developed to the point of being functional as a predictive or evaluative model of the sustainability of facilities. Both models help practitioners to understand what important variables of sustainability might be for built facilities, but neither is based on a rigorous operationalization of the concept.

The third and fourth sources present representational system models of built facilities, and identify properties and characteristics of facility systems on a holistic level that are important for classifying and evaluating their impacts on the environment (Lyle 1994; Yeang 1995). While both of these sources mention the concept of sustainability, neither model is explicitly billed as being a model of facility sustainability. Lyle's model illustrates the results of applying "regenerative design" to the process of creating built facilities and communities, and shows how this paradigm of design can help technological systems more closely mimic the behavior of natural ecosystems. Yeang's model of "ecological design" presents a systems representation of built facilities, and identifies the flows of matter, energy, and information into, out of, and within facility systems as the critical driver of ecological impact. Both of these models provide significantly more insight into how facilities affect their contexts, but neither provides the capacity to evaluate or predict how changes will impact the sustainability of a facility system.

The fifth model, a "framework for the attainment of sustainable construction", differs from the rest of the models in that it targets sustainable construction from an organizational, rather than a physical facility, point of view. This framework was conceived as a process model for organizations to implement "integrated environmental management" of their construction projects (Hill et al. 1994). This prescriptive model is targeted to policy makers and managers in construction organizations.

2.4.2 Limitations and Opportunities

The review of models and frameworks of built environment sustainability from the literature shows that disparities exist in terms of both the variables included for consideration and the intended applications of the work, thus corroborating the existence of the research problem as described in Chapter 1. Table 2.8 provides a summary of the information unearthed in the analysis of the models and frameworks. One significant problem apparent from examination of the table is the wide disparity in what variables are considered important for defining sustainability. While the variables included for the built environment may legitimately vary based on the phase of problem solving being addressed and the scale and type of facility being analyzed, the lack of consensus among models purporting to solve the same problem is further evidence of the need for alignment of the variables into a unified construct of sustainability.

Other weaknesses of existing models of built environment sustainability include insensitivity to contextual factors of built environment systems (e.g., Kibert 1994) and failure to provide a mechanism for evaluating sustainability in the context of built environment systems (e.g., Yeang 1993). Many of the researchers and practitioners whose models were examined here fail to provide examples of how their work could be applied to real built environment systems. Since many of the models are presented at a conceptual level, testing and validation is nearly impossible, and has not been conducted by the model developers. While these models are a necessary step in the evolution of built environment sustainability knowledge, they have limited usefulness for identifying, prioritizing, and solving problems in practice.

2.5. Existing Assessment and Evaluation Tools

The final class of work in the literature review is closest to being operationally useful for decision-making: assessment and evaluation tools for built environment sustainability. In the context of this analysis, assessment refers to a qualitative review of the attributes of a system, while evaluation refers to a more quantitative review where specific criteria for success or failure have been pre-defined. Each of the assessment and evaluation tools discussed in this section includes various parameters and objectives of sustainability, along with different sets of built environment variables that the authors consider to be important for sustainability.

Table 2.8: Models and Frameworks of Built Environment Sustainability

		Sustainability Variables	Built Environment Variables
Reductionist	Kibert (1994)	Resources: *Conservation* *Degradation* *Reuse* *Renewability* *Recyclability* Environment: *Impact* *Degradation* *Toxicity* Quality	Energy consumption Water use Land use Materials selection Indoor environmental quality Exterior environmental quality Building design Community design Construction operations Life cycle operation Deconstruction Embodied energy content Greenhouse warming gases Toxics generated/content
Reductionist	Vanegas & Pearce (1997)	Natural resources: *Consumption* *Depletion* *Degradation* Waste: *Generation* *Accumulation* Environment: *Impact* *Degradation* Humans: *Needs* *Aspirations*	Built environment health Integration with ecological systems Economic valuation Infrastructure requirements Waste recovery Construction process technology Building technology Stakeholder integration Human aspirations
Systems	Lyle (1994)	Resource use: *Renewable* *Nonrenewable* Waste: *Generation* *Composition* *Assimilation* Systems integration: *Human social systems* *Natural ecological systems* *Human technology systems*	Energy Water Waste Materials: *Embedded energy* *Renewability* *Permanence/Reusability* Indoor Air Pollution Density
Systems	Yeang (1995)	Ecosystem Impacts: *Spatial heterogeneity* *Spatial displacement* *Assimilative ability* Resource Use: *Energy* *Materials* User Requirements	Built System Environmental Context of System System/Environment Interactions: *External interdependencies* *Internal interdependencies* *System inputs* *System outputs*
Organizational	Hill et al. (1994)	Economic and Social: *Quality of human life* *Social disruption* *Equitable costs/benefits* Environmental: *Biological systems* *Biodiversity* *Resources* *Construction pollution* *Damage to sensitive areas*	Construction Impacts Organizational Structure Operational/Audit Procedures Record Keeping Environmental Awareness Standards/Penalties/Bonuses Environmental Management

2.5.1 Synthesis of Existing Assessment and Evaluation Tools

This section reviews a total of six assessment and/or evaluation tools. The six tools were selected for detailed analysis of the state of the art in building-related sustainability since they represent different scales in facility assessment or evaluation. These scales range from the individual material scale (Lawson 1992; Lippiatt & Norris 1995), to the facility scale (Building Research Establishment 1993; USGBC 1998), to the facility scale plus processes within the facility (DuBose & Pearce 1997; Graedel & Allenby 1995).

On the scale of individual materials, Lawson (1996) developed an index of sustainability for construction materials, based on three classes of variables: resource depletion, inherent pollution, and embodied energy. This index is quantitative, based on estimated or calculated values for a number of subvariables describing each of Lawson's parameters. Likewise, the Building for Economic and Environmental Sustainability (BEES) Index (Lippiatt & Norris 1995) focuses on the scale of individual building materials, and uses six subvariables to describe the environmental vs. economic performance of various materials. Unfortunately, both of these systems are still in their infancy, and precise values have been calculated for only a small number of materials.

Other sources have developed whole-facility scale assessment tools, including the Building Research Establishment Environmental Assessment Method, BREEAM (Building Research Establishment 1993), and the Leadership in Energy and Environmental Design LEED (USGBC 1998) Method. Both tools incorporate aspects of the building life cycle, its surroundings, and the components which comprise it. These tools are currently limited in application to commercial facilities, although versions of BREEAM are being adapted to apply to residential facilities as well. In contrast, the tool developed by Graedel & Allenby focuses on manufacturing or industrial facilities, and is one of only two sources uncovered in this review to include the processes housed by the facility in analyzing its greenness.

Also on this scale, DuBose & Pearce (1997) developed an evaluation tool based on the Natural Step approach to sustainability created by Robért and Eriksson (1994). This tool was developed as a first attempt to operationalize the Natural Step (see Appendix A) to a specific type of technological system, namely built facilities.

2.5.2 Limitations and Opportunities

As is the case with models and frameworks, the review of assessment and evaluation tools for built environment sustainability from the literature shows that disparities exist in terms of the variables included for consideration. Table 2.9 provides a summary of the variables unearthed in the analysis of the assessment and evaluation tools.

One notable conclusion to be drawn from this list of built environment and sustainability variables is that the scale and specificity of variables differs remarkably from tool to tool. For example, the tool developed by the Building Research Establishment identifies Legionnaires' Disease as being significant enough to warrant a separate variable, whereas none of the other tools identify this potential indoor environmental hazard as a specific indicator. Little or no consistency of specificity is shown even within tools, let alone among the set, and the rationale for selecting indicators or measures of each variable is not typically explained in each source. DuBose and Pearce (1997) are one exception to this weakness in that they specifically explain their rationale for indicator selection, albeit at the expense of actually demonstrating the use of their assessment tool.

Other limitations of existing assessment and evaluation tools include scope limitations in terms of variables considered and types of facilities to which the methods apply. One of the tools is also limited in terms of its dependence on databases of information about specific building materials (Lippiatt & Norris 1995). Unlike the models and frameworks, however, many of these assessment and evaluation tools are actively being used in the real world, and have demonstrated their usefulness in terms of increasing the marketability of those stakeholders who obtain certification. This real world utility may in fact be one of the reasons these tools are limited in scope to a small number of indicator variables — measurement and tracking of a large number of indicators has thus far been economically or physically infeasible due to the qualitative nature of many sustainability variables. The developers of the LEED tool, in fact, acknowledge these limitations of data and information, and have made explicit provisions for periodic updating of the indicators and thresholds which must be met to achieve a LEED rating.

2.6. Summary: Establishing a Point of Departure

Based on the triggers and drivers of change discussed in Chapter 1, built environment stakeholders are beginning to realize a need to consider the sustainability of the built environment. This need has resulted in a growing body of heuristics or rules of thumb about how to increase the sustainability of built facilities. While forward-thinking practitioners in the A/E/C industry are actively using this heuristic knowledge, heuristics are unable to provide the ability to control or optimize sustainability improvement efforts, or to predict the effects of those efforts on facility sustainability.

The understanding of sustainability in the built environment is following a path of evolution as shown in Figure 2.3. As shown conceptually in the figure, a limited number of first generation models, evaluation tools, and assessment methods have evolved from heuristic knowledge to address the need for predictability, control, and optimization in undertaking sustainability improvements, but these models suffer from a lack of alignment with both each other and the general theory of sustainability (Figure 2.4). They also fail to provide an operational measure of facility sustainability at a level of resolution sufficient to prioritize improvement options.

Table 2.9: 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*
Individual Material	**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*
Whole Facility	**USGBC (1998)** "LEED - Leadership in Energy and Environmental Design"	Prerequisites *Ozone-depleting chemicals* *Recyclables storage/collecti* *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
Facility + Processes	**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

As detailed in previous sections, these first generation tools are based on divergent implicit theories about the scope and definition of built environment sustainability as reflected in the diversity of variables considered from tool to tool, and the variability in levels of specificity among the variables. Tables 2.10 and 2.11 show the variables identified in analyzing the built environment sustainability literature, organized into like categories. As shown in these tables, the variables differ in specificity within literature categories, and differ in content from category to category. The category-specific tables in the previous sections (Tables 2.5, 2.7, 2.8, and 2.9) also illustrate the divergence of variables considered for sources even within the same category.

Based on the analysis of existing literature on built environment sustainability, three conclusions emerge about the point of departure for this research. First, based on the built environment and sustainability variables considered in the literature, one can conclude that existing theories, tools, and techniques are based on differing definitions of sustainability and apply to different parameters of the built environment (Tables 2.10 and 2.11). No common operationalization of sustainability exists for the domain of the built environment among sources in the published literature, and there is limited agreement about what variables of the built environment are important to consider in predicting or evaluating built facility sustainability.

Second, no generalized predictive or evaluative models or metrics of sustainability for buildings currently exist that meet the objectives of context specificity and generalizability to other types of facilities. Existing assessment and evaluation tools are limited to specific types of facilities (e.g., commercial office buildings or manufacturing facilities), and typically fail to incorporate attributes of the context of application into the

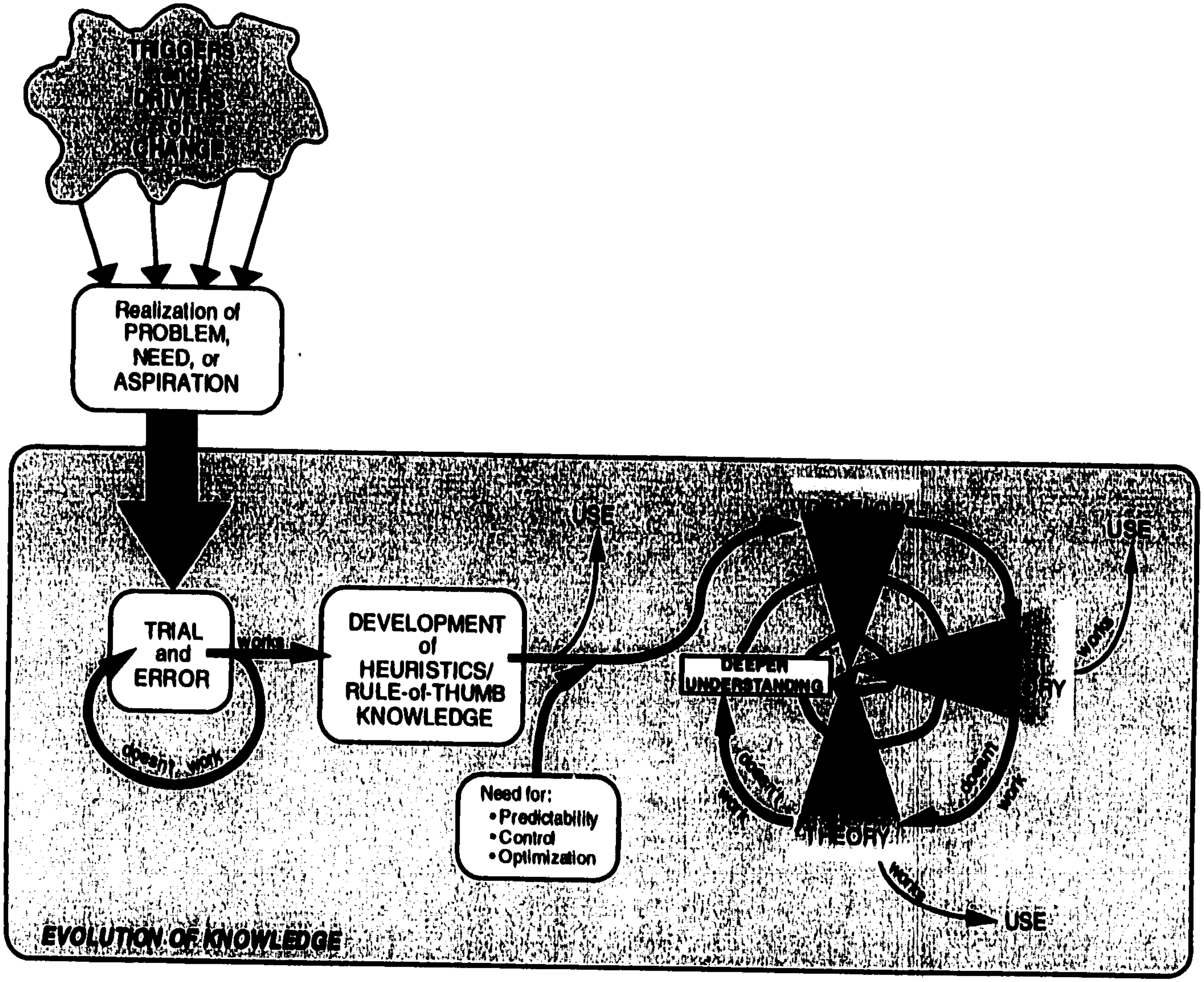


Figure 2.3: The Evolution of Knowledge about Sustainability (based on Petrowski 1994)

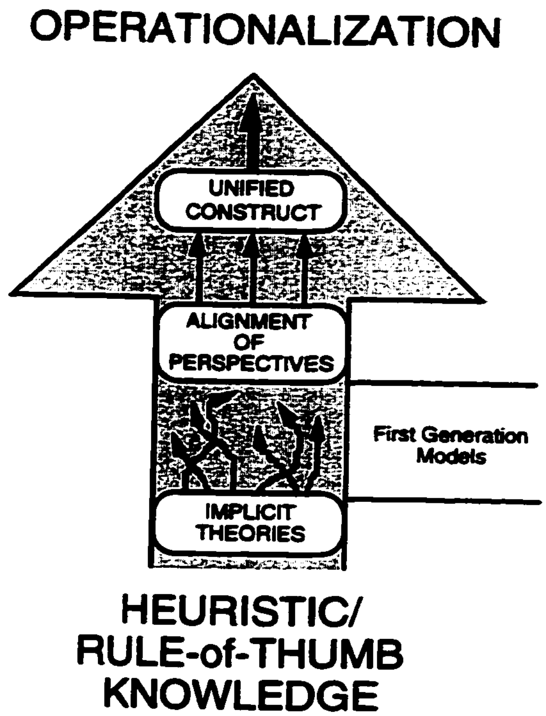


Figure 2.4: Moving from the Point of Departure to Operationalization

Table 2.10: Built Environment Variables from the Literature Review

Heuristics & Guidelines	Resource Guides	Models & Frameworks	Assessment & Evaluation Tools
Energy conservation	CSI Masterformat Divisions	Energy consumption	Resource depletion:
Energy efficiency	Foundations	Water use	*Raw material extraction damage*
Site/Siting	Framing and Panel Systems	Land use	*Extraction efficiency*
Building codes and inspection	Enclosures:	Materials selection	*Resource supply status*
Energy systems	*Sheathing & Wallboard*	Indoor environmental quality	*Recycled content*
Mechanical systems	*Roofing*	Exterior environmental quality	*Required maintenance*
Materials/finishes/fixtures/furniture	*Exterior Siding & Trim*	Building design	*Product recyclability*
Waste management/recycling	*Insulation*	Community design	Inherent Pollution:
Time	*Windows & Doors*	Construction operations	*Embodied solid waste*
Cost	Interior Finishes:	Life cycle operation	*Embodied liquid waste*
Quality	*Floor Coverings*	Deconstruction	*Embodied greenhouse gases*
Design	Landscaping	Embodied energy content	*Embodied toxics/particulates*
Materials	Job Site Recycling	Greenhouse warming gases	Embodied Energy:
Equipment	Site Design	Toxics generated/content	*Process energy requirements*
Safety and Health	Building Size and Shape	Built environment health	*Transport energy*
Systems	Structure and Construction	Integration with ecological systems	*Construction energy*
Indoor air quality	Selling	Economic valuation	Building Materials:
Water conservation		Infrastructure requirements	*Life Cycle*
Recycling and waste management		Waste recovery	Local/Indoor Issues:
Facility Life Cycle:		Construction process technology	*Legionnaires' Disease*
Pre-design		Building technology	*Wind Effects*
Design		Stakeholder integration	*Noise*
Preparing to Build/Procurement		Human aspirations	*Overshadowing*
Construction		Energy	*Water economy*
Occupation/Maintenance		Water	*Ecological value of site*
Refurbishment		Waste	*Cyclists' facilities*
Demolition		Materials:	*Ventilation/smoke/humidity*
Building Design:		*Embedded energy*	*Hazardous materials*
Passive solar design		*Renewability*	*Lighting*
Indoor Environmental Quality		*Permanence/Reusability*	*Thermal comfort*
Materials and specifications		Indoor Air Pollution	*Asbestos-free*
Local Government		Density	*Commissioning*
		Built System	*Energy codes*
		Environmental Context of System	*Indoor Air Quality*
		System/Environment Interactions:	Construction Waste Management
		External interdependencies	Existing Building Rehabilitation
		Internal interdependencies	Landscaping/Exterior Design
		System inputs	Using a LEED-certified Designer
		System outputs	Occupant Recycling Equipment
		Construction Impacts	Operations & Maintenance Facilities
		Organizational Structure	Siting
		Operational/Audit Procedures	Transportation
		Record Keeping	Facility Life Cycle
		Environmental Awareness	Resource Flows into/out of facility
		Standards/Penalties/Bonuses	Environmental Impact:
		Environmental Management	*On site*
			Embodied in resources
			Resulting from waste disposal
			Facility efficiency
			Site selection, dev't. and infrstrc.
			Business products
			Business processes
			Facility operations
			Refurbishment/transfer/closure

Table 2.11: Sustainability Variables from the Literature Review

Heuristics & Guidelines	Resource Guides	Models & Frameworks	Assessment & Evaluation Tools
Natural Resources:	Natural Resources:	Natural Resources:	Ecology impacts/biodiversity
Water supply	*Efficiency*	*Consumption*	Cyclic processes
Energy	*Energy Efficiency*	*Depletion*	Ecosystem damage
Consumption	Materials:	*Conservation*	Environmental Performance
Materials	*Benign substitution*	*Degradation*	Ecological impacts/pollution
Efficiency	*Recycled content*	*Reuse*	*CO_2 emissions*
Cultural resources	*Use of recycled materials*	*Renewability*	*Acid rain*
Energy management	*Energy savings in mfg.*	*Recyclability*	*Ozone depletion*
Efficiency:	*Durability*	*Use of Renewables*	*Ozone-depleting chemicals*
Energy	*Dimensional lumber alts.*	*Use of Nonrenewables*	Water Quality:
Water	*Embodied Energy Efficiency*	*Energy Use*	*Water quality stds.*
Resources	*Material Efficiency*	*Materials Use*	Material accumulation:
Sensitive ecosystems	Environment Protection	Ecosystem Impacts:	*Lithospheric*
Materials:	Environmental Impacts:	*Spatial heterogeneity*	*Synthetic*
Ecologically sound	*Toxics*	*Spatial displacement*	Residues:
Healthy	*Sensitive ecosystems*	*Assimilative ability*	*Solid*
Site development impacts	Environmental responsibility	Environment:	*Liquid*
Pollution prevention	Competitiveness	*Impact*	*Gaseous*
Environmental performance:	Consensus of endorsement	*Degradation*	Waste minimization:
Human health and safety	Health and Safety	*Toxicity*	*Recycled materials*
Environmental damage	Affordability	*Biological systems*	*Recyclables storage/collection*
Energy consumption		*Biodiversity*	Resources:
Materials from threatened species or environments		*Resources*	*Use*
Human satisfaction		*Construction pollution*	*Depletion*
Waste generation		*Damage to sensitive areas*	Water Conservation
Renewable resources		Waste:	*Water conservation stds.*
Waste:		*Generation*	Energy:
Reduction		*Accumulation*	*Consumption*
Prevention		*Composition*	*Use*
Healthy environments		*Assimilation*	Economic Performance
Human Satisfaction		Quality	
Building durability		Humans:	
Stakeholder partnerships		*Needs*	
Public dialog and education		*Aspirations*	
Construction costs		*Requirements*	
Building maintenance & management savings		*Quality of life*	
Insurance & liability		*Social disruption*	
User health/productivity		*Equitable costs/benefits*	
Building value		Systems integration:	
		Human social systems	
		Natural ecological systems	
		Human technology systems	

analysis. In other words, existing tools do not include any consideration of the relative scarcity or abundance of local resources, the richness or poverty of local ecosystems, or other situation-specific factors that influence decision making on a facility scale. For example, the outcome of applying the BREEAM method (Building Research Establishment 1993) to a building in Phoenix, AZ (where water is extremely scarce) would be exactly the same as for a building in Seattle, WA (where water is relatively abundant). As discussed in Chapter 1, considering the context of the system or technology being evaluated is key to accurately assessing sustainability (DuBose 1994). Thus, this lack of context specificity is a major limitation of existing assessment tools.

Third, none of the existing tools for assessment or evaluation can effectively be used to prioritize alternatives on an intra-facility scale. Some of the tools (e.g., the BES Index and BEES) can compare individual materials and thus provide a basis for prioritizing raw materials in terms of their relative sustainability. Likewise, the whole facility and facility + process tools (e.g., BREEAM, LEED, The Natural Step, and Industrial Ecology) can generate values, either quantitative or qualitative, for evaluating and comparing whole facilities in terms of the variables they include. In other words, one could compare two separate buildings using these tools and draw some conclusions about which building might be more sustainable, environmentally friendly, or ecologically responsible than the other. However, none of these tools provides any guidance for examining complete solutions (e.g., lighting retrofit, envelope sealing, etc.) in terms of the sustainability of the facility in which they are implemented. This capability is critical for decision makers who need to choose solutions for their facilities that are customized to the specific situation being addressed. Thus, meeting this need, i.e., creating an assessment tool to compare and prioritize improvement alternatives in the context of specific facilities, is the primary goal of this research.

To summarize, the built environment sustainability literature as a whole includes gaps, inconsistencies, and redundancies in how sustainability is represented (Figure 2.4). These divergent perspectives must be aligned with existing theories of general sustainability to create a unified construct of the concept as it applies to built facilities before developing a measure of facility sustainability. Chapter 4 describes the processes and outcomes of creating such a unified construct of sustainability, based on corroborating analyses of the published literature on theoretical sustainability. Before proceeding to this first contribution of the research, however, Chapter 3 presents details of the approach and methodology that guided this research, and the validity criteria and strategies used to verify the research outcomes.

CHAPTER III

RESEARCH APPROACH

The previous two chapters presented the problem of prioritizing opportunities for increasing the sustainability of built facilities and established a point of departure for this research in terms of existing work. Some approaches exist to set priorities based on quantitative parameters such as cost, economics, functionality, etc., but none of this work enables prioritization according to the whole concept of sustainability. Likewise, while a significant body of literature exists on sustainability for the built environment, it fails to provide a method to help facility decision makers set priorities to change their facilities, or to understand how selected options will impact the sustainability of their facilities.

This research has created a quantitative model of built facility sustainability that can be used to set priorities among incremental improvements in the sustainability of facilities. The hypothesis tested in this research is that it is possible to create such a quantitative model of sustainability for built facilities. The purpose of this chapter is to describe the research process used to test this hypothesis by operationalizing sustainability in terms of the built environment and developing a model and accompanying process for evaluating the relative sustainability of improvement options on a facility scale as a whole.

3.1. Research Process

The research process consisted of three primary steps: (1) developing a unified construct or mental model of sustainability based on the theoretical sustainability literature; (2) operationalizing the construct of sustainability in the form of a quantitative model of built facility sustainability; and (3) developing a process for applying the model to prioritize improvement options for increasing facility sustainability.

3.1.1 Developing a Unified Construct of Sustainability

The first key part of this research was to analyze the theoretical sustainability literature to determine what set of principles or constraints can be used to uniformly and completely describe the concept of sustainability. This step provided the opportunity to reevaluate sustainability outside the specific domain of built facilities and establish a consistent and unified theoretical construct or mental model to address existing definitional disparities within the built environment literature. The methodology for developing a unified construct of sustainability consisted of two corroborating methods of naturalistic inquiry (Guba & Lincoln 1980; Yin 1989; Krippendorf 1980) to capture the essence of perspectives on sustainability using available expert knowledge represented in the published literature. Chapter 4 details the processes and outcomes of this step of the research.

Identifying Parameters to Define Sustainability: In the first step of construct development, a review of general literature on sustainability was undertaken to identify a set of parameters and constraints that define the concept, outside the domain of built facilities. Chapter 4 contains the results of this literature review, supported by a detailed review of the general sustainability literature in Appendix A. The outcome of this step was a classification of three parameters (human-related parameters, resource base-related parameters, and ecosystem-related parameters) that define the sustainability of all systems, with specific constraints relevant to systems at global and technological system scales.

Supporting the Choice of Parameters Using Content Analysis: A content analysis of 83 definitions of sustainability from the published literature was used to corroborate the three element set of sustainability principles and establish their validity (Guba & Lincoln 1981; Yin 1989). Content analysis is a linguistic technique for "the objective, systematic and quantitative description of the manifest content of communication" (Berelson 1952, p. 18, in Krippendorff 1980). Of the choices of methods to capture the essence of sustainability, content analysis afforded an objective and systematic approach without potential informant confounds and logistical constraints associated with other approaches such as the Delphi method (Krippendorff 1980). As such, content analysis provides an unbiased appeal to authority, represented in the published literature, to determine what are the salient issues of sustainability in general. Content analysis also serves to support the conclusion of translation validity by providing a direct comparison between the construct definition derived from the content domain in the literature analysis, and the construct itself as identified in the content analysis (Trochim 1998d). Appendix B presents a detailed discussion of the methodology and interim results of the content analysis, along with a list of the 83 definitions included in the analysis and their sources.

The Unified Construct of Sustainability: Having corroborated the parameters of sustainability using content analysis, the next step was to develop a representation of the construct to serve as a framework for sustainability evaluation. The outcome of this first part of the research was a set of three parameters to define a construct of sustainability for systems at both global and technological scales, along with relevant thresholds and limits of those parameters to structure the construct as a decision space. This construct contributes a unified and theoretically corroborated point of departure from the general sustainability literature, and comprises the foundation for the quantitative model of built facility sustainability developed in the next step of the research.

3.1.2 Operationalizing Sustainability for Built Facilities

The next step in the research was to operationalize the construct of sustainability to built facilities. Operationalization is a way of translating a theoretical construct into a set of variables related by mathematical or logical relationships, the value of which defines the set of conditions under which the concept exists (Peters 1991). Chapter 5 details this step of the research.

Defining and Representing Built Facility Systems: The process of modeling built facility sustainability began by developing a systems representation of built facilities, including definition of an appropriate scale of analysis and selecting a way to consistently define the boundary of the system at the desired scale. This step is part of the problem formulation phase of model development and problem solving (Zandi 1993; Sage 1991), and is necessary to frame the construct of sustainability in terms of the domain to which it will be applied, i.e., built facilities. Defining built facilities in terms of a systems representation also helps to establish construct validity by providing a consistent point of reference to describe and characterize the domain of application (Cook & Campbell 1979; Trochim 1998d).

The representation was used to create a classification of facility system and contextual factors relating to built environment sustainability, and served as a way to systematically identify relevant variables for each sustainability parameter in the construct developed in Chapter 4.

Identifying Variables and Subvariables Comprising the Model: The primary variables identified via the representation of facility systems were expanded into a hierarchy of subvariables based on relationships and principles identified in the review of the literature. The total depth of the hierarchy was determined by the point at which subvariables could actually be measured or estimated. In other words, the process of splitting a given variable into more detailed subvariables stopped when a value for the subvariable could be estimated, calculated, or measured using data available to built environment decision makers.

At each level of the hierarchy, the mathematical relationships between variables at that level were determined based on an appropriate behavior of the parent variable/parameter at limit states of the subvariables (i.e., positive and negative scalar extremes and zero). Values for the appropriate behavior of each variable were obtained from the sustainability literature reviewed in Chapter 4 and Appendices A and B. For example, the appropriate behavior of a variable describing resource base impact would be to become increasingly negative as the total quantity of resources goes to zero, indicating that resources are being used up (Daly & Cobb 1994; Solow 1994; etc.).

Developing Operational Measures for Model Variables: After the sustainability parameter functions were expanded to a measurable level, the next step was to identify sources of data for all of the subvariables that could be measured or calculated directly, and to define strategies or methods for estimating the subvariables that could not be directly measured. The final step was to specify sources of data to be used to calculate each subvariable. This process comprised the actual operationalization of sustainability parameters in terms of variables that could be measured directly, calculated, or estimated using available data.

The Model of Facility Sustainability: The outcome of this part of the research was a quantitative model or operational objective function (Simon 1986; Peters 1991) defining the sustainability of built facility systems, in terms of the three operational parameters of sustainability from Chapter 4 and the facility-related subvariables used to calculate them. The operational objective function provides decision-makers with a mechanism for evaluation and prioritization of facility improvement options using the principles of decision theory (Simon 1986) described in Chapter 6.

3.1.3 Applying the Model of Facility Sustainability to Prioritize Improvement Options

The final phase of the research was to specify a method for applying the model of facility sustainability to prioritize improvement opportunities facing decision makers, to demonstrate the process as it was applied to a case study facility, and to analyze the performance of the model using comparison with expected outcomes, sensitivity analysis, and analysis of mathematical properties.

Specifying a Method for Applying the Model of Sustainability: The first step in applying the model of sustainability for facilities was to specify a process or method in which the model could be used to accomplish the goal of the research: prioritizing improvement opportunities for increasing facility sustainability. Chapter 6 contains a description of the application method. Using a decision tree approach based on classical decision theory (Simon 1986), a method was specified to establish a baseline state of sustainability, identify potential improvement options, forecast future sustainability states after implementing the options, prune infeasible options, and prioritize remaining options for implementation. A decision model consisting of a single deterministic outcome for each alternative and a bounded, satisficing approach to identifying alternatives (Meyer & Miller 1984) was used. This decision model is appropriate for this research because it provides sufficient complexity to prioritize options, while remaining understandable to and usable by built environment decision makers.

Demonstrating the Method Using a Case Study: The next step in applying the model was to demonstrate the application process using a case study of a residential facility in Atlanta, GA. This approach is appropriate given the nature of the research, which had the goal of transforming theory into a vehicle for examining other cases (after Yin 1989). The case itself had multiple embedded alternatives to illustrate the operation of the metric over six different improvement options. This embedded research design provided the context for experimenting with model sensitivity under different forecasting scenarios, as undertaken in the process of analyzing model performance.

Analyzing Model Performance: The last part of the research process involved analyzing the performance of the model using three separate approaches: comparison of model results with expected results, sensitivity analysis, and analysis of mathematical properties of the model. These three approaches to analyzing model performance permitted evaluation of the model from three separate perspectives and afforded the opportunity to identify lessons learned with respect to the utility, efficacy, and usability of the process and model. These three approaches are followed in Chapter 6 by an analysis of the validity of the model and process in terms of the validity questions developed in the next part of this chapter.

A Process for Using the Metric of Sustainability to Prioritize Improvement Options: The outcome of this final phase of the research was a process for applying the model of sustainability to prioritize facility improvement options, along with an example of the process as applied in the context of an existing, operating facility and a set of lessons learned from that application. The model of sustainability, developed from a unified construct of sustainability grounded in the theoretical sustainability literature and accompanied by a process for applying it to prioritize improvement options, comprises the contribution of this research.

3.2. Validation of the Research Product

An important aspect of the research is to evaluate its validity. Validity is the "best available approximation to the truth of a given proposition, inference, or conclusion" (Trochim 1998b). The purpose of establishing the validity of a proposition, inference, or conclusion is to allow others to have confidence in its accuracy, applicability, and use.

The methodological literature identifies four general types of validity: Conclusion Validity, Internal Validity, Construct Validity, and External Validity. Each of these types of validity builds cumulatively upon the others to establish the overall validity of the research (Figure 3.1). The following subsections define these four types of validity with respect to the research hypothesis, and set up evaluation questions that must be answered to evaluate the validity of the work. Chapter 6 contains the answers to these questions in terms of the research findings.

3.2.1 Conclusion Validity

Conclusion validity is defined as "the degree to which conclusions we reach about relationships in our [study] are reasonable...credible or believable" (Trochim 1998f). For causal studies, establishing conclusion validity involves answering the question, "In this study, is there a ***relationship*** between the two variables [being examined]?" (Trochim 1998b, emphasis original). In this research, the hypothesis being tested is that it is possible to develop a model of built facility sustainability that allows decision makers to prioritize facility improvement options according to their relative influence on facility sustainability. In terms of this hypothesis, the question becomes, "Was it possible to construct a quantitative model of built facility sustainability that does what it was designed to do, i.e., prioritize improvement options in terms of their relative sustainability?" Section 6.4.1 examines this question in terms of the research findings.

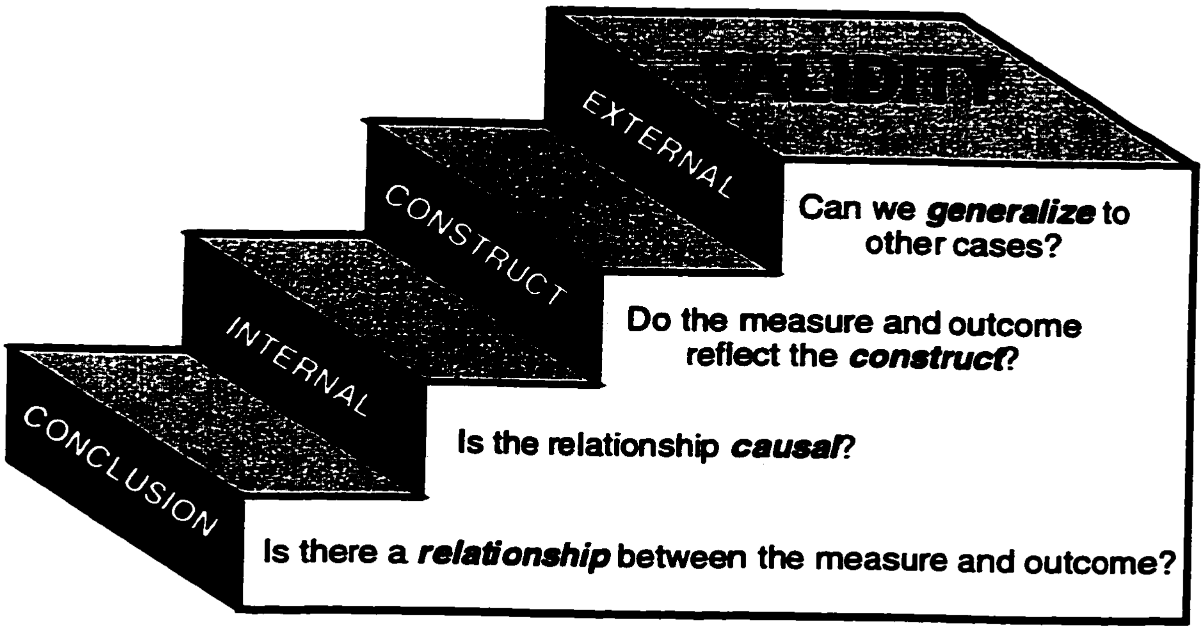


Figure 3.1: Cumulative Steps to Establishing Validity (after Trochim 1998b)

3.2.2 Internal Validity

Internal validity is the quest to determine whether or not an identified relationship is causal (Trochim 1998b). To establish causal validity, one must answer the question, "Could the difference [i.e., observed relationship] have been the result of some other factor?" (ibid.). For descriptive or exploratory studies, internal validity refers to the accuracy and quality of the study, and elimination or control of potential biases that may have influenced the results identified in conclusion validity. In terms of the hypothesis of this research, the question becomes, "Do the variables used in the model really reflect the properties of a built facility that determine its sustainability?" Section 6.4.2 examines this question in terms of the research findings.

3.2.3 Construct Validity

Construct validity is "the degree to which inferences can legitimately be made from the operationalizations in your study to the theoretical constructs on which those operationalizations were made" (Trochim 1998e). It is an assessment of "how well you translated your ideas or theories into actual programs or measurement instruments" (ibid.). Figure 3.2 provides a graphical representation of the idea of construct validity. In terms of the hypothesis being tested in this research, the question of construct validity becomes, "Does the prioritization of options generated by the model make sense in terms of what is known about built environment sustainability?" To establish construct validity, Trochim presents three conditions:

1. The construct must be set with in a semantic net that shows how the construct relates to other constructs.

2. Operationalizations of the construct should match what one would expect based on knowledge of theory.
3. Data from the research should support the theoretical view of the relations among constructs.

Section 6.4.3 examines each of these conditions, including evidence to support the following qualities of the model:

- Predictive Validity – can predict something it should theoretically be able to predict
- Concurrent Validity – can distinguish groups between which it should theoretically be able to distinguish
- Convergent Validity – is similar to other operationalizations to which it theoretically should be similar
- Discriminant Validity – is not similar to other operationalizations to which it theoretically be dissimilar

3.2.4 External Validity

The final type of validity to be established is external validity, defined as the degree to which the effects identified in a study can be generalized to other persons, places, things, or times (Trochim 1998b). In terms of the hypothesis tested in this research, the question to establish external validity becomes, "Will the model work in other situations? If so, in what other situations will it work?" Section 6.4.4 examines this question in terms of the research findings.

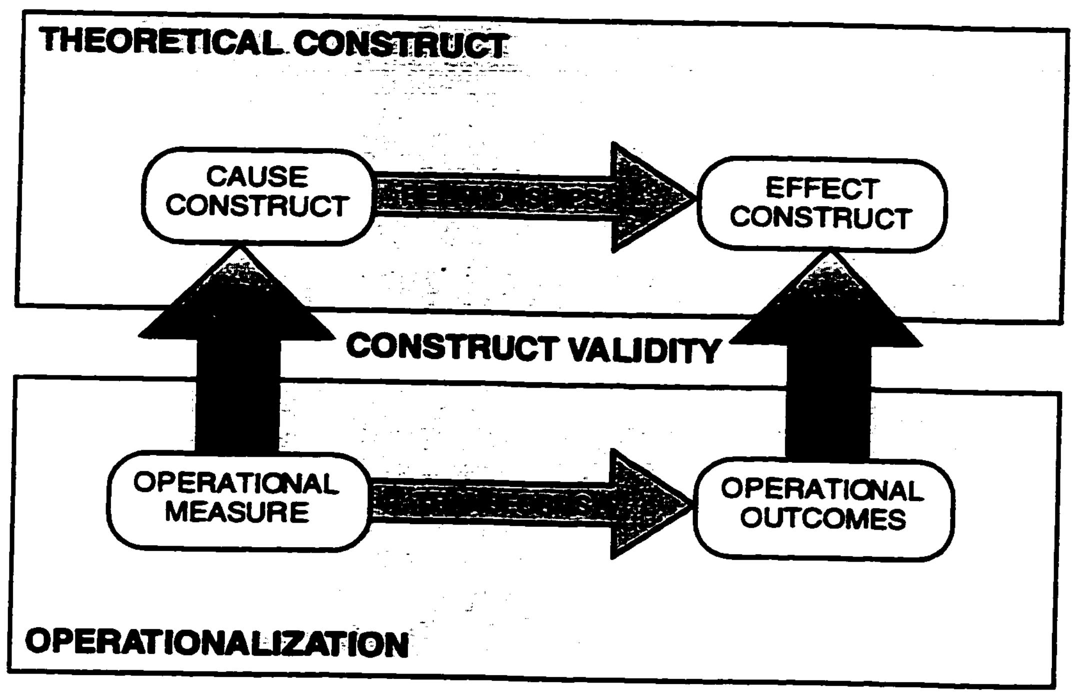


Figure 3.2: The Concept of Construct Validity (after Trochim 1998e)

3.3. Summary: Expected Outcome of the Research

This chapter described the research approach and validation strategy used in this work to test the research hypothesis: it is possible to develop a model of built facility sustainability that allows decision makers to prioritize facility improvement options according to their relative influence on facility sustainability. As described in the point of departure in Chapter 2, none of the models, frameworks, or tools in the existing body of built environment sustainability knowledge provides the capability to prioritize improvement options on the scale of individual facilities. Furthermore, little or no agreement exists among these models, frameworks, and tools regarding what variables are important to measure the concept of sustainability as it applies to built facilities. Thus, the first step of the research is to establish a unified construct of sustainability that resolves the gaps, conflicts, and disparities among existing notions of sustainability with respect to global and technological systems. The expected outcome of this first step of the research is a unified construct or mental model of the concept of sustainability as it applies to systems, including a set of parameters that define the concept, thresholds of those parameters that define the boundary between sustainability and unsustainability, and a representation of the relationship among those parameters that takes into account said thresholds.

With the construct of sustainability developed in the first step, the next step is to operationalize the construct of sustainability for the domain of built facilities. Operationalization of the construct includes expanding the parameters of sustainability into variables that can be measured for built facilities, and establishing mathematical relationships to combine those variables to permit calculation of values for the parameters themselves. The expected outcome of this second step is a quantitative model of the construct of sustainability as it applies to built facilities, that can be used to calculate values of sustainability for a particular state of a facility.

A third step of the research is needed to embed the quantitative model of facility sustainability within a process or method that uses the model to prioritize improvement options. This research step includes specifying procedural steps for benchmarking the initial state of sustainability for a facility, identifying candidate improvement options, evaluating the sustainability of the facility after implementing the improvement options, pruning any options that are infeasible, and prioritizing the set of feasible options according to their relative influence on the sustainability of the facility as a whole. The expected outcome of this step is an operational process for prioritizing improvement options that can be used to support decisions to increase the sustainability of built facilities.

Toward achieving these expected outcomes, the following three chapters describe the three steps of the research to establish a unified construct of sustainability (Chapter 4), a quantitative model of facility sustainability based on the unified construct (Chapter 5), and a process for using the model to prioritize facility improvement options (Chapter 6).

CHAPTER IV

DEFINING SUSTAINABILITY FOR SYSTEMS

As discussed in Chapter 2, each of the existing models of sustainability for built facilities is based on a slightly different implicit theory of what is important for built environment sustainability. Thus, the first key step in this investigation was to align these disparate perceptions into a unified construct of sustainability that: (1) defines a set of parameters that uniformly describe the concept of sustainability for systems; (2) supports the selection of these parameters using the methodology of content analysis; and (3) assembles these parameters into a unified construct of sustainability on the scale of the global Earth system and, on a smaller scale, technological systems in general. Subsequent chapters will then describe the operationalization of the construct of sustainability to the domain of built facilities and the development of a process for using it to prioritize facility improvement options. The first step is to examine the parameters that can be used to define sustainability.

4.1. Developing Parameters to Define Sustainability

In order to develop a set of parameters to comprise a unified construct of the concept of sustainability for systems, differentiation among the possible scales on which operationalization can occur is important. This section examines two scales for which sustainability is a relevant concept: the global systems scale and the technological systems scale. Understanding the constraints of sustainability on a global scale is useful before considering the parameters that govern the concept on smaller scales, since ultimately the constraints of the global scale govern smaller systems as well. This section provides a summary of the relevant parameters and constraints of sustainability on a global scale, followed by a discussion of how these parameters and constraints can be scaled down for technological systems. Appendix A contains a detailed discussion of the theoretical literature of sustainability on which these sections are based.

4.1.1 The Issue of Scale in Defining Sustainability

Various scales of systems analysis can meaningfully apply to the concept of sustainability. This chapter considers two possible scales of analysis: the global scale and the technological system scale. In the context of this dissertation, the term technological systems refers to systems smaller in scale than the entire global system, i.e., sub-global systems, or systems at a more human scale. These scales lie along a continuum of system sizes, and are discussed here since they represent a way to classify current discussions of sustainability in the literature and to distinguish between differing objectives used to achieve sustainability.

The Global System Scale of Sustainability: The largest level of analysis generally considered in the sustainability literature is the global scale of analysis. Analysts who take this perspective (e.g., Vitousek et al. 1986) look at the system of Earth as a whole, with inputs of solar radiation from the sun and outputs of waste heat. At this level, issues such as survival of the human species, equity among humans, and maintaining resource bases and ecosystems are meaningful.

The Technological System Scale of Sustainability: The remainder of the sustainability literature focuses on smaller scales of analysis; that is, with respect to specific technologies and technological subsystems of the global Earth system. At the technological level of analysis, meaningful issues include the degree to which technological systems serve the purpose for which they were designed, the direct and indirect impacts those systems have on natural ecosystems, and the flows of matter and energy which result from system creation, operation, and decommissioning.

In this dissertation, the term technology is taken to mean "the *application* of knowledge to the achievement of particular goals or to the solution of particular problems" (Moore 1972, p. 5). Thus, technologies can be defined as the manmade components or entities that comprise subsystems of the global Earth system. Technologies include "not only the physical tools we use to interact with our environment, but also symbols, processes, and other non-tangible effectors such as language and economic transactions which serve as interfaces between humans and enable actions to occur toward the solution of problems" (Vanegas et al. 1995).

Coupled with naturally existing entities such as plants and animals, manmade technologies comprise the systems humans use to meet their needs and aspirations. Humans, as the creators and users of technologies, are also entities within these systems. It is these subsystems of the global Earth system – influenced, created, or manipulated by humans to meet their needs and aspirations – of which built facilities are a part.

4.1.2 Sustainability at a Global System Scale

In developing a unified construct of sustainability, basic laws of thermodynamics provide a useful foundation, since they govern the global system and the natural and manmade systems that comprise it. After the laws of thermodynamics, human-related objectives under the anthropocentric paradigm of sustainability add to the richness of the concept, resulting in three fundamental objectives of sustainability. These fundamental constraints serve as a framework for examining technologies created by humans and the systems of which they are a part, in terms of how they contribute to or detract from overall global sustainability.

Thermodynamic Foundations: In order for any system to be sustainable, there must be no net loss of the sum total of matter and energy circulating within the system. Such a state is possible for the system defined as Earth, since energy lost as thermal radiation from the Earth can be offset by solar radiation absorbed from the sun.

In addition to conservation of matter and energy, the state of entropy within the system must be stable in order for the system to survive into perpetuity (Georgescu-Roegen 1971). Entropy is the degree of disorder of a system, and is usually the inverse of the potential usefulness something has for humans. For example, an unlit match has lower entropy and higher potential usefulness than a match which has already been lit and extinguished. By lighting the match, we as humans can make use of its potential energy; however, as the match is lit and extinguished, its entropy increases irreversibly - it is impossible to unlight a match.

In all systems, entropy increases with every expenditure of energy, and can only be offset in one system by a greater sacrifice of entropy in some other system; therefore, the net entropy of the universe is continually increasing toward a state of disorder (Van Wylen & Sonntag 1985). For the Earth system, however, the potential exists for the amount of energy received by Earth from the sun to exceed the amount of energy lost as thermal radiation (the difference is commonly called the solar energy budget), and can be used to offset increases in entropy resulting from transformations of matter and energy within the Earth system. Thus sustainability is theoretically possible for the system defined as Earth, as long as the inhabitants of Earth consume less energy than supplied by the solar energy budget. To remain within this budget (described quantitatively by Vitousek et al. 1986), two global objectives of sustainability can be identified:

1) **Ecosystem Degradation:** Minimize degradation of natural ecosystems (since they are the mechanism for capturing solar energy in the form of photosynthesis)
2) **Resource Consumption:** Minimize the gain in entropy as a result of consumption-related processes.

These basic physical constraints represent limits within which actions on Earth must remain in order to be sustainable. However, they must be considered in the context of anthropocentric concerns in order to provide a useful concept for human decision making.

The Human Component: In describing how humans are affected by actions to increase sustainability, it is necessary to consider issues of inter-generational (between generations) and intra-generational (within generations) equity (WCED 1987), as well as the self-interest of those whose task is to achieve sustainability. To elaborate, three basic objectives can be identified:

1) **Motivation for Initiators:** Maintain standards of living at least as high as the ones that currently exist
2) **Intergenerational Equity:** Leave the Earth in at least as good a condition as it presently exists
3) **Intragenerational Equity:** Bring everyone else up to at least a decent standard of living.

The first of these goals, maintain standards of living at least as high as the ones which currently exist, is borne of practical considerations. By definition, no rationally self-interested person will voluntarily sacrifice his or her own standard of living without some compensating benefit of equal or greater utility (Simon 1983). Moreover, reliance on such constructs as conscience or guilt to motivate human behavior to become more sustainable is unwise, since such motives tend to be generally unreliable and often self-extinguishing (Hardin 1968). Therefore, in order to foster acceptance of any proposal for sustainability, assurances must be included that those who undertake to change their lifestyles to achieve sustainability will benefit as a result of their commitment.

The second goal, leave the Earth in at least as good a condition as it presently exists, is aimed at achieving intergenerational equity. By leaving the Earth as good as or better than at present, decision makers ensure that future generations will not only have the same set of resources with which to work, but also the accumulated body of lessons learned that humans have developed as a result of our life experiences. The phrase at least as good has been interpreted in various ways in the sustainability literature, ranging from leaving the nonrenewable resource base completely unchanged from its present state (as discussed in Daly 1994), to using nonrenewable resources as necessary provided that adequate substitutes are created (e.g., Solow 1993; Mikesell 1992). Adopting the more conservative view described by Daly, the ultimate goal should be to strive to leave resource bases and natural ecosystems as unchanged or improved as possible while working toward achieving the first and third goals.

The third goal, bring everyone else up to at least a decent standard of living, is concerned with the issue of intragenerational equity. In defining what comprises a decent standard of living, this investigation stipulates the interpretation of Liverman et al. with respect to setting a threshold of acceptability: survival of the human species "with a quality of life beyond mere biological survival" (1988, p. 133). To what level beyond mere biological survival is a question that is largely culturally dependent. In situations where the biological survival of human individuals is currently infeasible, taking action to improve living conditions to the point of survival is a first step toward intragenerational equity. In other situations such as in developed countries, living standards are generally far above the minimum required for basic human survival, and fall under the first constraint discussed earlier: Motivation for Initiators.

Achieving intragenerational equity is important not only because of ethical considerations for the welfare of people in developing nations, but also because humans cannot hope to develop common goals and a coordinated course of action for achieving sustainability when people are concerned for their very survival and lacking in basic human rights (e.g., Jacob 1994). Common goals and coordinated action are required to achieve sustainability because no action within the Earth system is entirely without ramifications for other entities and processes in the system. Due to the contextual nature of sustainability, actions which seem rational and sustainable to one party acting in isolation may actively conflict with the rational actions of other parties in the interconnected real world (DuBose 1994; Hodge 1995; Cernea 1993). Thus, global objectives and cooperative actions are needed to reach a state of sustainability, and achieving some degree of intragenerational equity is essential to elicit that cooperation (Ruckelshaus 1989; Mink 1993).

4.1.3 Sustainability at a Technological Systems Scale

Three fundamental objectives of sustainability follow from the thermodynamic and anthropocentric objectives of sustainability developed in Section 4.1.2. In making decisions with respect to selecting a sustainable course of action or technology for a given context, decision makers should strive to meet the following objectives:

1) Minimize negative impacts to resource bases, while
2) Satisfying human needs and aspirations both now and in the future, and
3) Causing minimal negative ecological impacts.

The following sections explore each of these fundamental objectives in more detaii.

Minimizing Resource Consumption: The use or consumption of matter and energy resources should be minimized because consumption of these resources inherently involves increasing the entropy of materials and energy, rendering them of lower utility for future use (Roberts 1994; Rees 1990). By subjecting materials and energy to consumption processes, humans decrease their potential utility to current and future generations. Therefore, consuming as little matter and energy as possible, or doing more with less, is a fundamental objective of sustainability at a technological level.

Satisfying Human Needs and Aspirations: Doing more with less relates as well to the second objective: satisfying human needs and aspirations. While it is true that one cannot simultaneously optimize more than one variable at a time (e.g., Daly 1994), some sort of tradeoff may ultimately need to be made between human satisfaction and resource consumption in order to achieve sustainability. For the same reasons that justify maintaining current standards of living to achieve sustainability, including human satisfaction as an objective is important: most humans will not accept the measures necessary to change the state of the world unless they are personally satisfied as a result of those changes. Thus, maintaining human satisfaction and satisfying basic human needs (i.e., those needs that must be met for biological survival—air, water, food, and shelter) and aspirations (desires beyond biological survival needs) is an objective for the sustainability of a human system or technology along with minimizing resource consumption and subsequent adverse impacts to resource bases.

In the context of this dissertation, the term human satisfaction should be interpreted as satisfying human needs and aspirations. Economics also ties into the human satisfaction component of sustainability – within the current paradigm of economics-driven development, human satisfaction is unlikely to occur without ensuring that economic interests are protected.

Minimizing Negative Impacts to Ecosystems: Finally, the degree to which a technology causes negative or positive ecological impacts is an important factor for technological system sustainability, since the environment consists of ecosystems whose ongoing health is essential for human survival on Earth (e.g., Goodland 1994). Sustainability of the human race requires that ecosystems be protected and preserved in a reasonable state of health through maintaining biodiversity, adequate habitat, and ecosystem resilience. Decision makers must therefore seek to minimize pollution and ecological destruction resulting from the creation and deployment of technologies, and to preserve the health of ecosystems that are impacted by our technologies.

4.1.4 Defining Parameters of Sustainability

Based on the objectives described in the previous sections, analogous sets of three sustainability parameters can be identified for the global and technological systems scales of analysis. Figure 4.1 illustrates these parameters for the two system scales of sustainability. The next section provides support for the selection of these parameters, followed by a conceptual representation or construct of sustainability that takes into account the limits and desired values for each parameter in Section 4.3.

4.2. Supporting the Choice of Parameters to Define Sustainability

To provide support for the set of parameters identified in the previous section, a parallel technique was used for the purposes of corroboration. The technique used to support the choice of parameters was content analysis, a linguistic tool for extracting the meaning or content of written or verbal text or narrative (see Chapter 3). Appendix B contains the details of the content analysis, which was applied to 83 definitions of sustainability from the theoretical literature on the topic. The following subsections present an overview of the analysis and a discussion of the results.

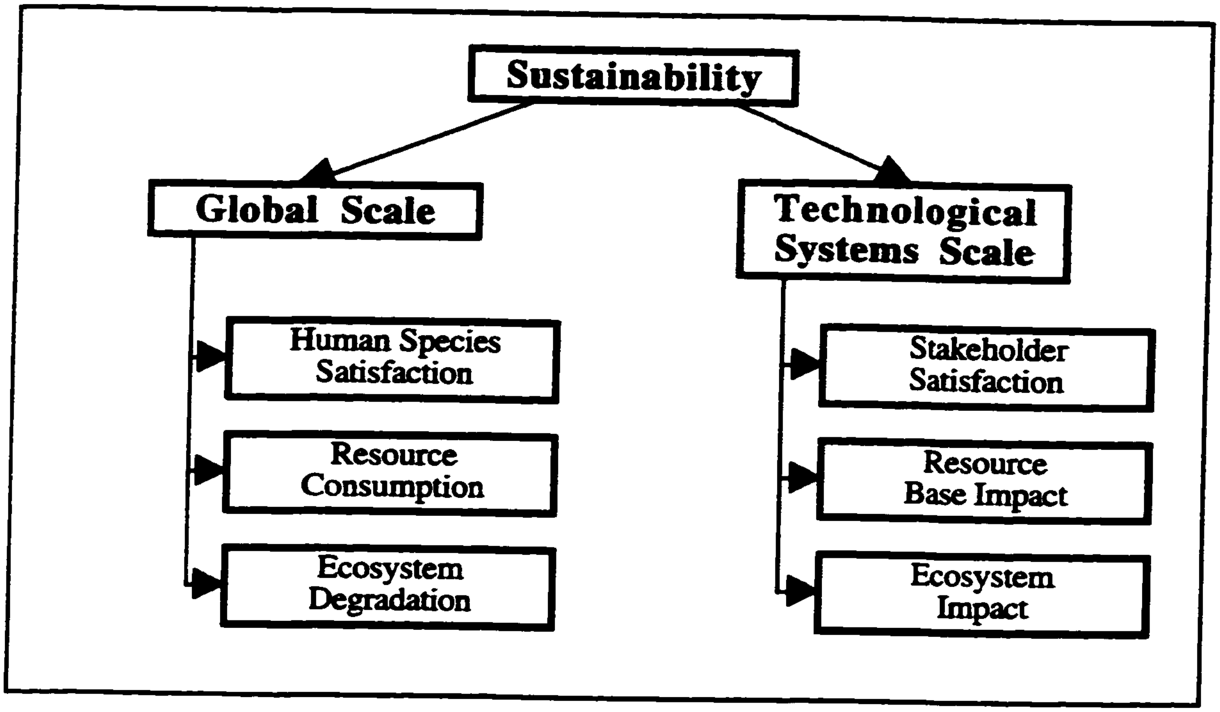


Figure 4.1: Parameters to Define Sustainability

4.2.1 Hierarchical Organization of Propositional Units

The literature examined in the content analysis is expressed in terms of propositional units drawn from key words in the 83 definitions of sustainability. These units naturally cluster into three categories analogous to the three sustainability parameters developed in Section 4.1 (Human-Related Parameters, Resource-Related Parameters, and Ecosystem-Related Parameters), along with a fourth category (Economic-Related Parameters). Appendix B contains a complete listing of the coded propositional units derived from the sample set of sustainability definitions, sorted into the four categories.

Each set of propositional units contains parameters with varying degrees of overlap and specificity. The four categories were deduced from a review of the complete list of propositional units. Figures 4.2 through 4.5 show hierarchical configurations of the variables for each class, based on the similarities between variables as determined in the content analysis.

By placing the variables derived from the propositional units into hierarchies, gaps in the sets of variables become more apparent. In the next section, these gaps and the implications of the hierarchies for defining sustainability are explored.

4.2.2 Results of Content Analysis and Discussion

The four categories of variables identified in the content analysis show that existing definitions of sustainability vary in the detailed sub-variables they consider on an individual basis. For example, in the Resource-Related Variables hierarchy shown in Figure 4.3, specific classes of non-renewable resources such as minerals are mentioned in the literature, whereas only general types of renewable resources are covered. As a whole, however, the same three classes of variables emerge that were established in the literature review (Human-Related, Resource-Related, and Ecosystem-Related), along with an added class, Economic-Related variables.

The hierarchies of variables identified in the content analysis support the same three sustainability parameters presented in the first part of the chapter (satisfaction of human needs and aspirations, resource base impact, and ecosystem impact). These three classes of sustainability variables also appear in the breakdown of variables developed in the content analysis of sustainability definitions, and thus are important considerations for defining sustainability.

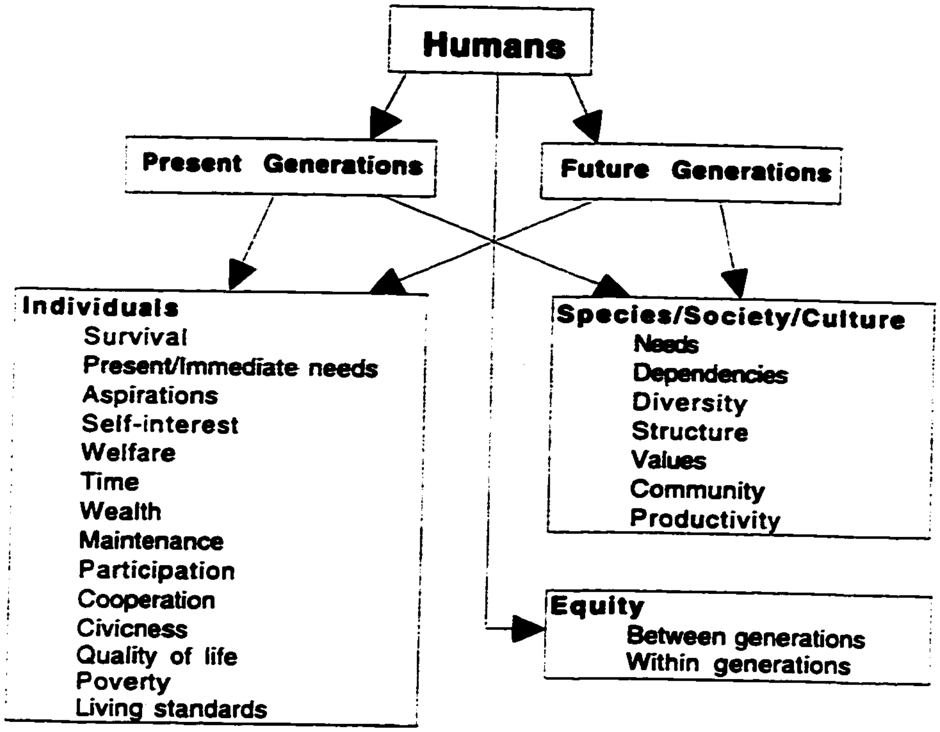


Figure 4.2: Hierarchical Configuration of Human-Related Variables

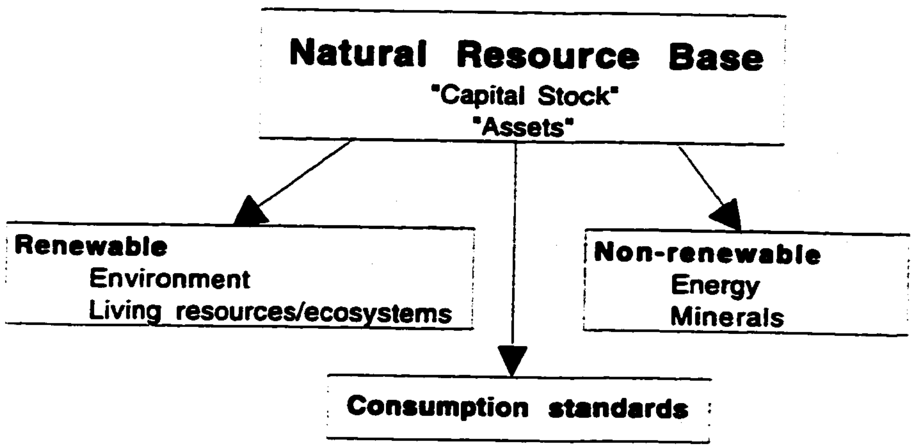


Figure 4.3: Hierarchical Configuration of Resource-Related Variables

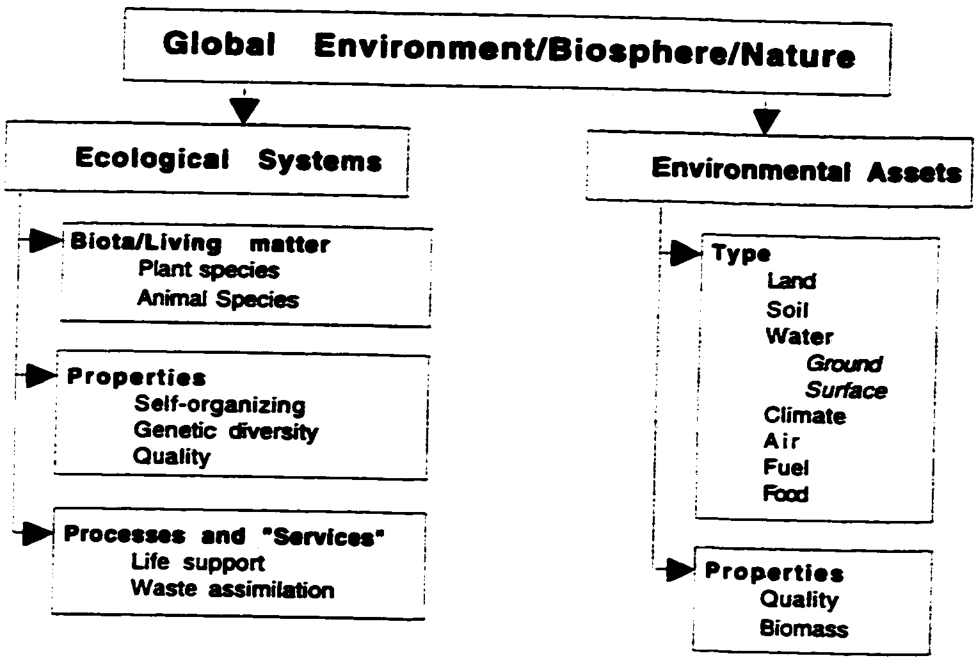


Figure 4.4: Hierarchical Configuration of Ecosystem-Related Variables

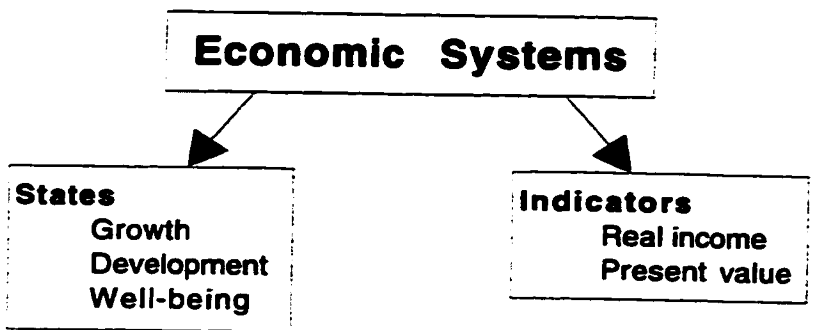


Figure 4.5: Hierarchical Configuration of Economic-Related Variables

Although a fourth class of variables appears in the content analysis, Economic-Related variables, it is not defined as a separate sustainability parameter in this research but rather as a constraint on the other three classes of variables. The rationale behind this decision is based on two separate reasons. First, economics and economic development are dependent upon the other three parameters. For example, prices in economic theory are based on the supply of products (dependent on resource bases and natural ecosystems) and the demand for those products (dependent on the degree to which those products result in human satisfaction). As such, many of the mathematical models in general sustainability literature use economics as a common language to resolve incommensurability of sustainability variables (e.g., Mikesell 1994).

Secondly, the economic paradigm currently in use to guide development activities is the neoclassical economic paradigm (described in detail in Daly & Cobb 1992 and Norton 1992). This paradigm is pervaded by assumptions ill-suited to the basic premises of sustainability, e.g., all resources are fungible (every natural resource has a feasible substitute), nature consists of limitless resource sources and sinks, all consumers make perfectly informed decisions, and all risks are monetarily compensable (see Solow 1993; Daly 1994). The current system of free market economics under which present decisions are made also fails to include so-called externalities or social costs which must be borne by society as a whole, such as degradation of commons resources like air quality and biodiversity (Hawken 1994; Hardin 1993). Although revising the economic paradigm to address these weaknesses is a task being addressed by many other researchers at present (e.g., Hawken 1994; Daly & Cobb 1994; etc.), the current system of neoclassical economics is inappropriate to define and describe sustainability (Daly 1990; Daly & Cobb 1994).

Since revising the current paradigm of economics is outside the scope of this research and the current paradigm is inappropriate to describe sustainability, economics is not considered to be a separate sustainability parameter in this research. Rather, the research focuses on the basic physical and ecological constraints and requirements that underlie sustainability, and that drive the economic measures adopted by society. However, economic considerations have not been omitted from the representation of sustainability used in this dissertation, but are included in two separate ways. First, economics is included as part of human satisfaction considerations, in terms of protecting economic interests. As discussed in more detail in Chapters 5 and 6, stakeholders whose primary interest is economic profitability may choose to calculate values for the Stakeholder Satisfaction parameter based entirely on economic or financial costs and benefits. Second, the economic feasibility of alternatives is explicitly represented as a constraint in the option prioritization process for built facility systems (see Sections 6.1 and 6.2), and implicitly in the structure of the research problem itself—there would be no need for prioritization of options if no economic limits existed to restrict the choice of options. Thus, while economics is not a included as a fourth sustainability parameter in this dissertation, it is incorporated directly into the prioritization process in multiple ways.

4.3. A Unified Construct of Sustainability for Systems

To increase the utility of sustainability objectives for problem solving and decision making, decision makers need a method to systematically evaluate systems according to those objectives. Toward that end, this section examines how the objectives of sustainability developed in the previous sections can be expanded into a decision space representation of sustainability for general systems at global and technological levels.

4.3.1 The Global Earth System

From the objectives of sustainability developed in Section 4.1 for the global Earth system as a whole, three primary parameters can be identified to define sustainability at a global level:

- Human Species (Survival/Prosperity)
- Resources (Consumption)
- Ecosystems (Impacts)

For each of the three parameters, the following subsections present a continuum of values divided in the center by a threshold of sustainability, i.e., a value at which the system goes from being unsustainable to sustainable in terms of that variable. The section concludes by combining the continua developed in the first three sections into a composite representation of sustainability for the global Earth system.

The Human Species Parameter: The first variable, the Human Species, is based on the anthropocentric objectives of sustainability as described in Section 4.1. Values for the Human Species variable can be represented along a continuum (Figure 4.6), where the threshold of sustainability is biological survival for the human species (after Brown et al.1987).

Values for the Human Species Parameter to the right of the sustainability threshold represent a state of sustainability beyond the minimum requirements, and include satisfaction of human needs and aspirations beyond the requirements for mere biological survival. Values to the left of the sustainability threshold represent a state of unsustainability for the Earth system, and include those conditions under which the basic requirements for human biological survival are not being met at a species level.

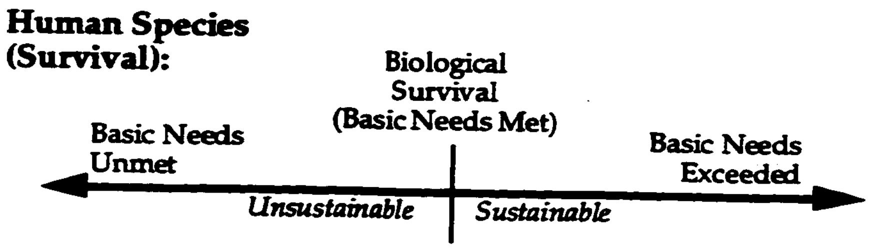


Figure 4.6: Continuum of Values for the Global Human Species Parameter

The Resources Parameter: The second parameter, Resources, is based on the thermodynamic objectives of sustainability as described in Section 4.1. Values for the Resources parameter can be represented along a continuum (Figure 4.7), where the threshold of sustainability is consumption of resources equal to the regeneration rate of the resource base (Daly 1991). Regeneration rate is a concept that describes the level at which a base of renewable resources can generate a supply of those resources without damaging its ability to provide that level of supply in the future (ibid.). For example, in terms of a renewable resource such as wood, the regeneration rate is the amount of wood that could be harvested from a particular forest system over time without reducing the basis for supplying wood in the future.

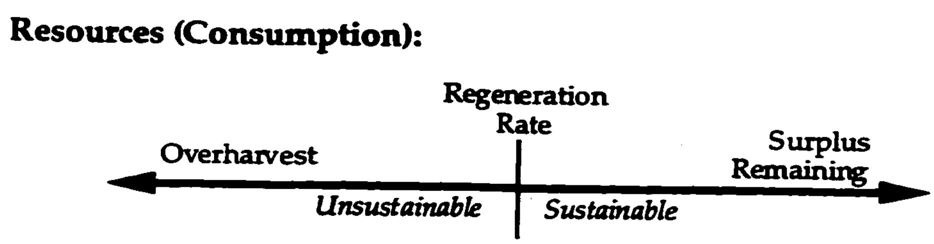


Figure 4.7: Continuum of Values for the Global Resources Parameter

In terms of non-renewable resources, the concept of regeneration rate has led to many disputes. By definition, non-renewable resources have a zero or negligible regeneration rate, and according to sustainability principles should not be used at all lest they be depleted. One convincing argument to the contrary is that if non-renewable resources are never to be used, either now or in the future, then there is no reason to arbitrarily preserve them (Mikesell 1992). A substitute definition of regeneration rate for non-renewable resources is the amount of non-renewable resources which, when consumed, are replaced by an equivalent investment in natural or technological substitutes (Solow 1993).

Along the continuum of the Resources parameter, values to the right of the sustainability threshold represent a state of sustainability beyond the minimum requirements, and include harvest of resources for human use at a level which is less than the regeneration rate of the resource base. These values might be achieved at a global level by either restricting consumption to levels less than natural regeneration rates, or by supplementing natural regeneration with human technological interventions so as to increase the net regeneration rate to levels greater than consumption rates. Values to the left of the sustainability threshold represent a state of unsustainability for the Earth system, and include all conditions under which resource consumption exceeds natural or human-supplemented regeneration rates.

The Ecosystems Parameter: The third parameter of sustainability, Ecosystems, is based on the biological objectives of sustainability described in Section 4.1, and is related to resource consumption due to the fact that humans are currently reliant on natural ecosystems for regeneration of the resource base, assimilation of human wastes, and transformation of solar radiation into usable products and services via the mechanisms of photosynthesis. Given this symbiotic reliance of humans on natural ecosystems, values for the Ecosystems parameter can be represented along a continuum (Figure 4.8), where the threshold of sustainability is the carrying capacity of ecosystems for humans.

Carrying capacity is the maximum number of organisms of a particular type that an ecosystem can support without experiencing degradation of its capacity to regenerate itself and thus support reduced numbers of organisms in the future (Hardin 1993).

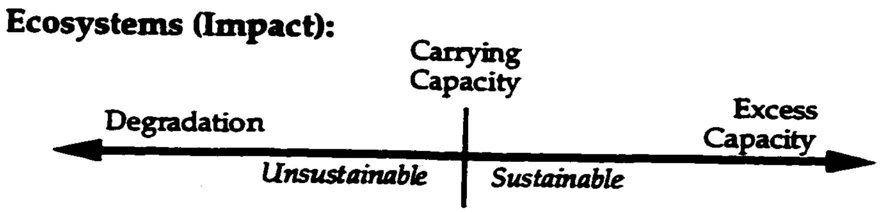


Figure 4.8: Continuum of Values for the Global Ecosystems Parameter

Values for the Ecosystems parameter to the right of the sustainability threshold represent a state of sustainability beyond the minimum requirements, and include limiting impacts to ecosystems to a level which maintains their carrying capacity above the level required by humans. Values to the left of the sustainability threshold represent a state of unsustainability for the Earth system, and include those conditions where ecosystems are impacted to a point beyond which they can maintain their carrying capacity, i.e., they can no longer support the influence of humans without damage, and they begin to degrade.

A Composite Representation of Sustainability for the Global Earth System: Having explored each of the parameters of global sustainability in detail, the next task is to examine how they can be combined to provide a composite picture or decision space for the sustainability of the global Earth system at a given point in time. Figure 4.9

shows the triaxial representation of the parameters of global sustainability selected for this research. The intersection of the three axes represents the thresholds of sustainability for each parameter, i.e., the conditions under which the global Earth system shifts from being unsustainable to sustainable. This representation, one of several possible ways to visualize the construct of sustainability, was selected because it is a convenient representation for the purpose of visually comparing sustainability states (see Section 6.3.1).

The positive region for each axis, i.e., the upper right octant of the three-dimensional space, represents the spectrum of possibilities for desirable states of the global Earth system in terms of sustainability. The following three thresholds define a state of sustainability for the global Earth system:

1) Human Species Survival ≥ Basic needs met
2) Resource Consumption ≤ Regeneration rate
3) Ecosystem Impact ≤ Carrying capacity

Based on the previous definitions of each dimension, the independence of the dimensions and their subsequent orthogonality in the decision space is a matter that is traditionally resolved using mathematical techniques such as factor analysis or structural equation modeling. With the availability of a large body of empirical data, these techniques could be used not only to verify the completeness of the descriptive parameters, but also to establish independence among them. However, in this case, establishing axis independence on a mathematical basis is left to future research. Instead, this research distinguishes between the axes operationally, in terms of specific attributes and characteristics of each parameter included in the operationalization. Chapter 5 describes the operationalization of these dimensions for built facility systems, and presents operational distinctions to hypothesize their independence (i.e., Resources = goods; Ecosystems = services).

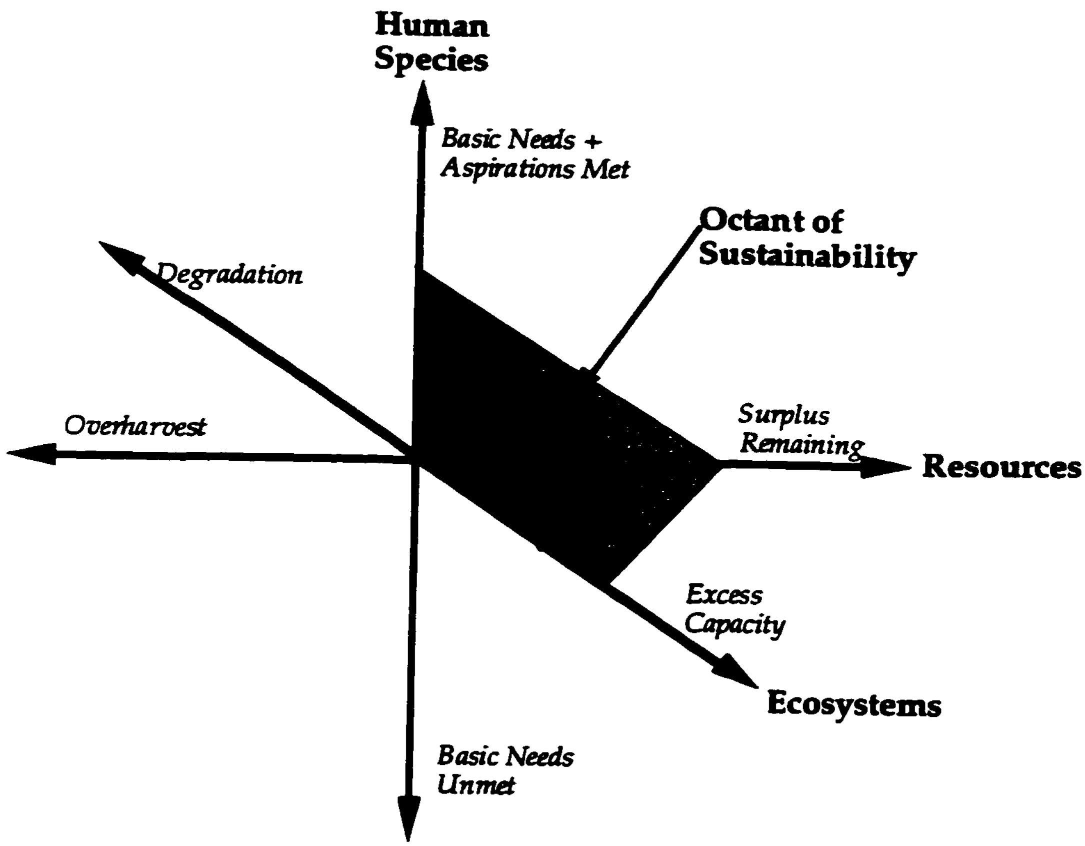


Figure 4.9: Triaxial Representation of Global Sustainability

4.3.2 Technological Systems

In parallel to the global objectives of sustainability, the three parameters of Humans, Resources, and Ecosystems emerge as being important in determining the sustainability of technological systems. In contrast to sustainability at the global level, these parameters must be reduced in scale when considering the sustainability of technological systems. At a technological level, the parameters become:

- Stakeholder Satisfaction
- Resource Base Impacts of the System
- Ecosystem Impacts of the System

The following subsections present a continuum of values for each parameter, divided in the center by a threshold of sustainability, i.e., a value at which the technological system goes from being unsustainable to sustainable in terms of that parameter. The fourth part of this section combines the three continua into a composite representation of sustainability for technological systems.

The Stakeholder Satisfaction Parameter: The first variable in technological sustainability, Stakeholder Satisfaction Impacts, is based on the anthropocentric objectives of sustainability described in Section 4.1, and ties into the question of who is being sustained at a technological systems level – System Stakeholders (Appendix A). Values for the Stakeholder Satisfaction parameter can be represented along a continuum (Figure 4.10), where the threshold of sustainability is biological survival of the system stakeholders, i.e., a state in which the basic human needs of system stakeholders are met.

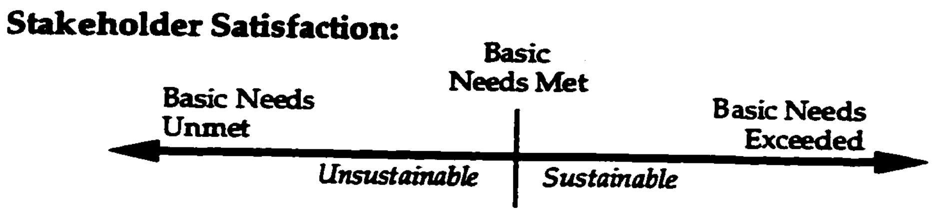


Figure 4.10: Continuum of Values for the Stakeholder Satisfaction Parameter

As with the Human variable in the global sustainability representation, values for the Stakeholder Satisfaction parameter to the right of the sustainability threshold represent a state of sustainability beyond the minimum requirements, and include satisfaction of stakeholder needs and aspirations beyond the requirements for mere biological survival. Values to the left of the sustainability threshold represent a state of unsustainability for the technological system, and include those conditions under which the basic requirements for stakeholder biological survival are not being met.

The Resource Base Impacts Parameter: The second parameter, Resource Base Impacts, is based on the goal of minimizing negative impacts to resource bases. Values for the Resource Base Impacts variable can be represented along a continuum (Figure 4.11), where the threshold of sustainability is a state of zero net resource base impact for the system. This state can occur either when the negative impacts of the system on resource bases equal the positive impacts, or when there are no resources accumulating in or being lost from the system, or flowing into or out of the system.

In the case of the technological systems being considered in this dissertation, zero net resource base impact can be achieved by creating equilibrium between the damage to resource bases inflicted by the system and the restoration of those resources by the system. Another way to think of this equilibrium state is symbiosis: at the threshold of sustainability, the system is in a complementary relationship with its environment, where it takes resources from that environment to function and returns resources back to the environment which enable the environment to function properly.

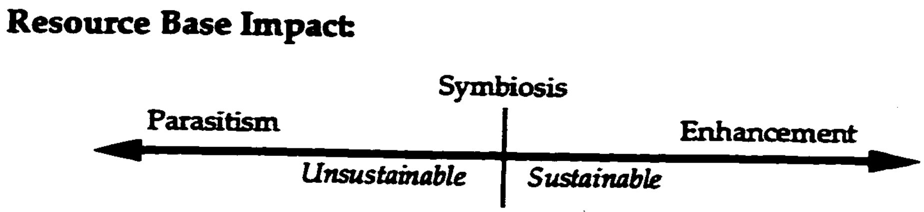


Figure 4.11: Continuum of Values for the Resource Base Impact Parameter

In the case of the Resource Base Impact parameter, the entropy gain as a result of the resource flows through the system is also of interest. In the case of a technological system which consumes matter and energy, the inevitable gain in entropy resulting from that consumption can be offset by influxes of matter or energy from outside the global system or by the addition of value or information to the outputs of the system.

Along the continuum of the Resource Base Impact parameter, values to the right of the sustainability threshold represent a state of sustainability beyond the minimum requirements, where the system acts as a host for other systems in its environment. This region of the continuum represents a net terrestrial resource flow into the system which is less than zero, i.e., a net positive *outflow* of resources (without depleting resources within the system) which can serve as input to support other systems. Values to the left of the sustainability threshold represent a state of parasitism for the system, and include all conditions where the system takes more from its environment than it gives back.

The Ecosystem Impacts Parameter: The final parameter for technological sustainability is the Ecosystem Impacts parameter, similar to the corresponding parameter for the global Earth system and based on the objective of minimizing negative ecosystem impact. Values for the Ecosystem Impacts variable can be represented along a continuum (Figure 4.12), where the threshold of sustainability is neutral or no impact on ecosystems as a result of the technology.

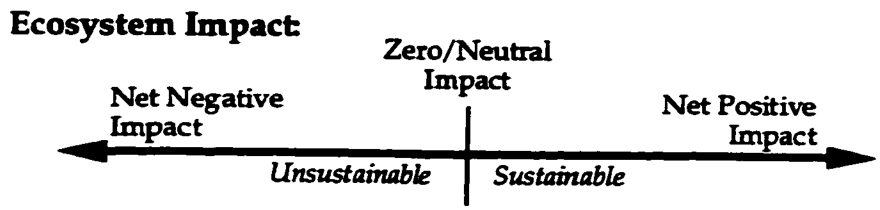


Figure 4.12: Continuum of Values for the Ecosystem Impacts Parameter

Values for the Ecosystem Impacts parameter to the right of the sustainability threshold represent a state of sustainability beyond the minimum requirements, and include situations where the technology results in net positive impacts to ecosystems inside and outside the system such as restoration of damaged ecosystems. Values to the left of the sustainability threshold represent a state of unsustainability for the technological system, and include situations where the net ecological impact of the technology is negative.

A Composite Representation of Sustainability for Technological Systems: Having explored the parameters of technological sustainability in detail, the next step is to examine how they can be combined to provide a composite picture or decision space for the sustainability of technological systems at a given point in time. Analogous to the composite representation of global sustainability (Section 4.2.1), Figure 4.13 shows a triaxial representation of the parameters of technological sustainability, where the intersection of the three axes represents the thresholds of sustainability for each parameter.

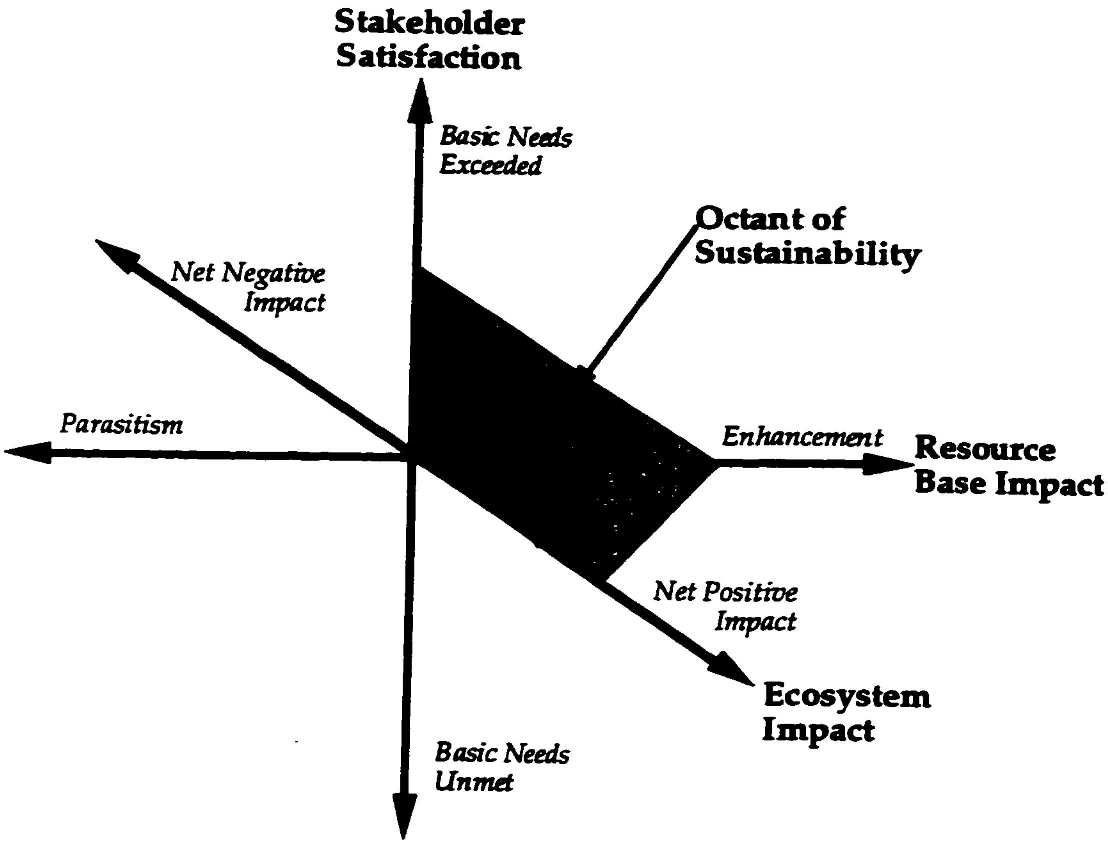


Figure 4.13: Triaxial Representation of Technological Sustainability

The positive region for each axis, i.e., the upper right octant of the three-dimensional space, represents the spectrum of possibilities for the desirable states of technological systems in terms of sustainability. The following three thresholds define a state of sustainability for the technological systems:

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

4.4. Summary: A Unified Construct of Sustainability

This part of the research established a unified construct of sustainability in terms of sustainability of the whole Earth system (i.e., global sustainability) and in terms of the sustainability of technological systems on a smaller scale (i.e., technological sustainability). After the constraints which govern global sustainability were identified based on a review of the theoretical sustainability literature and corroborated using content analysis of definitions of sustainability, these constraints were articulated in the form of three parameters that can be evaluated along three corresponding scales.

Based on this understanding of the global constraints defining sustainability, corresponding constraints and parameters were deduced from the global sustainability representation to define and represent the sustainability of technological systems which together comprise the global Earth system. While sustainability must ultimately be considered in terms of global impacts created by the set of all technological systems, stakeholders make decisions at the level of individual technological systems – thus the need for reducing the scale of evaluation to a technological systems level.

To summarize the constraints of sustainability for a technological system, the stakeholders of the system should have conditions under which they can survive or prosper and in which their needs and aspirations are met or exceeded. Additionally, the impacts to resource bases and natural ecosystems caused by the system should be positive, zero, or neutral. These three objectives, corroborated by content analysis of the general sustainability literature, comprise the unified construct of sustainability developed in this chapter and used through the rest of the dissertation.

CHAPTER V

OPERATIONALIZING BUILT FACILITY SUSTAINABILITY

The next step in translating sustainability into a meaningful and operational model for built facilities is to identify variables for each parameter that are meaningful in the context of built facility systems and establish relationships among them. The purpose of this chapter is to establish these variables and relationships to define an operational objective function for evaluating the sustainability of built facilities. The chapter concludes with a description of the measures and data sources that can be used to apply the objective function for a facility system.

5.1. A Unified Construct of Sustainability for Built Facility Systems

The first task in developing an operational objective function for the sustainability of built facilities was to exhaustively classify all the possible ways a built facility system could influence the parameters of sustainability defined in Chapter 4, and to identify variables to calculate those influences. Section 5.1.1 describes how a representation of facility systems was developed and used to identify the ways a built facility could impact sustainability. Sections 5.1.2 through 5.1.4 identify parent variables that influence Stakeholder Satisfaction, Resource Base Impacts, and Ecosystem Impacts, respectively. The section concludes with a summary of the built facility system variables that are used in this research to determine values for sustainability parameters.

5.1.1 Scale and Boundary

To begin the task of mapping built facility variables onto the parameters of sustainability, it was necessary to classify the possible impacts a facility system could have on these parameters. The classification scheme required defining a representation of a facility system, with a meaningful boundary to distinguish it from its context. To delineate this boundary, it was necessary to select an appropriate scale of analysis for evaluating the sustainability of built facilities. For the purpose of this research, the boundary of the facility system was defined as the legal boundary of the site, and the scale of analysis was defined as the site and all of the structures, direct stakeholders, ecosystems, and resource bases present within the site boundary. This boundary and scale of analysis (hereafter denoted as facility scale) was selected for the following reasons:

- The legal boundary of the site represents the limits of the owner's direct control over the elements of the global system.
- This scale is the simplest hierarchical level where all of the system's emergent properties for Stakeholder Satisfaction become meaningful.

Choosing a system scale to represent the limits of the owner's direct control is important because it provides a discrete differentiation between system and context besides the otherwise arbitrary politically defined site boundary. The second reason, ensuring that the scale of the system affords consideration of salient emergent properties, is possibly an even more critical reason to choose the facility scale of analysis. According to systems theory, emergent properties are those attributes that exist for a system as a whole, but not for its individual parts (Capra 1996; Zandi 1993; von Bertalanffy 1968). For example, when intact within a single organism, the combined set of tissues, muscle, bone, and other body components exhibit an emergent property known as life. In contrast, the individual components do not possess this property in isolation from the organism (ibid.). From the standpoint of a built facility, some properties of stakeholder satisfaction such as thermal comfort are not meaningful for individual building materials, or even for building systems in isolation from one another. In general, one cannot understand how the system affords the emergent property of thermal comfort by looking only at the HVAC system. Rather, one must consider the facility as a whole, including but not limited to the enclosure and the roof, the supporting structure, and the exterior landscaping and environment. Thus, the most convenient scale of analysis for understanding these emergent properties is the facility and its site as a complete system.

The combined objectives of direct owner control and incorporation of relevant emergent properties can only be met by a facility-level scale of analysis. Figure 5.1 provides a graphical representation of the entities and flows between the entities for typical facilities at this scale.

5.1.2 Key Facility and Context System Variables for Stakeholder Satisfaction

The first sustainability parameter to be considered is Stakeholder Satisfaction. As described in Chapter 4, the operationalization of sustainability scopes consideration of human satisfaction to direct, or intra-system, stakeholders. The set of intra-system stakeholders includes residents/tenants, maintenance staff, owners, developers, and others within its boundary who are directly impacted by the facility system, and corresponds to direct internal stakeholders as discussed in Chapter 1 (see Figure 1.3).

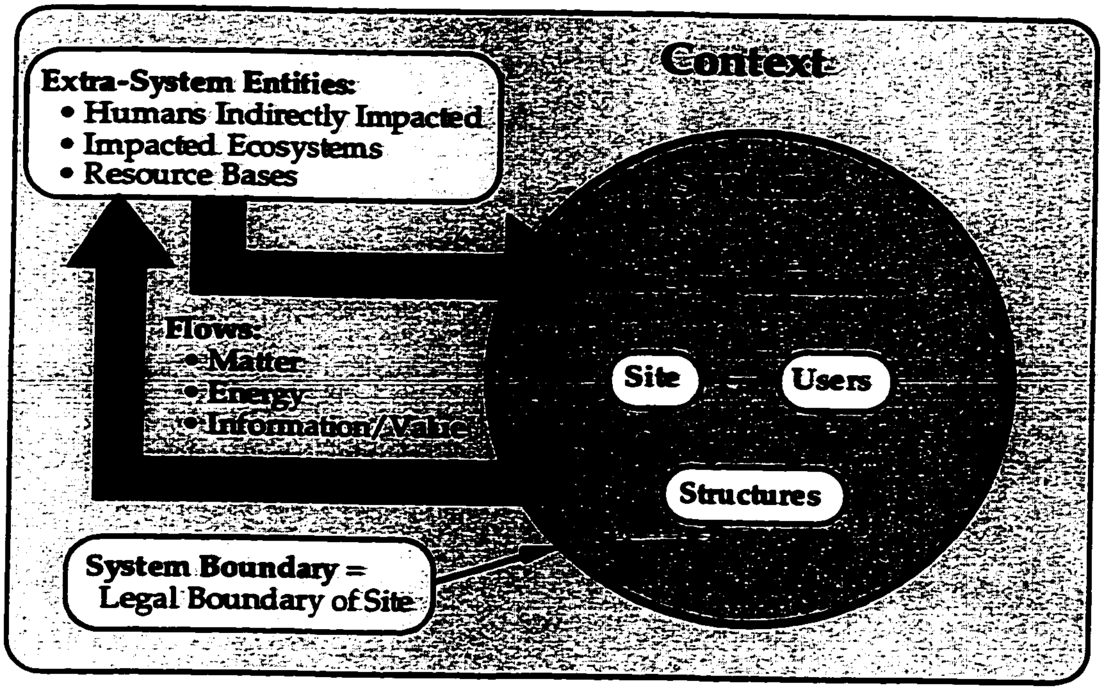


Figure 5.1: Entities and Flows of a Built Facility System (after Yeang 1995)

The choice to limit Stakeholder Satisfaction to intra-system stakeholders is based on the premise that the sustainability obligations of a given system's stakeholders to humans outside the system are met by striving for neutral or positive impacts to ecosystems and resource bases (based on DuBose & Pearce 1997). This research assumed that assessing the satisfaction of humans other than direct system stakeholders is outside the scope of sustainability assessment, since it is already reflected by assessing how well resource bases and ecosystems are maintained to meet intra-generational human needs.

Given this scope, determining what influences the satisfaction of direct stakeholders with respect to the facility is necessary. First and foremost is to establish what is meant by the term satisfaction. Recall from Chapter 4 that in the context of this research, Stakeholder Satisfaction refers to satisfying the needs and aspirations of the system's stakeholders, specifically in terms of the needs and aspirations relating to the facility system itself. Many measures of satisfaction have been developed for various contexts and applications, including job satisfaction (e.g., Smith et al. 1976, Weiss et al. 1967), customer satisfaction with products (e.g., VARBiz 1997, Wirthlin Worldwide 1997), and satisfaction with services (e.g., Stanger 1996, Terry 1996).

Two primary schools of thought exist to define satisfaction. The first, known as the disconfirmation of expectations model, explains satisfaction in terms of how closely experiences match expectations (Spreng et al. 1996). In this model, humans experience satisfaction when events match or exceed the individual's preexisting expectations for those events. Likewise, the individual would tend to experience dissatisfaction when events fail to meet his or her preconceived expectations.

The disconfirmation of expectations model can be useful in terms of facility systems if stakeholder expectations for facility performance can be identified and predicted. Specifically, areas of dissatisfaction can be easily identified by contrasting stakeholder expectations with the existing performance state of the facility system. However, in the event that stakeholders have unreasonably low or uninformed expectations about what levels of performance can be achieved by the facility, this model may result in overlooking potential opportunities for improving facility performance.

The second school of thought is based on needs theory (e.g., Maslow 1943, Alderfer 1972). While needs theory was developed to predict and model human motivation, it can also be applied to understand satisfaction with respect to the degree to which human needs are being met in a given situation. From the many categorizations of human needs in the psychological literature, two general models of human needs have stood the test of time, and can be used to measure how well human satisfaction is being achieved: Maslow's Hierarchy of Needs, and Alderfer's ERG Theory.

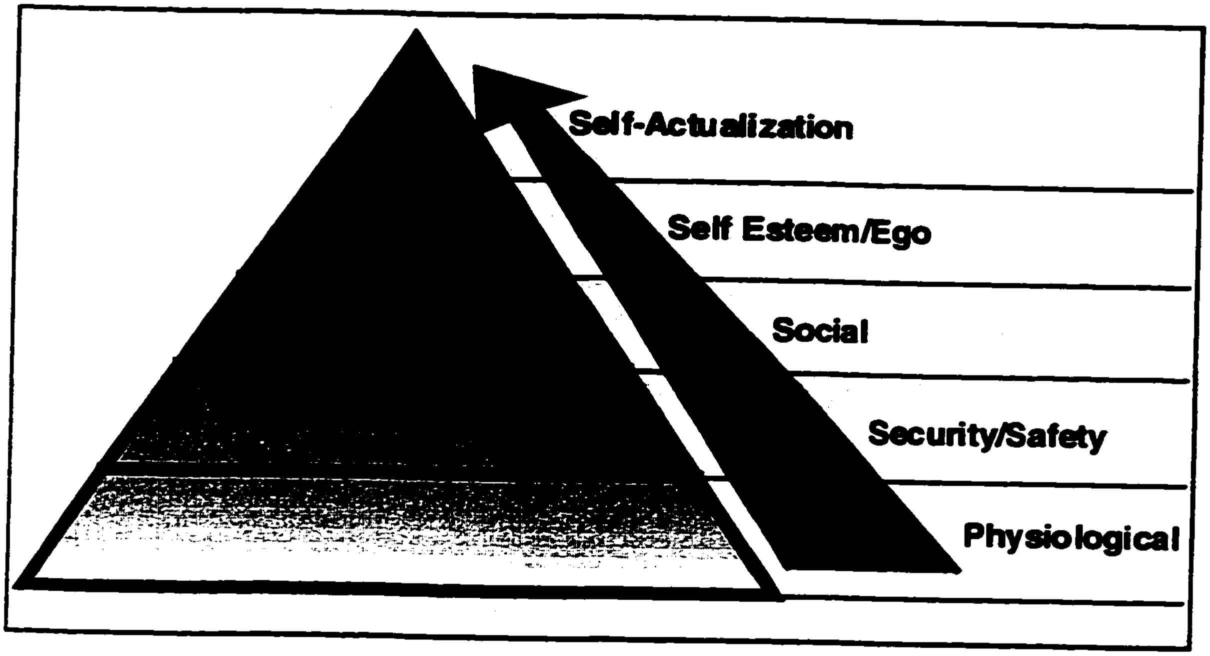


Figure 5.2: Maslow's Hierarchy of Needs (Maslow 1943)

The first theory, developed in the 1940's by Abraham Maslow, proposes five hierarchical levels of human needs, ranging from the most basic physiological needs such as food and shelter, to the highest levels of human aspiration, called self-actualization by Maslow (1943). Figure 5.2 shows the five levels of Maslow's hierarchy of needs.

Maslow's theory of motivation states that humans are motivated by unmet needs at the lowest level of the hierarchy at any specific point in time. For example, a person who is in the process of meeting a third-level need of being social by attending a party may become motivated by first-level needs if a deficit develops in those areas. If the person becomes hungry, he or she may decide to leave the party and find a restaurant to meet his or her physiological needs at a point when they become imperative. From the perspective of satisfaction, Maslow's hierarchy serves as a convenient way to organize the various needs human beings experience, and which humans are motivated to meet.

While satisfaction can occur as needs are met on all levels of the hierarchy, Maslow's theory states that for any specific period time, people tend to move progressively up the hierarchy in terms of what motivates their behavior as lower level needs are met. From a facilities perspective, prioritization of functional performance capabilities should begin with meeting the lowest level needs of the inhabitants, i.e., providing shelter and security, and progress from there to affording qualities such as aesthetic beauty only after lower-level needs have been met in order to achieve human satisfaction. In other words, humans will be unable to appreciate the most beautiful and spiritual building if it fails to provide a habitable climate for occupation.

Clayton Alderfer developed the second theory of motivation, ERG Theory, in response to Maslow's Hierarchy in the early 1970's. Alderfer believed that Maslow's basic premise of motivation being driven by needs was correct, but he felt that human needs should be classified into three categories instead of five: existence, relatedness, and growth (1972). In ERG Theory, existence needs are analogous to Maslow's physiological and safety needs, relatedness needs are analogous to interpersonal safety, love, and interpersonal esteem needs, and growth needs are analogous to self-actualization and self-esteem needs (Nelson & Quick 1994).

Alderfer also added a regression hypothesis to help explain what happens when a person's attempt to meet higher-order needs is frustrated. The regression hypothesis states that people regress to a state of seeking to fulfill lower-order needs and intensify their desire to gratify those needs when frustrated in attempting to meet higher-order needs. For example, people who are unable to meet their relatedness needs in terms of having social relationships may regress to meeting existence needs, turning their focus instead to satisfying biological needs such as eating or sleeping.

These two theories of human motivation are representative of needs theory, and provide two hierarchical frameworks of the spectrum of human needs which should be met to achieve increasing levels of human satisfaction. Since Maslow's Hierarchy provides a greater degree of resolution with respect to categorizing human needs, it has been selected as the basis for representing the spectrum of potential elements of human satisfaction.

Together with the model of disconfirmation of expectations, one can not only measure levels of stakeholder satisfaction based on expectations for built environment performance, but also assess the relative importance of these expectations across the spectrum of possible needs that built facility systems could meet. The hybrid combination of these two schools of thought provides a foundation for measuring stakeholder satisfaction as afforded by built environment systems. In summary, the following variables are the most critical drivers of the Stakeholder Satisfaction parameter of sustainability:

- Degree to which stakeholder expectations of the facility are being met.
- Relative importance of expectations to the stakeholder.

5.1.3 Key Facility and Context System Variables for Ecosystem and Resource Base Impacts

The next step is to identify driving variables for ecosystem and resource base impacts. The boundary of the system as defined in Section 5.1.1 is useful to delineate two mutually exclusive and collectively exhaustive categories of impacts caused by the facility system: intra-system impacts and extra-system impacts (after Yeang 1995).

Extra-System Impacts of Facility Systems on Ecosystems and Resource Bases: According to the chosen representation of a built environment system (Figure 5.1), the only way a facility system can impact its context is via the two-way flows of matter, energy, or information across the boundary of the system. As shown in Figure 5.3 in terms of matter, these flows vary across the life cycle of the facility, with flows of matter into a typical throughput facility system being greatest in the construction and operation phases of the building life cycle, and flows of matter out being most significant at the end of the life cycle or during operation if the facility generates products (Yeang 1995). In this research, a throughput facility can be defined as any facility system whose primary function is not as a large-scale source or sink of matter and energy. Typical residential, commercial, and industrial buildings fall into the category of throughput facilities, whereas landfills are classic examples of sink facilities, and a tree farm is a good example of a source facility.

From the perspective of the context of the facility system, each unit of flow across the boundary exerts either a positive, negative, or neutral impact on the source or sink of the flow within the context system. This impact exerted by the flow on the source or sink system has a certain degree of significance based on the nature of the flow and the properties of the source or sink system.

Based on this representation, three key facility and context system variables can be identified that should be part of the mapping of extra-system impacts to the operational parameters of sustainability:

- Amount of cross-boundary resource flow
- Unit impact exerted by flow on source/sink system
- Significance of unit impacts to the source/sink system

These three factors can be used to define the relationship between the features of a built facility system and its impacts on extra-system resource bases and ecosystems.

Intra-System Impacts of Facility Systems on Ecosystems and Resource Bases: The remaining impacts caused by a facility system are felt *within* the bounds of the system itself. These impacts are reflected in changes in the quantity and quality of the ecosystems and resource bases on site. From a perspective outside the system, facility systems can add to, maintain as constant, or deplete their initial on-site quantities of resources or ecosystems (Yeang 1995). In terms of the quality of on-site ecosystems and resource bases, facility systems can have intra-system impacts when resources within the boundary of the system are consumed by other entities within the system. In this case, the term consume means increasing the entropy of a resource, thus reducing its utility for further use (see Chapter 4 for a more detailed discussion of entropy and consumption). No matter or energy may actually cross the system boundary in the case of intra-system resource use, but impacts to on-site resource bases and ecosystems can exist nonetheless.

In the case of throughput facilities as described earlier, the main drivers of negative intra-system impact are the destruction or displacement of on-site ecosystems by the system stakeholders and their structures. For example, an owner may decide to install a paved parking lot in an area currently occupied by an ecosystem, destroying vegetation and displacing fauna during construction, and causing negative impacts to groundwater from stormwater runoff after the lot is installed. This action on the part of the owner will have negative intra-system ecosystem impacts. To offset these impacts, the owner could attempt to restore an ecosystem on another part of the site, or try to mitigate the negative impacts of the paved area by using porous paving material to reduce runoff.

For source facilities, the main driver of negative intra-system impacts is the consumption or excessive export of on-site resource bases. For example, a source system such as a logging facility may impact its intra-system resource base by actively cutting trees and exporting them from the site at a rate faster than they can be restored (Goodland 1992). This loss is reflected in the status of the on-site resource base by the fact that there are fewer remaining trees after logging has taken place. It has implications not only for future availability of trees on the site, but also for the capacity of the site's ecosystems to perform load-bearing services to other systems, such as absorbing rainfall and recycling it into the ground to recharge aquifers (ibid.). Instead of absorbing the rainfall, a more likely possibility is that the rain will run off the site to local streams, carrying with it precious topsoil, clogging the stream courses, and creating a situation of even further degradation—a classic example of a reinforcing feedback situation (Hardin 1993).

Likewise, resource base impacts are often severe for sink systems. For example, performing a mass/energy balance on a landfill facility system shows that significant quantities of matter accumulate within the facility system over time (Tchobanoglous et al. 1993). Since the typical landfill does not have any mechanism for reducing the entropy of the waste deposited within it, continued influxes of high-entropy waste accumulate within the system and eventually overwhelm the capacity of the system to absorb more input (ibid.). If, however, a viable method was developed to reduce the entropy of the waste stored in landfills, such systems might go from being sink systems to source systems, reflecting an increased demand for the matter and potential energy accumulated in the system. This example illustrates a major subvariable of significance: the utility of existing or accumulated resources within the system, which is itself a function of the availability of systems to render matter and energy useful for meeting human needs.

Intra-system impacts are felt within the facility system as increases or decreases in the capacities of baseline ecosystems and resource bases to generate or absorb flows of matter and energy. By definition, they are most significant for source and sink facility systems, and less significant for typical throughput systems.

In evaluating the impacts of a facility system to on-site ecosystems and resource bases, the objective is to calculate the differences between some baseline and the current or predicted post-action state. Intra-system impacts are a function of two principal variables:

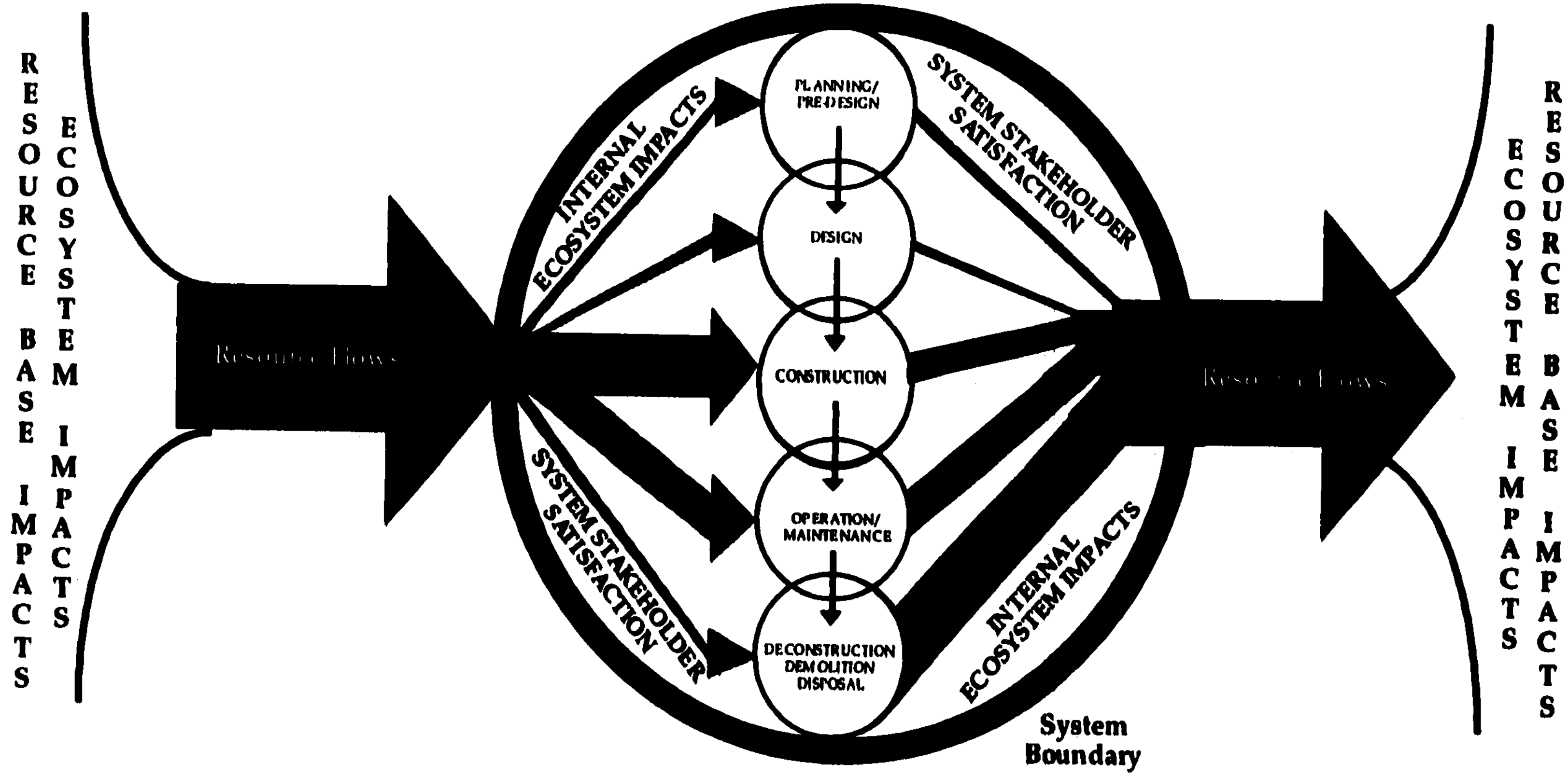


Figure 5.3: Resource Flows and their Impacts over the Life Cycle of a Typical Throughput Facility

- Change in ecosystems or resource bases within the system
- Significance of that change, in the context of the source/sink system

Each of these variables can be broken down further into measurable factors that will facilitate evaluation of the Resource Base Impact and Ecosystem Impact parameters of sustainability.

5.1.4 Mapping Key Variables of Facility Sustainability onto Sustainability Parameters

In summary, the key variables that define facility sustainability can be classified in terms of how the existence and operation of the facility system creates impacts both within itself and outside its boundary in its context (Table 5.1).

Table 5.1: Classification of Key Variables Defining Facility Sustainability

	Intra-System Impacts	**Extra-System Impacts**
Stakeholder Satisfaction	• Stakeholder expectations met • Relative importance of stakeholder expectations	NA – See §5.1.2
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

5.2. Establishing Functional Relationships Among Facility Subvariables

The next step in developing a model of the sustainability of built facility systems is to understand how the key variables of facility systems can be connected to model the operational parameters of sustainability with respect to the facility system. The following subsections describe how the key facility variables identified in the previous section can be expressed as functions to predict values for Stakeholder Satisfaction, Resource Base Impacts, and Ecosystem Impacts. In terms of notation, the convention in the remainder of this chapter is as follows:

$$\sum_{S} X_i$$

denotes the sum of all variables X over the complete set S.

5.2.1 Desired Range of Parameter Function Values

Before proceeding to the derivation of parameter functions, it is necessary to specify a desired range of values for the three functions (Stakeholder Satisfaction, Resource Base Impacts, and Ecosystem Impacts). Limiting each parameter function value within the range [-1, 1] is desirable so that the parameter values for one facility can be used directly in the analysis of other affiliate systems (See Section 6.3.1 for further discussion of this modeling stipulation). Within this range, -1 indicates the highest degree of unsustainability, +1 indicates the highest degree of sustainability, and 0 represents the threshold at which a system moves from unsustainable to sustainable.

As discussed in Sections 5.3.3 and 5.3.4, the values for extra-system impacts in each parameter function are dependent on the values of the same parameter function for the source or sink system affiliated with each flow. If the parameter functions for all systems are scaled using the same minimum and maximum limits, values for affiliate systems can be substituted directly into the functions for the system of interest without a need to transform them during the analysis.

For example, in analyzing a facility with resource flows to a wastewater treatment plant where the treatment plant has already been analyzed, then the known values for the treatment plant's sustainability parameters can be directly plugged into the facility's extra-system impact functions. For the analysis to work without needing to preprocess the data, the sub-impact factors must all be between [-1, 1]. If the parameter functions are automatically squashed to this range for each analysis, then the parameter values for the treatment plant can be used directly in the analysis of the facility of interest without any further transformation.

The desired transform can be accomplished by applying a so-called squashing function to each parameter function. Squashing functions are mathematical transforms used to scale or squash one value between some minimum and maximum into another value between different, more convenient minimum and maximum limits. One familiar kind of squashing function is normalization, which scales values between 0 and 1 in a linear fashion (Eberhart & Dobbins 1990; Wasserman 1992).

The squashing function permits consideration of different systems on a constant scale, and significantly facilitates subsequent analyses of other facilities that may be related to previously analyzed facilities. Other benefits of using a nonlinear squashing function include its role in preventing large impact values of affiliate systems from dominating the impact function for the system of interest. The mathematical role of the squashing function is similar to an analog electronic amplifier, where the strength of an electronic signal is boosted if it is weak or reduced if it is strong (Eberhart & Dobbins 1990).

Possible squashing functions include sigmoid, hyperbolic tangent, and linear transform functions (Eberhart & Dobbins 1990; Wasserman 1992). From this set of three possibilities, the sigmoid function can be eliminated since it squashes to a range of [0,1] (ibid.). The linear squashing function requires knowledge of the largest possible maximum and the smallest possible minimum (ibid.), and would be extremely challenging to use over the set of all facility systems, where a facility could conceivably have impacts ranging through plus or minus infinity. The hyperbolic tangent function is more appropriate than either of the other alternatives, since it requires no prior knowledge of minimum or maximum values and maps to a range of [-1, 1] (ibid.). Therefore, the model developed in this research uses the hyperbolic tangent function as a squashing function.

5.2.2 A Function for Stakeholder Satisfaction (SS)

According to the definition developed in the first part of this chapter, Stakeholder Satisfaction for a facility system is a function of the degree to which expectations of stakeholders are met and the relative significance of each of the expectations. The breakdown of the expectation variables can be expressed as:

- Stakeholder expectations for the system that are met (E_M)
- Stakeholder expectations for the system that are not met (E_{NM})
- Stakeholder expectations for the system that are exceeded (E_E)

When defined this way, the set of variables are mutually exclusive and collectively exhaustive, and can be related as follows if they are expressed as percentages of total expectations:

$$E_M + E_{NM} + E_E = 1 \qquad (1)$$

The desired behavior of the Stakeholder Satisfaction Function can be expressed in terms of the following three equations, given that values of the function lie between -1 and 1:

$$100\%\ E_M + 0\%\ E_{NM} + 0\%\ E_E = 0 = SS \tag{2}$$

$$0\%\ E_M + 100\%\ E_{NM} + 0\%\ E_E = -1 = SS \tag{3}$$

$$0\%\ E_M + 0\%\ E_{NM} + 100\%\ E_E = 1 = SS \tag{4}$$

Equation (2) shows that when all stakeholder expectations are exactly met, the value for the Stakeholder Satisfaction parameter is indexed at zero. When none of the expectations of stakeholders are met, the function value is indexed at -1 as shown in Equation (3), reflecting a value-dependent state of total unsustainability. Likewise, Equation (4) shows that when all stakeholder expectations are exceeded, the value for the parameter is indexed at +1, reflecting maximum sustainability in terms of this parameter. By solving this set of linear equations, the logical relationship among the variables can be expressed as a percent of the total number of expectations (E_T) as follows:

$$SS = (E_E - E_{NM}) / E_T \tag{5}$$

The function can also be computed using weighted expectations as follows, to account for some expectations being more important to particular stakeholders than others:

$$SS = \sum_{E_E} E_i w_i - \sum_{E_{NM}} E_j w_j \qquad (6)$$

where

i = Expectation that is exceeded
w_i = Normalized weight of exceeded Expectation i
j = Expectation that is not met
w_j = Normalized weight of unmet Expectation j

Weightings for stakeholder expectations can either be preset using a hierarchical scheme such as Maslow's Hierarchy of Needs (see Section 5.2.2) or can be specified by the stakeholder being queried. The preceding formulae are useful for calculating Stakeholder Satisfaction for a single stakeholder. When considering systems with multiple stakeholders, the net Stakeholder Satisfaction for the facility can be approximated by the average SS value over the set of all stakeholders.

Stakeholder Satisfaction is straightforward to calculate using these formulae if a stakeholder has a finite list of expectations, each of which can be identified as met, not met, or exceeded. While expectations vary widely for different facilities, contexts, and stakeholders, developing a basic checklist of typical stakeholder expectations is useful, since this list can be used as a starting operational measure for evaluating Stakeholder Satisfaction. One such list is developed in Section 5.4.1 of this chapter. Alternative measures may also be used to assess Stakeholder Satisfaction as appropriate to the needs and aspirations of the stakeholders in a particular situation.

5.2.3 A Function for Resource Base Impact (RBI)

According to the classification developed in the first part of this chapter, Resource Base Impact for a facility system is a function of:

- Intra-system Resource Base Impacts (RBI_I)
- Extra-system Resource Base Impacts (RBI_E)

To determine the nature of the relationship between these variables, the desired behavior of the function as deduced from the sustainability literature (Daly 1990, Solow 1993, El Serafy 1992, Daly 1992, Howe 1979, Repetto 1985, etc.) can be expressed as shown in Figure 5.4. Possible values of the subvariables RBI_I and RBI_E are assumed to range from negative to positive infinity, as indicated in the table in Figure 5.4. The desired range of the function is between -1 and 1, to permit substitution of the impacts of affiliate systems when known.

$$RBI = f(RBI_I, RBI_E) \rightarrow [-1, 1]$$

RBI_I \ RBI_E	$-\infty$	0	$+\infty$
$-\infty$	- 1	- 1	0
0	- 1	0	1
$+\infty$	0	1	1

Figure 5.4: Desired Behavior of Resource Base Impact Function

The desired behavior can be deduced from Figure 5.4 as the sum of the subvariables transformed by the hyperbolic tangent squashing function as follows:

$$RBI = \tanh\,(RBI_I + RBI_E) \qquad (7)$$

On the basis of the previous description of RBI_I and RBI_E, these variables cannot be measured directly as defined. Each of these variables must be further expanded in order to evaluate the Resource Base Impact function. The following subsections describe the expansion of these variables.

Intra-System Resource Base Impacts (RBI_I): As shown in Table 5.1, Intra-system Resource Base Impacts are a function of the following two subvariables:

- Change in intra-system resource bases (ΔRB_I)
- Significance of change ($\omega_{\Delta RB}$)

To develop a function for RBI_I, it is necessary to understand the meaning and scope of these variables in terms of the representation of built facility systems developed in the first part of this chapter. Change in intra-system resource bases refers to the accumulation or depletion of resources on site due to unbalanced flows of those resources through the facility system, or due to consumption or restoration of resources on-site by entities within the system (see Section 5.1.3). Change can occur in terms of quantity (as for non-renewable materials) as well as in terms of quality (more relevant for renewable resources dependent on biological processes for renewal). Change is reflected only in terms of the condition of resource bases, and is independent of any complementary impacts outside the system bounds.

The variable ΔRB_I reflects changes in quantities of resources on site over the time period being analyzed. Evaluating this variable requires establishing a baseline state of resource bases for the facility system being analyzed, to be able to compare some future state of the resource bases due to changes to the system. Assuming that sustainability analysis can be undertaken for any arbitrary unit of time in the life cycle of the facility (see Section 6.3.1 for further discussion), ΔRB_I can be represented as follows:

$$\Delta RB_I = (RB_I)_{t+1} - (RB_I)_t \qquad (8)$$

where

t = time at the beginning of the period analyzed
$t+1$ = time at the end of the period analyzed
RB_I = state of internal resource bases at a specified point in time

ΔRB_I is positive if more of a given resource exists within the system after one time period, and negative if less of the resource exists after that unit of time (after Daly 1990).

The significance variable $\omega_{\Delta RB}$ corresponds to the ability of a given resource base to bear the load imposed on it by ΔRB_I. The role of this variable is to impose a penalty on resource depletion for scarce or non-renewable resources, and a penalty on the accumulation of harmful resources or resources with low utility/high entropy within a system (Daly 1990, Mikesell 1992). Likewise, the significance function should effect a reward for systems that restore/reduce the entropy of scarce or non-renewable resources, or that absorb and positively transform harmful resources (Solow 1993, Daly & Cobb 1994).

Expressing resource bases in terms of the change in their quantities over the time period analyzed, intra-system resource base impacts can be represented as a function dependent on change in quantity and significance of that change, with desired behavior of the resulting function deduced from the sustainability literature (Daly 1990, Solow 1993, El Serafy 1992, Daly 1992, Howe 1979, Repetto 1985,Mikesell 1992, etc.) and shown in Figure 5.5.

$$RBI_I = f(\Delta RB_I, \omega_{\Delta RB}) \rightarrow [-1, 1]$$

		$\omega_{\Delta RB}$		
		$-\infty$	0	$+\infty$
ΔRB_I	$-\infty$	1	0	- 1
	0	0	0	0
	$+\infty$	- 1	0	1

Figure 5.5: Desired Behavior of Intra-System Resource Base Impact Function

From Figure 5.5, the form of the function can be deduced as follows:

$$RBI_I = \Delta RB_I * \omega_{\Delta RB} \qquad (9)$$

where ΔRB_I = Change in the quantity of a resource during the time period analyzed

$\omega_{\Delta RB}$ = Significance of change in quantity of resource

The quantity of a resource within a system can change due to:

- Export of that resource from the system
- Import of that resource into the system
- Transformation of that resource into another resource within the system, by increasing or decreasing its entropy

Since there may be more than one kind of flow accumulating in or being depleted from the system, the total intra-system resource base impacts must be expressed as a sum of the impacts of all of the different kinds of flows, as follows:

$$RBI_I = \sum_{R} \Delta RB_i * (\omega_{\Delta RB})_i \tag{10}$$

where

R = the set of all intra-system resources

ΔRB_i = the total change in Resource i over the time period analyzed

$\omega_{\Delta RB}$ = the significance of the change in Resource i

Extra-System Resource Base Impacts (RBI_E): Recalling the classification of subvariables in Table 5.1, Extra-system Resource Base Impacts are a function of:

- Resource flows into/out of the facility system
- Loads on extra-system resource bases imposed by resource flows
- Ability of extra-system resource bases to bear imposed loads

The effects of the resource flows on extra-system resource bases can be expressed in terms of the net Resource Base Impact RBI_S for affiliate system S, if the value for this variable is known or can be estimated. The desired behavior of the Extra-System Resource Base Impact function as deduced from the sustainability literature (Daly 1990, Solow 1993, El Serafy 1992, Daly 1992, Howe 1979, Repetto 1985, Mikesell 1992, etc.) can then be expressed as shown in Figure 5.6.

$$RBI_E = f(Q, RBI_S) \rightarrow [-1, 1]$$

		RBI_S		
		$-\infty$	0	$+\infty$
Q	0	0	0	0
	$+\infty$	$-\infty$	0	$+\infty$

Figure 5.6: Desired Behavior of Extra-System Resource Base Impact Function

From Figure 5.6, the form of the function can be deduced as follows:

$$RBI_E = Q * RBI_S/Q_T \qquad (11)$$

where RBI_E = Extra-system Resource Base Impact
Q = Quantity of Resource crossing system boundary
RBI_S = Net Resource Base Impact of Source or Sink System for Resource
Q_T = Total Quantity of Resource handled by Source or Sink System

Since there may be more than one kind of flow crossing the system boundary, the total extra-system resource base impacts must be expressed as a sum of the impacts of all of the different kinds of flows, as follows:

$$RBI_E = \sum_R Q_i * (RBI_S/Q_T)_i \qquad (12)$$

where R = the set of all cross-boundary flows
Q_i = cross-boundary quantity of Resource i
$(RBI_S/Q_T)_i$ = impact per unit flow of Resource i to source or sink system

These subvariables and the functional relationships among them operationally define the impacts of a facility on resource bases.

5.2.4 A Function for Ecosystem Impacts (EI)

According to the classification developed in Section 5.1, Ecosystem Impact for a facility system is a function of:

- Intra-system Ecosystem Impacts (EI_I)
- Extra-system Ecosystem Impacts (EI_E)

To determine the nature of the relationship between these variables, the desired behavior of the function as deduced from the sustainability literature (Vitousek et al. 1986, Braat & Steetskamp 1991, Brundtland 1989, Daly 1990, Goodland 1992, Hardin 1993, Holmberg & Robért 1997, Munasinghe & McNeely 1995, Nijkamp & Soeteman 1988, Norton 1994, Rees 1990, etc.) can be expressed as shown in Figure 5.7. The possible values of the subvariables EI_I and EI_E are assumed to range from negative to positive infinity, as indicated in the table in Figure 5.7. The desired range of the function is between -1 and 1, to permit direct substitution of this parameter into the calculations for affiliate systems.

$$EI = f(EI_I, EI_E) \rightarrow [-1, 1]$$

EI_I \ EI_E	$-\infty$	0	$+\infty$
$-\infty$	- 1	- 1	0
0	- 1	0	1
$+\infty$	0	1	1

Figure 5.7: Desired Behavior of Ecosystem Impact Function

From Figure 5.7, the equation can be expressed as the sum of the subvariables transformed by the squashing function as follows:

$$EI = \tanh(EI_I + EI_E) \tag{13}$$

On the basis of the previous description of EI_I and EI_E, these variables cannot be measured directly as defined. Each of these variables must be further expanded in order to evaluate the Ecosystem Impact function.

Intra-System Ecosystem Impacts (IE_I): Recalling Table 5.1, Intra-system Ecosystem Impacts are a function of the following two subvariables:

- Change in intra-system ecosystems (ΔEI_I)
- Significance of change ($\omega_{\Delta EI}$)

An understanding of the meaning and scope of these variables is necessary to develop a function for EI_I, in terms of the representation of built facility systems developed in the first part of this chapter. Change in intra-system ecosystems refers to the increase or decrease in ecosystems on site due to destruction, restoration, displacement, or change in human activity with respect to the ecosystem (Daly 1990, etc.). Change can occur in terms of quantity as well as in terms of quality. Change is reflected in terms of the condition of ecosystems, and is independent of any complementary impacts outside the system bounds.

The variable ΔEI_I reflects changes in quantities or qualities of ecosystems on site over the time period being analyzed. Evaluating this variable requires establishing a baseline state of ecosystems for the facility system being analyzed, to be able to compare some future state of those ecosystems due to changes to the system. Assuming that sustainability analysis can be undertaken for any arbitrary unit of time in the life cycle of the facility (see Section 6.3.1 for further discussion of this stipulation), ΔEI_I can be represented as follows:

$$\Delta EI_I = (EI_I)_{t+1} - (EI_I)_t \tag{14}$$

where
- t = time at the beginning of the period analyzed
- $t+1$ = time at the end of the period analyzed
- EI_I = state of internal resource bases at a specified point in time

ΔEI_I is positive if a greater quantity or higher level of viability of an ecosystem exists within the system after one time period, and negative if less of the ecosystem exists after that unit of time (Vitousek et al. 1986, Braat & Steetskamp 1991, Brundtland 1989, Daly 1990, Goodland 1992, Hardin 1993, Holmberg & Robért 1997, Munasinghe & McNeely 1995, Nijkamp & Soeteman 1988, Norton 1994, Rees 1990, etc.).

The significance variable $\omega_{\Delta EI}$ corresponds to the ability of a given ecosystem to bear the load imposed on it by ΔEI_I. The role of this variable is to impose a penalty on ecosystem depletion for scarce or endangered ecosystems, and a penalty for further taxing an already stressed source or sink ecosystem (ibid.). Likewise, the significance function should effect a reward for systems that restore or improve the quality of a scarce or endangered ecosystem, or that absorb and positively transform negative ecosystem loads imposed by other facility systems (ibid.).

If ecosystems are expressed in terms of the change in their quantities and viability over the time period analyzed, intra-system ecosystem impacts can be represented as a function dependent on change in quantity and significance of that change, with desired behavior of the resulting function deduced from the sustainability literature (Vitousek et al. 1986, Braat & Steetskamp 1991, Brundtland 1989, Daly 1990, Goodland 1992, Hardin 1993, Holmberg & Robért 1997, Munasinghe & McNeely 1995, Nijkamp & Soeteman 1988, Norton 1994, Rees 1990, etc.) as shown in Figure 5.8.

$$EI_I = f(\Delta EI_I, \omega_{\Delta EI}) \rightarrow [-1, 1]$$

ΔEI_I \ $\omega_{\Delta EI}$	$-\infty$	0	$+\infty$
$-\infty$	- 1	0	- 1
0	0	0	0
$+\infty$	- 1	0	1

Figure 5.8: Desired Behavior of Intra-System Ecosystem Impact Function

From Figure 5.8, the form of the function can be deduced as follows:

$$EI_I = \Delta EI_I * \omega_{\Delta EI} \qquad (15)$$

where ΔEI_I = Change in the quantity or viability of an ecosystem during the time period analyzed

$\omega_{\Delta EI}$ = Significance of change in quantity or viability of ecosystem

The quantity or viability of an ecosystem within a system can change due to (ibid.):

- Consumption or destruction of that ecosystem by the system
- Import or export of components of that ecosystem by the system
- Displacement or change in human activity with respect to that ecosystem within the boundary of the facility system

Since there may be more than one kind of ecosystem being impacted within the system, the total intra-system ecosystem impacts must be expressed as a sum of the impacts of all of the different kinds of ecosystems residing in the system, as follows:

$$EI_I = \sum_{E} \Delta EI_i * (\omega_{\Delta EI})_i \qquad (16)$$

where

	E	=	the set of all intra-system ecosystems
	ΔEI_i	=	the total change in Ecosystem i over the time period analyzed
	$\omega_{\Delta EI}$	=	the significance of the change in Ecosystem i

Extra-System Ecosystem Impacts (IE_E): Recalling Table 5.1, Extra-system Ecosystem Impacts are a function of:

- Resource flows into/out of the facility system
- Loads on extra-system ecosystems imposed by resource flows
- Ability of extra-system ecosystems to bear imposed loads

The effects of the resource flows on extra-system ecosystems can be expressed in terms of the net Ecosystem Impact EI_S for system S, if the value for this variable is known or can be estimated. The desired behavior of the Extra-System Ecosystem Impact function as deduced from the sustainability literature (Vitousek et al. 1986, Braat & Steetskamp 1991, Brundtland 1989, Daly 1990, Goodland 1992, Hardin 1993, Holmberg & Robért 1997, Munasinghe & McNeely 1995, Nijkamp & Soeteman 1988, Norton 1994, Rees 1990, etc.) can then be expressed as shown in Figure 5.9.

$$EI_E = f(Q, EI_S) \rightarrow [-1, 1]$$

		EI_S		
		$-\infty$	0	$+\infty$
Q	0	0	0	0
	$+\infty$	$-\infty$	0	$+\infty$

Figure 5.9: Desired Behavior of Extra-System Ecosystem Impact Function

From Figure 5.9, the form of the function can be deduced as follows:

$$EI_E = Q * EI_S/Q_T \qquad (17)$$

where
EI_E = Extra-system Ecosystem Impact
Q = Quantity of Resource crossing system boundary
EI_S = Net Ecosystem Impact of Source or Sink System for Resource
Q_T = Total Quantity of Resource handled by Source or Sink System

Since there may be more than one kind of flow crossing the system boundary, the total extra-system ecosystem impacts must be expressed as a sum of the impacts of all of the different kinds of flows, as follows:

$$EI_E = \sum_{R} Q_i * (EI_S/Q_T)_i \tag{18}$$

where

R	=	the set of all cross-boundary flows
Q_i	=	cross-boundary quantity of Resource i
$(EI_S/Q_T)_i$	=	impact per unit flow of Resource i to source or sink system

5.2.5 Summary of Sustainability Parameter Functions

Table 5.2 shows the parameters and variables resulting from the derivations in the previous sections. For each parameter or variable, the table shows a description of the notation and the desired range. The next section of the chapter describes sources of data for those variables that can be directly measured, and proposes methods and data sources for approximating the remaining variables.

Table 5.2: Summary of Model Variables for Sustainability Parameters

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	$[0, \infty]$

5.3. Measuring or Estimating Each Variable and Subvariable

The next task of the research was to determine methods for measuring or approximating each variable in the sustainability parameter functions for built facility systems. In determining the measurability of these variables, availability of data plays a large part in whether or not a facility decision-maker could measure each variable directly, or if values would have to be estimated or approximated. The following subsections identify sources of available data for each variable or subvariable, and discuss how the values can be calculated or approximated using existing data. The outcome of this section is a set of three functions that can be evaluated using either reasonable value estimates or real data available to facility decision-makers. The first task is to assess values for the subvariables of the Stakeholder Satisfaction parameter.

5.3.1 Assessing Stakeholder Satisfaction

According to Table 5.2, a facility decision-maker needs to be able to assess the following subvariables to calculate a value for the Stakeholder Satisfaction parameter function:

- E_M = Number of Stakeholder Expectations Met
- E_{NM} = Number of Stakeholder Expectations Not Met
- E_E = Number of Stakeholder Expectations Exceeded

All of these variables are highly context-specific, and depend not only on what a given facility is used for, but also its stakeholders' past experiences and interactions with other systems, including researchers trying to evaluate them. As a result, Stakeholder

Satisfaction is subject to the Hawthorne effect (discussed in Nelson & Quick 1995): its level can be influenced and changed as a result of observation and evaluation. In addition, if the facility decision maker elects to use context- or user-specific weightings for each of the expectations considered, another level of complexity is added to the problem of calculating values for these variables.

To provide a starting point for the task of determining values for these variables, a search of the literature was conducted to identify typical expectations facility stakeholders have of existing facilities in the operations phase. Allen (1980) has developed a hierarchical listing of functional expectations owners and/or occupants have of built facilities, and this listing provided a starting point for an evaluation mechanism to assess satisfaction of stakeholder expectations during the operations phase of the life cycle. As described in Chapter 1, the set of stakeholders involved in the operational phase of a built facility can be classified as internal or external, direct or indirect stakeholders. Given the research scope discussed in Section 1.2.2, the set of stakeholders in this research can be considered in terms of the interests of a single stakeholder type: the facility's owner, which for residential facilities of the type considered, is equivalent to the facility's occupants. Table 5.3 shows Allen's list of functional expectations, augmented with the expectations denoted by an asterisk to enrich the list based on other expectations identified in the literature search. This set of expectations, while not necessarily comprehensive, is acceptable for this research in that it provides the capability to distinguish among improvement options of the type considered by stakeholders (i.e., homeowners) within the scope of the research (see Section 7.2.6; Trochim 1998c).

Using this list of expectations, a facility decision maker (e.g., a homeowner) can survey a representative set of facility stakeholders (e.g., the home's occupants) and ask them to weight or rank each expectation, then check the corresponding box on the right side of the list to indicate the status of their expectation for the survey period. If a uniform weighting was desired (as illustrated in Table 5.3), stakeholders need only report whether

Table 5.3: Stakeholder Expectations Evaluation Mechanism (after Allen 1980; augmented using Urban Ecology Australia 1995a, b; AtKisson & LaFond 1994)

Importance	Item	Expectations Not Met	Expectations Met	Expectations Exceeded
1	Clean Air Supply		1	
1	Fresh Water Supply		1	
1	Solid Waste Removal		1	
1	Wastewater Removal		1	
1	Comfortable Air Temperature		1	
1	Comfortable Surface Temperature		1	
1	Comfortable Humidity		1	
1	Comfortable Air Flow		1	
1	Protection from Weather		1	
1	Adequate Lighting		1	
1	Visual Privacy		1	
1	Adequate Noise Conditions		1	
1	Acoustical Privacy		1	
1	Adequate Security/Safety		1	
1	Adequate Protection from Vectors	1		
1	Adequate Power		1	
1	Adequate Communication Capacity - Phones		1	
1	Adequate Functional Surfaces - Floor Areas		1	
1	Adequate Functional Surfaces - Work Surfaces		1	
1	Adequate Functional Surfaces - Storage			1
1	Adequate Structural Stability		1	
1	Adequate Protection of Building from Water Damage		1	
1	Adequate Structural Integrity/Flexibility		1	
1	Adequate Fire Safety		1	
1	Adequate Operational Cost		1	
1	Adequate Ease of Operation/Maintenance		1	
1	*Adequate Indoor Aesthetics		1	
1	*Adequate Outdoor Aesthetics		1	
1	*Adequate Access to Transportation		1	
1	*Adequate Access to Shopping		1	
1	*Adequate Access to Parking		1	
1	*Adequate Access to Dining/Entertainment		1	
1	*Adequate Circulation Capacity		1	
1	*Adequate User Amenities		1	
1	*Adequate Hygeine/Sanitation/Cleanliness		1	
35		1	33	1

or not they have an expectation for each item on the survey by crossing out the category or marking a zero in the column on the left side of the list to indicate no expectation for particular list items. This list of functional expectations provides one possible structured, discrete, and quantitative way to assess values for the Stakeholder Satisfaction variables. Note that certain types of facilities may have unique measures of stakeholder satisfaction, such as Level of Service (LOS) for highways. These unique measures, although not used in this research, may be added in other applications to increase the specificity of the scale and its ability to distinguish among specific cases.

5.3.2 Quantifying Cross-Boundary Flows

The second step in applying the model to a facility system is to identify and quantify all the flows of matter and energy into and out of the system. While the number of different kinds of potential flows for facilities is staggering, this research focuses on a discrete, smaller number of flow categories to make the task of quantification manageable for facility decision-makers. In particular, consideration of flows is scoped to those types that facility decision-makers may already track as part of the normal operation of their facility. Table 5.4 shows examples of these major types of active flows that can impact sustainability for a typical throughput facility such as a house, office building, or warehouse. Active flows can be defined as flows stemming from the presence of the facility on site, such as power, water, and waste, as opposed to passive flows such as wind and solar radiation that occur whether or not facilities exist on site.

The number of flows considered can easily be expanded as desired to increase the resolution of the analysis; however, the classification in Table 5.4 covers many of the significant types of flows for the scope of built facilities considered in this research. In particular, the classes of Building Consumables and Building Durables are highly context-dependent and can differ greatly from facility to facility. One strategy for organizing these flow classes is to use an existing classification scheme such as CSI Masterformat or Uniformat (see Barrie & Paulson 1993, Hendrickson & Au 1989, Vanegas et al. 1998) to identify and organize possible subclasses of materials within these categories. However, these classification schemes are appropriate primarily for building durables. They do not provide a means for capturing other critical types of facility-related flows such as electricity, water, waste water, fuel, air pollutants, or process-related flows.

Masterformat and Uniformat classification schemes were designed as a means to facilitate project management and cost estimating during the *construction* phase of a facility's life cycle (ibid.). Given that the scope of this research focuses on facilities in the *operations* phase of their life cycle (see Section 1.2.2), flows such as power, water, wastewater, fuel, etc. are more significant in this phase than building durables, and must be captured in the analysis to assess facility sustainability. For these reasons, the CSI Masterformat and the Uniformat classification schemes were not used in this research.

Instead, a direct monitoring strategy is proposed to identify and quantify flows in this research. This strategy consists of monitoring the boundary of the system and measuring and characterizing the flows of matter and energy as they occur over a period of time. After all relevant cross-boundary flows have been identified, the next step is to quantify the flows, in terms of available data sources. Sources of information to calculate quantities include utility bills for flows such as electricity or natural gas, and store receipts for flows such as plants, lumber, etc. For other types of flows such as outputs of solid waste, quantities may need to be estimated directly via inspection of the materials themselves. Finally, quantities of waste heat, line losses of electricity, air pollutants, and other kinds of residual flows can be determined either by direct measurement using appropriate instrumentation, or using simulation models such as the DOE-2 model of building energy consumption, developed by the U.S. Department of Energy (see PTI 1996).

One final issue to note in calculating cross-boundary flows is that a consistent and appropriate increment of time must be selected for the quantification. As discussed further in Section 5.4.6, a useful increment of time for sustainability modeling is one year, to adequately incorporate changes in flow quantities due to seasonal fluctuations and other periodic annual factors such as budgeting and resource allocation processes.

Table 5.4: Examples of Flows for an Operating Facility

Direction	Class	Examples	Unit
Flows In	Power	Electricity	kWh
	Water		gal
	Fuel	Oil Propane Wood	gal gal cords
	Building Consumables	Light bulbs HVAC Filters Fertilizer Annual Plants	each each bags each
	Building Durables	Showerheads Faucets Toilets Wood Steel Concrete	each each each bd ft pound cu. yd.
Flows Out	Waste Water	Black Water Gray Water Storm Water	gal gal gal
	Air Pollutants	SO_x NO_x HCs	$\mu g/m^3$ $\mu g/m^3$ ppm
	Solid Waste	Mixed Waste Source-separated Recyclables Compostables Construction/Demolition Waste	cu. yd. lb cu. yd. tons
	Process-Related	Manufactured Products Specialized Waste Other	

5.3.3 Identifying Sources and Sinks and Their Properties

The third step in operationalizing the model to built facility systems is to identify the sources and sinks of cross-boundary flows. As discussed in Section 5.2.1, if the model has already been applied to a source or sink facility, the RBI and EI parameter function values for that system can be directly substituted into the functions for the system being analyzed. However, if the values for RBI and EI have not already been calculated for the sources and sinks, they must be either estimated or calculated to perform the analysis for the system of interest. Since calculating exact values for all affiliate systems could potentially expand to involve all systems on Earth, this discussion focuses instead on a method to approximate the EI and RBI of typical systems that serve as sources and/or sinks for built facility systems.

Estimating Values for RBI_E: Estimating values for extra-system resource base impacts involved identifying typical source and sink system technologies for the cross-boundary flows of the simulated facility type. The estimation began by generating a general classification of resource bases to reduce the potential complexity of the calculations. The general classification consisted of five categories of resource bases: Energy, Water, Nonrenewable Materials, Plants, and Animals. These classes served as a basis for estimating how typical technologies for the flows of a facility would impact these resource bases. Each type of source or sink system thus had a default vector RBI_S, with values in the range [-1, 1], over the five classes of resource bases.

For example, a typical sink system for exported wastewater in a United States urban setting is a publicly owned treatment works (POTW). Based on general engineering knowledge and specific technology descriptions from engineering handbooks (e.g., Metcalf & Eddy 1991; Tchobanoglous et al. 1993; Seinfeld 1986), a 1-of-N classification strategy was used to select approximate values for the unit impact of flows and significance of those flows in terms of the five elements of the resource vector. Appendix C shows the details of these calculations.

To add context-specificity to the significance factor, a locational load-bearing capacity 1-of-N rating was developed, based on geographic resource assets and problems broken down by United States bioregion (Sierra Club 1997). Table 5.5 shows the decision criteria corresponding to the 1-of-N capacity rating.

Table 5.5: Decision Criteria for 1-of-N Load-Bearing Capacity Rating

[illegible]	[illegible]	[illegible]
1	Significant positive impacts or immense supply of resource i	1
2	Some positive impacts or ample supply of resource i	0.5
3	No evidence	0
4	Some negative impacts or limited supply of resource i	-0.5
5	Significant negative impacts or scarce supply of resource i	- 1

The significance factor for a given source or sink system was then calculated using the step function shown in Table 5.6, where I_T is the unit load imposed by the source or sink system on a given resource base, C_R is the remaining capacity of the resource base as determined locationally, and $\omega_{\Delta RB}$ is the resulting significance of the impact. For example, if the unit load I_T imposed by a source or sink system is positive (>0) for a given resource class and the remaining capacity of that resource class is also positive (>0), then the value for significance $\omega_{\Delta RB}$ is 1.

Table 5.6: Step Function for Estimating Impact Significance

[illegible]	[illegible]	[illegible]
>0	>0	1
>0	=<0	0.5
0	NA	0
<0	>0	0.5
<0	=<0	1

The approximated value for the RBI of the source or sink system can thus be calculated using equations (19) and (20).

$$(RBI_E)_i = (Q * RBI_S/Q_T)_i \qquad (19)$$

$$RBI_S \equiv I_{ST} * (\omega_{\Delta RB})_{ST} \qquad (20)$$

where
$(RBI_E)_i$ = Extra-system Resource Base Impact for Flow *I*
RBI_S = Net Resource Base Impact for Source or Sink
I_{ST} = Unit load imposed by Source or Sink Technology
$(\omega_{\Delta RB})_{ST}$ = Significance of Imposed Unit Load

Since a location-specific significance factor was incorporated, general unit loads for specific technologies can be approximated and rendered context-specific using the significance factor. Table 5.7 shows the decision table used to determine these unit loads, based on evidence found in general engineering handbooks (e.g., Metcalf & Eddy 1991; Tchobanoglous et al. 1993; Seinfeld 1986). This strategy means that generic or default flow factors can be developed for potential source and sink technological systems, and customized to a given context based on their location and the properties of resource bases in that location.

Table 5.7: Decision Table for Determining Unit Loads

Criterion	Source/Sink Technology Flow Impacts
Substantial evidence of positive impact	1
Some evidence of positive impact	0.5
Evidence of no/neutral impact	0
Some evidence of negative impact	–0.5
Substantial evidence of negative impact	-1

Table 5.8 shows a listing of potential sink options (e.g., wastewater treatment plant technologies) for typical flows common to many built facility systems (e.g., wastewater), along with generic unit loads for those technologies. Having built-in default values for these technologies means that a facility decision maker can simply select from a menu of possible source or sink technologies for each flow type and specify the bioregion in which the technology is located, rather than having to calculate specific values for each affiliate system of each flow.

Alternatively, if the decision maker has access to more accurate data or wishes to collect the needed data to calculate the RBI of a specific source or sink affiliate system, these default values can be changed to reflect more precise values. By providing the capability to approximate RBI based on locational context and generic technology type, however, the usability of the sustainability model is increased.

Table 5.8: Sample Sink Technology Options and Unit Loads for Common Facility System Flows

[illegible]	[illegible]	Resource Base Unit Loads for Technology [illegible]				
Waste Water	Bioremediation	0	1	0	1	0
	POTW - Tertiary	-0.5	1	-0.5	0	0
	POTW - Secondary	-0.5	1	-0.5	0.5	0
	POTW - Primary	-0.5	0.5	0	0	0
	Direct Dump	0	-0.5	0	0	0
Mixed MSW	Central Sort/Recovery	-0.5	0	1	0	0
	Waste-to-Energy Incinerator	1	-0.5	0	0	0
	Sanitary Landfill	0.5	0	0	0	0
	On-site burning	0.5	0	0	-0.5	-0.5
	Off-site dumping	0	0	0	0	0
Bagged Compostable Waste	Central Composting Facility	-0.5	-0.5	0	-1	0
	Sanitary Landfill	0.5	0	0	0	0
Recyclable MSW	Recycling Plant	-0.5	-0.5	1	0	0
	Downcycling Plant	-0.5	-0.5	0.5	0	0
	Sanitary Landfill	0.5	0	0	0	0
	WTE Incinerator	1	-0.5	0	0	0
Mixed C&D Dry Waste	Central Sort/Recovery	-0.5	0	1	0	0
	Salvage Facility	0	0	1	0	0
	Sanitary Landfill	0.5	0	0	0	0
	Downcycling	-0.5	-0.5	0.5	0	0
	WTE Incinerator	1	-0.5	0	0	0

Estimating Values for EI_E: A similar strategy was used to approximate values for the EI_E variable of the ecosystems impact parameter. First, a general classification of ecosystem entities was developed that could be affected by facility flows, including Air, Water, Soil, Flora, and Fauna. These five categories of impactable entities enabled comparison of potential source and sink technologies in terms of their likely unit loads on these entities. As with RBI_E, a 1-of-N classification strategy was used to identify default unit loads for a variety of source and sink technologies typical of the range of options for built facility systems. The Remaining Capacity of ecosystems at a bioregional scale was also assessed using a 1-of-N strategy, in terms of these five classes of entities. Table 5.9 shows Remaining Capacity values for ecosystems according to bioregion, determined using the decision criteria specified in Table 5.7 with a bioregional source of data supplied by (Sierra Club 1997). The classification criteria were the same as those used for identifying remaining capacities of resource bases (See the criteria in Table 5.5).

The equations used to calculate approximate values for extra-system ecosystem impact are analogous to those for extra-system resource base impacts (see Equations 19, 20). As with Resource Base Impact, model users are able to substitute more precise values for the default variables as need warrants and data availability permits. The benefit of having arrays of default technologies and unit loads is that it enables users to simply select from a menu of potential technologies for each flow, and specify a location for that source or sink technology. The model user still has to determine the location of the technology, as well as the total quantity of flow served by that technological system. However, these types of data can be obtained in a straightforward manner by contacting the source or sink system directly and inquiring about their process and total flow.

5.3.4 Estimating Potential Changes to the Facility Over Time

After calculating values for extra-system RBI and EI as discussed in the previous sections, the last step in determining values of the RBI and EI parameters for a built facility system was to determine the intra-system impacts of the facility. As mentioned in Section 5.2, these impacts are typically most significant for source and sink facilities, but they must nonetheless be taken into account in evaluating the sustainability of all facilities. The following subsections describe methods for calculating values for RBI_I and EI_I in terms of information available to facility decision-makers.

Estimating Values for RBI_I: To estimate values for intra-system resource base impacts, a strategy was used similar to that for extra-system resource base impacts.

Table 5.9: Remaining Capacity Default Values for Ecosystem Entities by Bioregion (Sierra Club 1997)

Capacities by Bioregion	Ecosystem Load Bearing Capacity				
Bioregion					
Pacific Northwest	0	0	0	- 1	1
Pacific Coast	- 1	- 1	1	0	0
Sierra Nevada	1	1	0	0	0
Boreal Forest	1	1	1	1	1
Alaska Rainforest	1	1	1	1	1
Great Basin High Desert	1	- 1	- 1	- 1	0
Rocky Mountains	- 1	- 1	- 1	0	0
Colorado Plateau	0	0	1	1	1
Southwest Deserts	0	- 1	- 1	0	0
Great North American Prairie	1	- 1	- 1	- 1	- 1
Interior Highlands	- 1	- 1	0	- 1	- 1
American Southeast	- 1	- 1	- 1	1	1
Mississippi Basin	0	- 1	- 1	0	1
Great Lakes	- 1	- 1	0	0	0
South Appalachian Highlands	- 1	0	0	1	1
Central Appalachia	- 1	- 1	0	0	0
Northern Forest	- 1	- 1	0	0	0
Atlantic Coast	- 1	0	0	0	0

From Table 5.2, the salient subvariables for this value are:

ΔRB_I = Change in Intra-system Resource Base for unit time

$\omega_{\Delta RB}$ = Significance of Change in Intra-system Resource Base

To calculate changes in the intra-system resource base ΔRB_I, a decision-maker must conduct a site-specific benchmark inventory of resource bases and periodically monitor or estimate potential changes to those resources. For the demonstration case in Chapter 6, as may be the case for many urban residential facilities, none of the facility improvement options considered had significant changes to the five-item resource base vector entities, for two basic reasons. First, the typical urban housing lot is relatively small and has negligible quantities of energy or water sources, caches of nonrenewable materials, plants, or animals of any significant quality, meaning that the baseline state of the resource base for these kinds of sites is essentially zero. Secondly, the kinds of improvement options considered in the demonstration case (e.g., hot water heater jacket, improved insulation of the building envelope) have negligible impacts on any resources that may exist on the site itself.

To approximate the significance factor used to calculate RBI_I, the bioregion-specific location factors were used in conjunction with predicted ΔRB_I, using the same methodology as for extra-system resource base impact (see Section 5.3.3). In the analysis of a source or sink system, calculating more precise values for RBI_I would be more critical, since by definition these facilities either accumulate or lose resources within their boundaries. Correspondingly, the probability that the decision maker would already be monitoring the status of on-site resource bases is much greater for these types of facilities (after Ashby & Jones 1980), since the exploitation of these resource bases is likely to be the basis for the economic operation and management of the facility. Thus, one could hypothesize that the significance of RBI_I to overall facility sustainability is proportional to the likelihood of the decision maker having access to accurate data as a result of monitoring these changes for economic or other reasons.

Estimating Values for EI_I: The final function to be calculated in using the model is that of intra-system ecosystem impact. From Table 5.2, the critical subvariables for this value are:

ΔEI_I = Change in Intra-system Ecosystems for unit time

$\omega_{\Delta E}$ = Significance of Change in Intra-system Ecosystems

For this variable, an operational procedure was developed to calculate impacts to the five-item ecosystem impact vector [Air Quality, Water Quality, Soil Quality, Flora Quality, Faunal Quality] based on land use for the system. In developing this calculator (an example including the percent breakdown of areas for an urban residence is shown in Table 5.10), it was hypothesized that the quality of the ecosystems on site is related to the type of land use to which the site is put.

The process for developing the Site Ecosystem Impact Calculator involved developing a breakdown of four ecosystem classes relating to land use (virgin/undisturbed areas, managed natural ecosystems, artificial ecosystems, and built areas), and then specifying sets of potential land uses that corresponded to each of these four classes, for a total of 13 possible categories (see Columns 1 and 2 in Table 5.10).

Each land use was ranked (from 1 to 13) in order of its relative estimated impact on site ecosystems (see Table 5.10, columns 4-8), based on decision criteria as shown in Table 5.7. After ranking, the Ecosystem Impact Unit Loads used to calculate EI were determined by normalizing the rankings in columns 5-8 to a range of [-1, 1]. Note that a rank of 7 is the median value of the ranking scale, and therefore corresponds to an Ecosystem Impact Unit Load of zero. Using this normalized ranking scale, designated virgin or undisturbed land has the maximum positive value for ecosystem impact unit load (designated by +1.0 in Table 5.10, columns 9-13), and built-out areas have the maximum negative value (designated by −1.0 in Table 5.10, columns 9-13).

Using a method similar to that for Extra-System Ecosystem Impacts, the values from columns 9-13 in the Ecosystem Impact Calculator (Table 5.10) were used as Ecosystem Impact Unit Loads, while the percent area for each land use (column 3, Table 5.10) served as the value for Q/Q_T within the boundaries of the site itself. Significance was calculated using the step function (Table 5.6) and locational context values (Table 5.9) for the site's bioregion, as in Equations 19 and 20.

The resulting approximation method enables model users to estimate the percentage of site area for each category of land use, and determine the bioregion in which the site is located. All other calculations to determine EI_I can be approximated using the Ecosystem Impact Calculator values shown in Table 5.10, columns 9-13.

5.4. Forecasting the Sustainability of Future Facility States

The preceding calculations can be used to establish a benchmark state of sustainability for a facility system in terms of the three parameter functions. However, in order to prioritize potential improvement options, it is necessary to predict or forecast what the state of sustainability might be after implementing those options. Currently, only limited

Table 5.10: Site Ecosystem Impact Calculator

			Ecosystem Impact Rankings					Ecosystem Impact Unit Loads				
Virgin/Undisturbed Areas	None	0	1	1	1	1	1	1	1	1	1	1
Managed Natural Ecosystems	Fallow	0	2	2	2	2	2	0.83333	0.83333	0.83333	0.83333	0.83333
	Sporadically Cleared	16.70%	3	3	3	3	3	0.66667	0.66667	0.66667	0.66667	0.66667
	Regularly Cleared	0	4	4	5	4	4	0.5	0.5	0.33333	0.5	0.5
	Used as Sink/Storage for Non-Toxics	0	5	5	10	6	5	0.33333	0.33333	-0.5	0.16667	0.33333
	Used as Sink/Storage for Toxics	0	10	8	12	7	10	-0.5	-0.1667	-0.8333	0	-0.5
Artificial Ecosystems	Lawn	33.30%	6	7	7	9	8	0.16667	0	0	-0.3333	-0.1667
	Ornamental Garden	8.30%	7	6	4	5	6	0	0.16667	0.5	0.33333	0.16667
	Agricultural	0	9	11	6	8	7	-0.3333	-0.6667	0.16667	-0.1667	0
	Bare Soil	0	11	10	9	11	9	-0.6667	-0.5	-0.3333	-0.6667	-0.3333
Built Areas	Hardscape with Container Plants	8.30%	8	9	8	10	11	-0.1667	-0.3333	-0.1667	-0.5	-0.6667
	Hardscape/Paved Area	16.70%	12	13	11	13	12	-0.8333	-1	-0.6667	-1	-0.8333
	Building Footprint	16.70%	13	12	13	12	13	-1	-0.8333	-1	-0.8333	-1
	Total =	100%										

vendor claims are available to predict how improvement options will affect the flows of matter and energy through facility systems, or the resource bases, ecosystems, or stakeholders on site. No known comprehensive studies have been conducted to actually measure the changes in resource flows due to improvement options, or to evaluate how changes affect resource bases, ecosystems, or stakeholders.

This research provides an impetus for development of such studies by identifying what types of data are important to collect. Nonetheless, in order to meet the objective of being able to prioritize improvement options, this research predicted future sustainability states for comparison against the benchmark state. To accomplish this task, it was necessary to estimate changes to each of the variables in the operational objective functions. Three strategies were used to estimate these changes.

5.4.1 Assumption of No Change

Some variables are not impacted by improvement options, and can therefore be assumed to remain the same for the prioritization process. For example, many improvements within buildings (e.g., retrofit with low-flow faucets, tightening the building envelope) do not impact on-site ecosystems or resource bases at all if the sources and sinks for the associated resource flows are located off site. For changes like these, all variables can be assumed to remain the same except for changes in extra-system impacts due to the raw materials brought on site and the revised flows resulting from the upgrades.

5.4.2 Calculation Based on Engineering Estimates

For variables that are likely to change as a result of implementing improvement options, a straightforward way to estimate values for the operational functions is to estimate changes based on engineering knowledge. For example, retrofitting with low-flow fixtures will change the quantities of fresh water flowing into the system and wastewater flowing out of the system due to reduction in aperture size (see Appendix D for an example). These quantity changes can be estimated based on the difference in flow rate between the new fixture and the old fixture, times the amount of time the fixture is currently used. This quantity can then be subtracted from the total flows of water to estimate quantities for the fixture retrofit scenario. Other changes in flows can be estimated in a similar fashion.

Estimating changes to intra-system resource bases and ecosystems requires predicting how improvement options will impact the total set of resources and/or ecosystems on site. For example, constructing a new structure on the site will involve converting some percentage of land use to building footprint, with corresponding changes in the breakdown of land uses. Likewise, timbering part of a site will shift the proportion of land uses, as well as reduce the amount of plant resources on site by some proportion. Estimates for the changes in these factors must occur on a case-by-case basis as appropriate to the nature of the change.

5.5. Summary: Model of Built Facility Sustainability

This chapter showed how the construct of sustainability developed in Chapter 4 could be broken down into variables relevant to facility decision makers, using a systems representation of built facility systems. Subvariables were identified for each of the three parameters (see Table 5.1), and the logical relationships between those subvariables was determined using mathematical solution for the desired behavior of the parameter functions (see Table 5.2). Finally, the chapter showed how variables in each parameter function could be calculated or approximated for real facility systems, based on data typically available to built facility decision makers (Sections 5.3 and 5.4). The next task is to demonstrate and test the operational functions developed in this chapter. Chapter 6 describes the strategy and presents the results for this final phase of the research.

CHAPTER VI

APPLYING THE MODEL OF BUILT FACILITY SUSTAINABILITY

The previous chapters developed a theoretical construct of sustainability for technological systems and a quantitative model for evaluating the sustainability of built facility systems. The purpose of this chapter is to present a process for applying the construct and model to the problem of prioritizing improvement opportunities, and to demonstrate the process using a case study of a suburban residential facility. The chapter concludes with an examination of the performance of the model and an evaluation of its validity in terms of the questions posed in Chapter 3: Methodology.

6.1. Process for Using the Model to Prioritize Improvement Options

In terms of the research objectives, facility decision makers would like to select the improvement options that are likely to have the greatest impact on the sustainability of their facility, while avoiding any negative ramifications for the facility's occupants and remaining within budgetary or other constraints. This section describes a process for applying the model developed in Chapter 5 to enable prioritization of options in terms of their impacts on facility sustainability, within the constraints of facility decision making.

6.1.1 The Deterministic Decision Model

The process for applying the model to prioritize improvement options is based on a basic decision model with deterministic outcomes for each of a bounded set of alternatives.

Figure 6.1 shows the deterministic decision model, adapted from classical decision theory (Simon 1986), underlying the prioritization process.

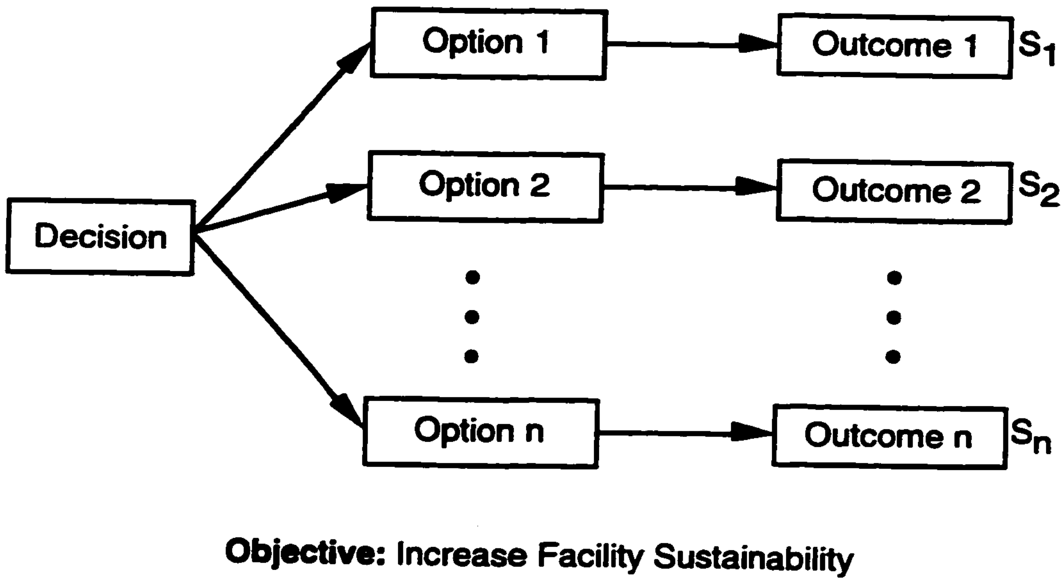


Figure 6.1: Deterministic Decision Model (adapted from Simon 1986)

In this adaptation of the classical model, a decision maker prioritizes improvement options based on the relative sustainability (S_i) of their outcomes. First, the decision maker identifies a bounded set of improvement options, each of which is associated with an expected outcome. Each outcome has a corresponding value for the objective function S (i.e., the degree to which the sustainability of the facility is changed after the option is implemented), based on deviations from the baseline state of sustainability S_0 initially calculated for the facility. The baseline state of sustainability for the facility is defined as the objective function evaluated at the decision point, prior to any changes being made.

After pruning infeasible options using constraints such as economic affordability, the decision maker examines remaining options within the envelope of constraints to determine how the options compare in terms of increase or decrease in facility sustainability. The outcome of the decision process is a prioritized list of feasible options or combinations thereof, ordered on the basis of greatest increase in facility sustainability.

The next section describes this decision process in terms of the operational parameters used to calculate facility sustainability as developed in Chapter 5 and summarized in Table 5.2. Note that these individual parameters (Stakeholder Satisfaction, Resource Base Impact, and Ecosystem Impact) for each improvement option signify a point (corresponding to S_i for that option) in the three-dimensional decision space developed in Chapter 4 (see Section 4.3.2 and Figure 4.13). The position of the points within the three-dimensional space determines the relative degree to which the improvement options result in increased facility sustainability.

6.1.2 Improvement Option Prioritization Process

The improvement option prioritization process follows the decision model described in Section 6.1.1. In the context of prioritizing improvement options, the process follows five sequential steps.

Determining Baseline Sustainability State: The first step is to apply the model of sustainability to the status quo state of the facility, to calculate a baseline value for sustainability in terms of the three functions described in Chapter 5: Stakeholder Satisfaction, Resource Base Impact, and Ecosystem Impact. Based on the methodology discussed in Chapter 5, the baseline value for Stakeholder Satisfaction can be calculated by requesting a representative set of stakeholders to complete the satisfaction assessment scale (Table 5.3) and determining an average level of satisfaction over all stakeholders. Values for baseline Resource Base Impact and Ecosystem Impact are calculated by:

1) Estimating or measuring quantities of matter or energy flows across facility boundaries

2) Identifying the sources and/or sinks for those flows, and selecting the corresponding default technology unit load from predefined values

3) Identifying the location of sources and/or sinks and the total flows serviced by those sources or sinks

4) Calculating Extra-System Ecosystem Impacts for each type of flow using the equations (repeated from Table 5.2):

$$(EI_E)_i = (Q * EI_S/Q_T)_i$$

where

EI_E = Extra-system Ecosystem Impact

Q = Quantity of Resource crossing system boundary

EI_S = Net Ecosystem Impact of Source or Sink System for Resource

$\equiv I_{ST} * (\omega_{\Delta E})_{ST}$

Q_T = Total Quantity of Resource handled by Source or Sink System

$(\omega_{\Delta E})_{ST}$ = Significance of Imposed Unit Load

5) Calculating Extra-System Resource Base Impacts for each type of flow using the equations (repeated from Table 5.2):

$$(RBI_E)_i = (Q * RBI_S/Q_T)_i$$

$$RBI_S \equiv I_{ST} * (\omega_{\Delta RB})_{ST}$$

where $(RBI_E)_i$ = Extra-system Resource Base Impact for Flow *I*
RBI_S = Net Resource Base Impact for Source or Sink
I_{ST} = Unit load imposed by Source or Sink Technology
$(\omega_{\Delta RB})_{ST}$ = Significance of Imposed Unit Load

6) Calculating Intra-System Ecosystem Impacts by estimating the changes in land use on the site and using the Ecosystem Impact Calculator as shown in Table 5.8

7) Specifying that Intra-System Resource Base Impacts = 0 for the baseline state of a throughput system

8) Summing Intra- and Extra-System Ecosystem Impacts and applying the hyperbolic tangent function to determine total baseline Ecosystem Impact

9) Summing Intra- and Extra-System Resource Base Impacts and applying the hyperbolic tangent function to determine total baseline Resource Base Impacts

The resulting values for Stakeholder Satisfaction, Resource Base Impact, and Ecosystem Impact represent a baseline point in three-dimensional sustainability space (Figure 6.2), defined by the triaxial representation of system sustainability developed in Chapter 4 (Figure 4.13). This point is the benchmark from which the decision maker calculates the change in sustainability for each improvement option. Note that in the example shown in Figure 6.2, the baseline state of sustainability lies in the positive octant of all three axes; however, the baseline states of a facility could lie in any octant within the triaxial space.

Identifying Options: The next step in the prioritization process is to identify potential options for improving system sustainability. Many sets of heuristics and guidelines are available to suggest possible options; the reader is referred to Chapter 2, Section 2.2 for a detailed discussion of these heuristics and guidelines. The option identification process is assumed to be bounded, i.e., not exhaustive, and is assumed to be constrained by the interests and preferences of the decision maker performing the analysis. The outcome of this step is a finite list of improvement options that appeal to the decision maker, representing possible ways to improve the facility. They may or may not increase the sustainability of the facility.

Forecasting Future Sustainability States: The third step in the prioritization process is to estimate how implementing each of the improvement options will change the variable values in the baseline model run. For example, the following variables will likely change the outcome of the sustainability model as a result of implementing an improvement option:

- Degree to which Stakeholder Expectations are met
- Resource Flows across system boundaries (one time or ongoing)
- Designated source or sink system for cross-boundary flows
- Proportion of land use on site
- Quantity of Resource Bases on site

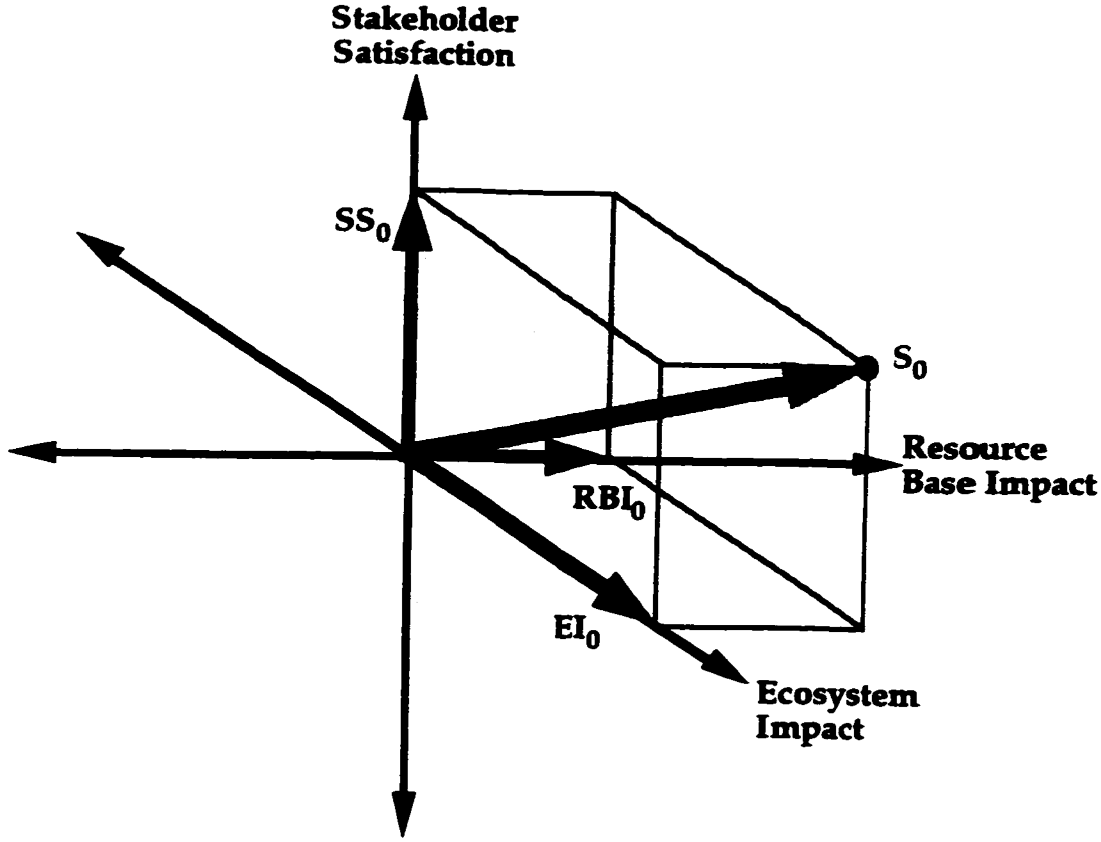


Figure 6.2: Baseline Sustainability State for a Facility

These variable values define the outcome state associated with each alternative. When the parameters have been recalculated for each of the potential improvement options, the decision maker can adjust the values in the baseline sustainability state calculations to forecast an expected value for the sustainability S_i associated with each alternative, resulting in new points in sustainability space at coordinates $[SS_i, RBI_i, EI_i]$. The vector between each new point and the original baseline point represents the change in sustainability for the associated improvement option (Figure 6.3). Note that operational costs are factored into calculations for Stakeholder Satisfaction, while the net cost of implementing improvement options is factored as a feasibility constraint in the next step.

Applying Constraints: The set of alternatives must now be evaluated in terms of any constraints imposed by the context of the decision maker. Examples of potential constraints include economic feasibility, code or regulatory constraints, minimum stakeholder satisfaction requirements, or other context-specific constraints. In this step, any infeasible alternatives are pruned from the set of possibilities, although prudent selection of alternatives in the second step may avert the need to prune any alternative by itself. Combinations of alternatives, however, may prove to be infeasible even though each alternative by itself is feasible. All combinations of alternatives may be evaluated in terms of the feasibility constraints, resulting in a set of feasible options and combination of options to be prioritized.

Prioritization of Improvement Alternatives: After all infeasible combinations of alternatives have been pruned from consideration, the last step is to order the combinations according to maximum increase in sustainability. To accomplish this ordering with the point and vector representation of sustainability in the three-dimensional decision space, this research used the method of resolving each option's sustainability change vector into its components along a unit vector within the three-dimensional space (Duke 1999, Griffin 1999), as follows.

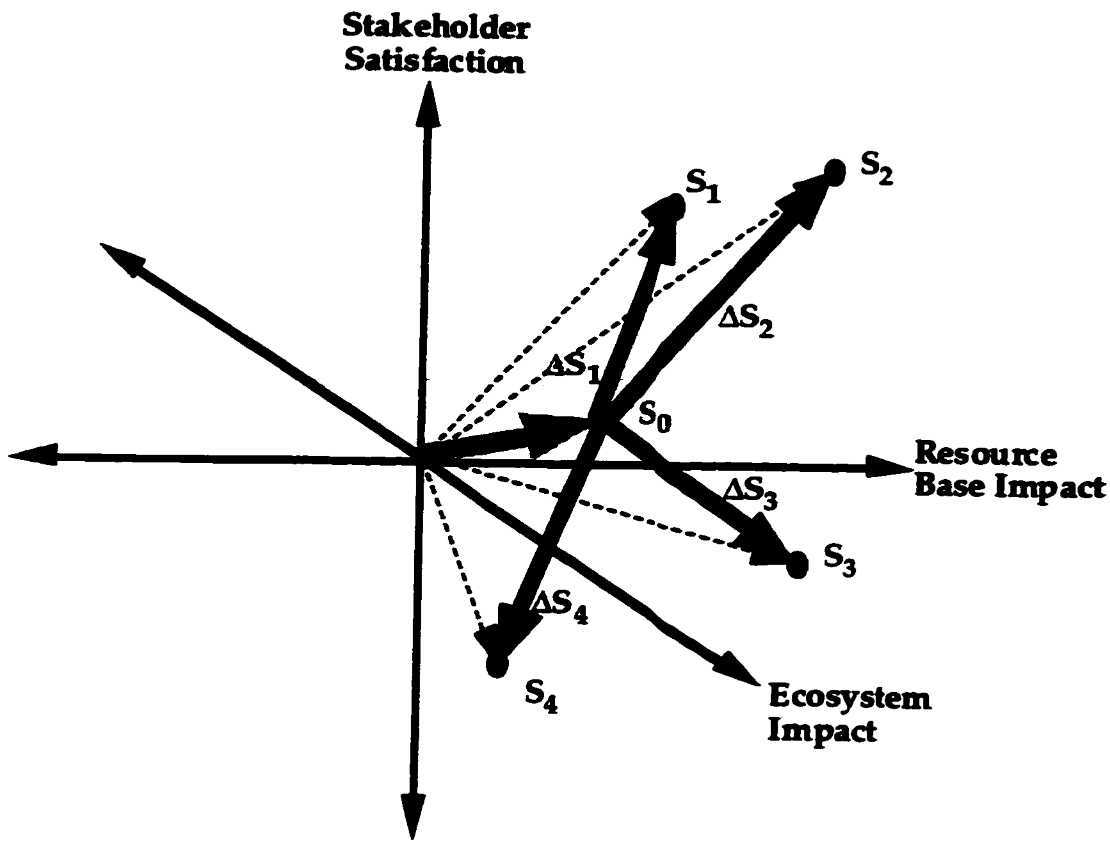


Figure 6.3: Sustainability States for Improvement Options, relative to the Baseline State

First, within the three-dimensional sustainability decision space there exists one possible vector that represents a maximum positive increase in sustainability with respect to the origin of the space (Figure 6.4). This vector, hereafter called the unit sustainability vector, represents maximum positive sustainability since it is exactly equidistant from each of the three axes in the positive direction (denoted by theta angles in Figure 6.4) and passes through the point [+1, +1, +1], defining the maximum positive limit of each parameter as described in Chapter 5, Table 5.2. For the purposes of accounting for points with negative coordinates, the unit sustainability vector can also be projected into the completely negative octant of the space with the exactly opposite direction and same magnitude (i.e., passing through the origin to the point [-1, -1, -1]). Resolving each change vector into its component along this unit vector obtains a single basis for comparison of the options, even though the change vectors themselves may be projecting into different directions (ibid.). Recall that a change vector is the vector representing the difference between the baseline state of sustainability for a facility S_0 and the sustainability of the facility after implementing some improvement option S_I, as denoted in Figure 6.3 by ΔS_I for each option S_i.

Resolving the change vectors into their components along the unit sustainability vector can be accomplished using basic vector mathematics for the vector components (ibid.), the principle of which is illustrated in Figure 6.5. Since each change vector is known in terms of its orthogonal components (SS, RBI, EI) along the original axis orientation, the projection onto the unit sustainability vector can be calculated by summing the set of each component divided by the cosine of its angle of deviation from the unit sustainability vector. Since the unit sustainability vector is equidistant from each axis, its angle of deviation must be 45 degrees from each axis, resulting in the following equation for the composite sustainability index ***S***:

$$S = \frac{SS}{\cos(45)} + \frac{RBI}{\cos(45)} + \frac{EI}{\cos(45)} \qquad (21)$$

Equation 21 can be reduced to the following, simplified equation since all parameters are divided by the same constant (ibid.):

$$S = \frac{(SS + RBI + EI)}{\sqrt{2}} \qquad (22)$$

The vector method for comparing the sustainability of change options resolves non-orthogonal vectors into their components along the desired axis, i.e., the unit sustainability vector. Note that using three-dimensional vector mathematics, two components orthogonal to the unit sustainability vector will also result from resolving the change vector into its components along the axis orientation defined by the unit sustainability vector. With respect to the original three-dimensional sustainability space, these perpendicular component vectors represent effects or forces resulting from the change that have no contribution to moving the facility in the direction of sustainability. As such, they are not considered in the vector-based comparison of options using the composite sustainability index.

Note that for convenience of representation, Figure 6.5 shows the baseline sustainability of the facility S_0 located at the origin of the three-dimensional space. Since this research is concerned with the *relative priorities* or *ranking* of improvement options, shifting all change vectors within the space while maintaining their magnitudes, directions, and relative position to one another is a valid operation (ibid.).

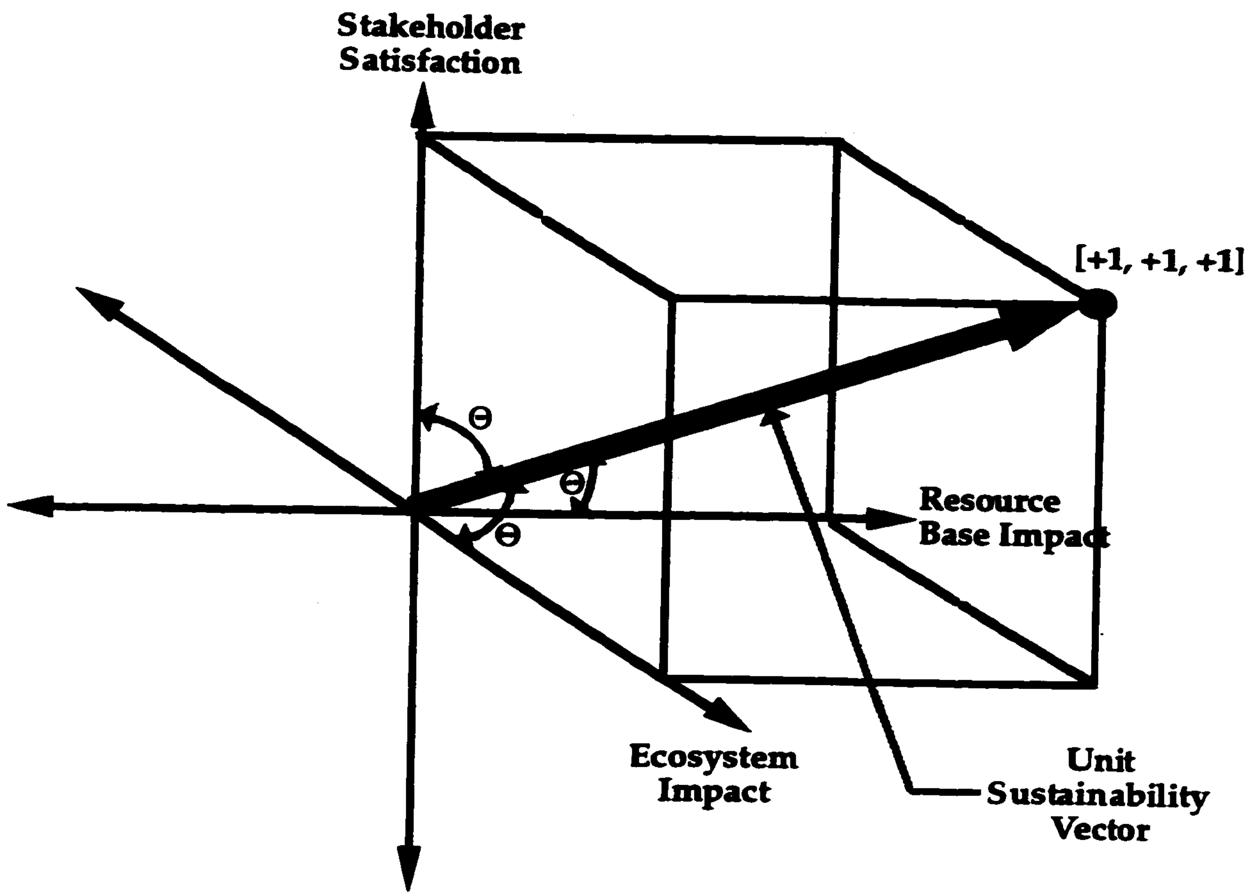


Figure 6.4: Unit Sustainability Vector in the Three-dimensional Sustainability Space

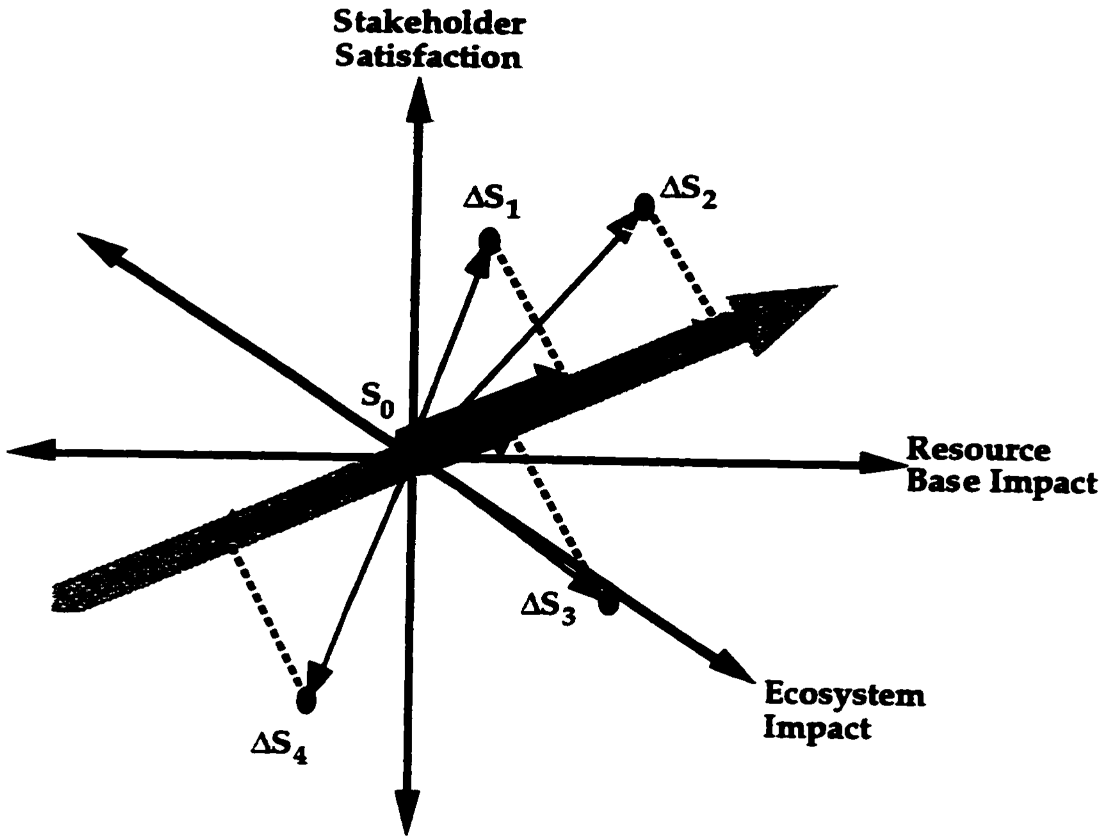


Figure 6.5: Projection of Change Vectors onto the Unit Sustainability Vector

The composite sustainability index (Equation 22), direct examination of the positions of points within the three-dimensional sustainability space, and parameter-by-parameter comparison are used in the remainder of the chapter to compare and prioritize improvement options for the case study and performance analysis. Each of these methods has implications for the outcome of the prioritization process, discussed in detail in Sections 6.3 and 6.4. To demonstrate the prioritization process from beginning to end and to provide a basis for analysis, the next section presents a case study of an urban residential facility.

6.2. Demonstration of the Prioritization Process

Having described a process to use the model for improvement option prioritization, the next part of the chapter is devoted to presenting an example of how the model and process can be applied to a real facility: a single-family detached residence in Atlanta, GA. Details and additional documentation of the features of the case study facility are included in Appendix D.

6.2.1 Case Study Selection

This facility type was selected for two primary reasons. First, according to a recent study, construction of single-family residences are projected to comprise 26.1% of all construction in 1999, making them the largest single category of facilities built in the United States (FMI Corporation 1998). The total number of single-family detached homes existing in the United States was over 62 million in 1993, and was estimated to be growing by 18 million per year (U.S. Department of Commerce 1993), making this type of facility a very significant component of the residential sector. Additionally, over $73 billion were spent on residential improvements in 1998, a figure representing approximately 13% of all construction volume in terms of current dollar expenditures (FMI Corporation 1998).

Thus, single-family detached residences and improvements thereto comprise a significant portion of all facilities being constructed in the U.S., and any changes or improvements to the state of the art in this segment of the industry have potentially widespread and cumulatively significant impacts.

Second, among all the sectors of construction (see Section 1.1), facilities in the residential sector incorporate all building systems and represent a broad range of materials, structures, engineering requirements, and other attributes. For example, in terms of a single kind of building system—the roof—single-family facilities can have a variety of materials (e.g., metal, asphalt, membrane, tile, slate, wood shingle, etc.), structures (e.g., flat/low-slope, pitched, gabled, hipped, etc.), and engineering requirements (e.g., snow loads, wind loads, insulation requirements, water control requirements, ventilation, etc.). Other residential building systems have similarly large varieties of possible materials, structures, and engineering requirements. Residences also exist in all ranges of climates, environmental settings, and cultural contexts. All levels of society and cultures can relate to single-family residences. This facility sector covers the whole gamut of construction and engineering attributes and requirements. With successful proof of concept in the residential sector, these impacts can begin to propagate and influence general building practice in other facility sectors.

6.2.2 Applying the Prioritization Process

In preparation for conducting the case study, the homeowner (hereafter referred to as the facility decision maker) was provided with a description of a generic decision maker performing a sustainability self-assessment to illustrate the kinds and quantities of data that would be required for the analysis. Upon receiving permission to use the facility as a case study, the first step was to establish a baseline state of sustainability for the facility.

Determining Baseline Sustainability State: The baseline flows for the facility, along with source and sink information, are shown in Appendix D, Table D.3. The baseline state of Intra-System Ecosystem Impact is shown in Appendix D, Table D.4. Intra-System Resource Base Impact was assumed to be zero for the baseline state, since no significant accumulation to or depletion of on-site resources was estimated over the time period of assessment, 1997. The facility decision maker completed the Stakeholder Satisfaction scale on behalf of all seven stakeholders on site, using a weighting scale of 0 to 5 to indicate relative importance of each scale item. The responses of the facility decision maker are shown in Appendix D, Table D.1. The baseline sustainability state of the facility is shown in Figure 6.6 as a point within the three-dimensional sustainability decision space developed in Chapter 4. The sustainability state was calculated using the default values for source and sink technologies described in Chapter 5 and provided in Appendix C. The baseline state calculations revealed the values for the sustainability components [SS, RBI, EI] to be [+0.410959, -0.000117, +0.022549]. RBI is negative due to the extra-system effects of the system's consumption of external resource bases, and RBI_I is assumed to be negligible/zero as described in Section 6.1.2. EI is positive due to the relatively large percent of the site covered with vegetation. While EI_E is negative due to the extra-system effects of the system's consumption of resource flows from off-site, these effects are offset by the ecologically positive distribution of land uses on the site itself.

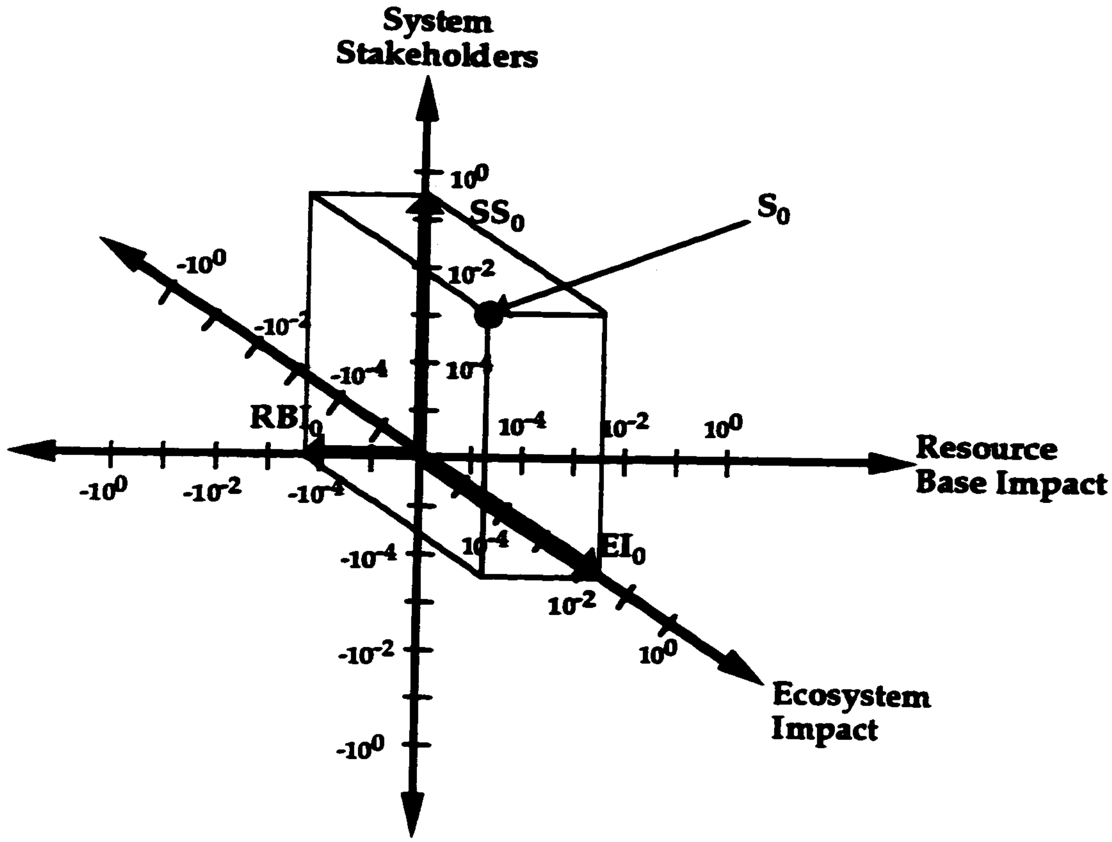


Figure 6.6: Baseline Sustainability State for Case Study Facility

Identifying Options: Following completion of the Stakeholder Satisfaction scale, an unstructured interview with the facility decision maker was used to identify potential options for consideration in the analysis. Without prior knowledge of heuristic information about sustainability improvements, the decision maker described several improvement options she had been considering for the facility. Of these alternatives, installation of a gazebo was selected as one option to be analyzed, since it was predicted to have the most significant impacts of all options identified by the decision maker and thus would represent a good point of comparison for other options selected from the body of sustainability heuristics.

Based on the areas of dissatisfaction indicated in the Stakeholder Satisfaction scale and a facility walk-through with the decision maker, the investigator recommended five other options from the body of sustainability heuristics to address specific complaints of the homeowner. One area of dissatisfaction was with respect to the surface temperature on the ground floor, reported to be uncomfortably cold in winter. In response to this complaint, the analysis included the option of insulating the crawl space beneath the ground floor (after Building Science Corporation 1996). Another area of dissatisfaction was the perceived large cost of operation and maintenance of the facility. To address this complaint, four additional options appropriate for the case study facility were selected from the body of heuristics:

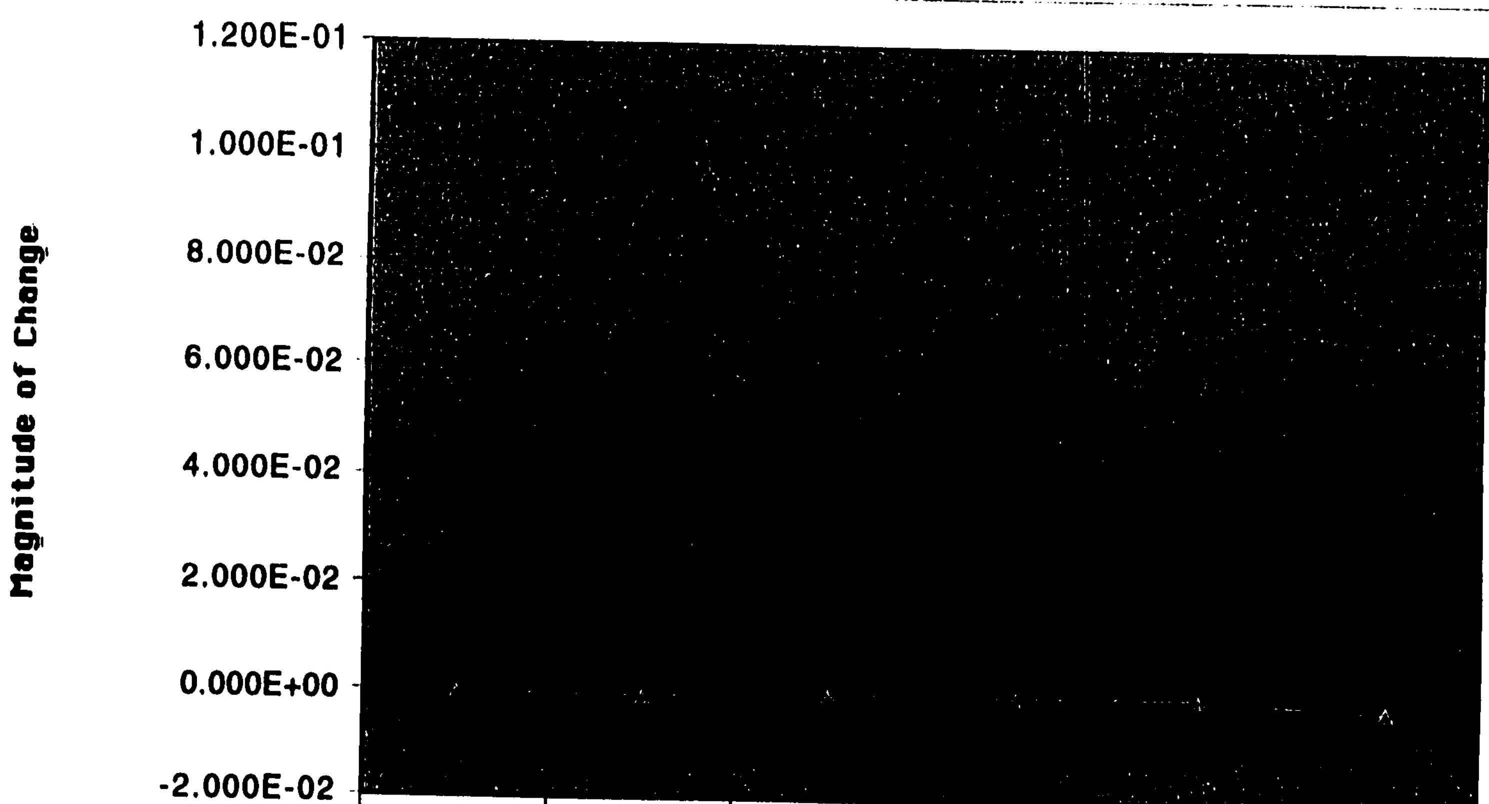
1) Installing low-flow showerheads and toilet dams in all baths (HOK 1994)
2) Procuring a solar blanket pool cover for the swimming pool (Sustainability Project 1996)
3) Installing a hot water heater jacket (Georgia Office of Energy Resources 1994)
4) Retrofitting 75% of incandescent light fixtures with compact fluorescent bulbs (HOK 1994)

Including installing the gazebo and insulating the crawl space, these six options comprised the set of alternatives considered in the analysis.

Forecasting Future Sustainability States: The third step in the process was to forecast how each improvement option would change the sustainability of the facility during the next year period. Supporting calculations are included in Appendix C to show the process used to estimate facility changes, along with documentation of all assumptions made. Adjusted flow values, stakeholder satisfaction scale values, and all other calculations used to forecast sustainability for each of the six alternatives are included in Appendix D. The resulting changes from the baseline state are shown in Figure 6.7, in terms of the three parameters of sustainability. Figure 6.8 shows the changes in terms of the composite sustainability index, based on using vector mechanics to resolve each change vector into its component along the unit sustainability vector (recall Section 6.1.2).

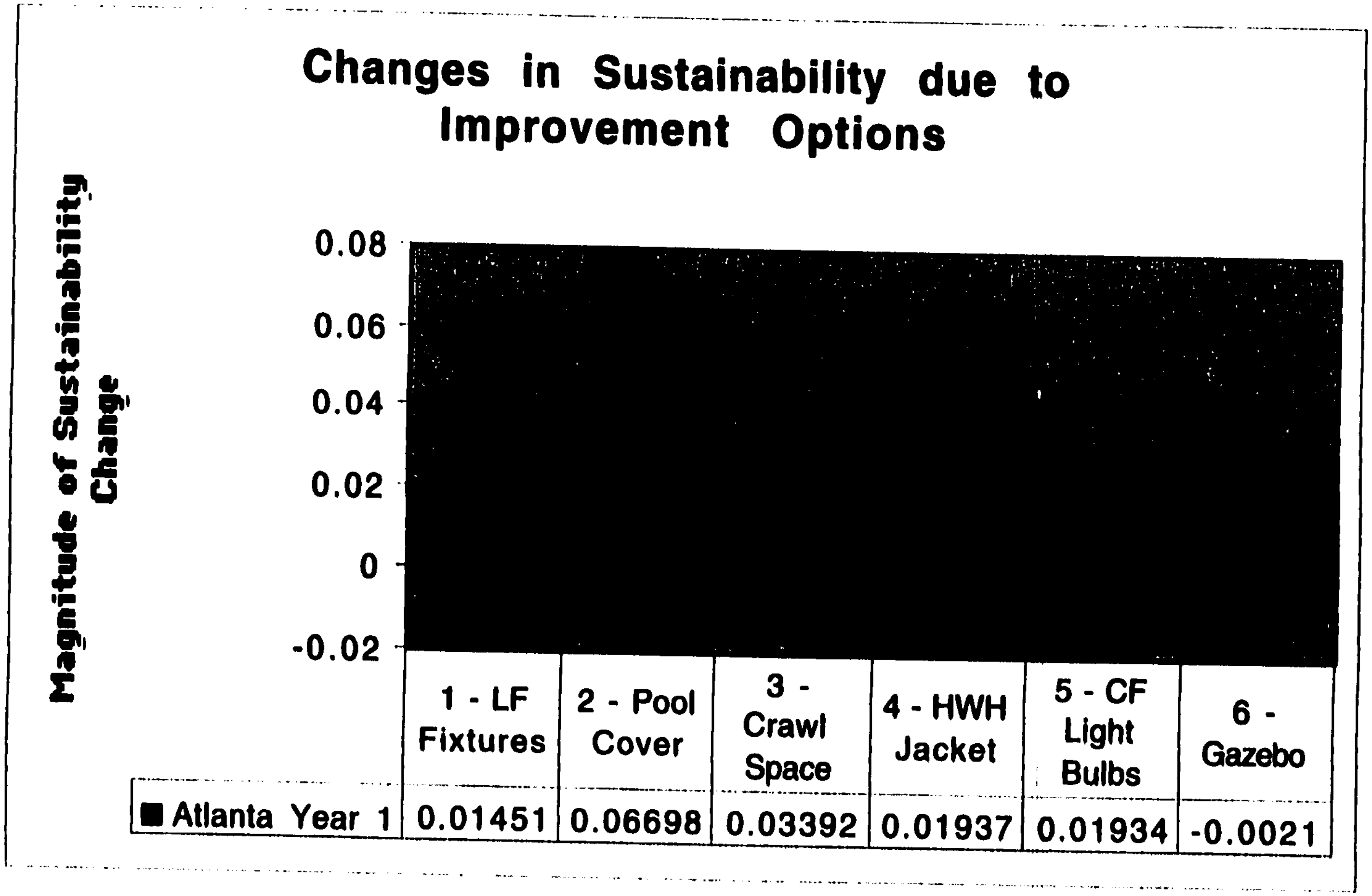
Applying Constraints: Having estimated the changes in sustainability due to implementing the six improvement options, the next step was to determine whether or not each was feasible, and in what combinations the improvement options could be applied to remain within feasibility constraints. Table 6.1 shows estimated costs for each of the options, based on the listed sources or methods.

Based on the decision maker's willingness to pay for the installation of a gazebo, the feasibility limit for total cost of improvements was set at $1,350. Within this feasibility envelope, each of the options was feasible individually, and all but the gazebo were feasible in combination with one another. Thus, the decision maker could either select the gazebo alone, or all other options together, and still remain within the first cost constraint of $1,350. Section 7.2.4 provides further discussion of the implications of selecting this cost threshold as a feasibility constraint.



	1 - LF Fixtures	2 - Pool Cover	3 - Crawl Space	4 - HWH Jacket	5 - CF Light Bulbs	6 - Gazebo
Stakeholder Satisfaction	2.055E-02	9.589E-02	4.795E-02	2.740E-02	2.740E-02	0.000E+00
Resource Base Impacts	-3.932E-05	-4.996E-04	1.125E-06	-3.751E-06	-3.243E-05	-8.281E-04
Ecosystem Impacts	1.098E-05	-6.601E-04	2.578E-05	1.936E-06	-1.173E-05	-2.171E-03

Figure 6.7: Parameter-based Sustainability Changes Due to Improvement Options



	1 - LF Fixtures	2 - Pool Cover	3 - Crawl Space	4 - HWH Jacket	5 - CF Light Bulbs	6 - Gazebo
■ Atlanta Year 1	0.01451	0.06698	0.03392	0.01937	0.01934	-0.0021

Figure 6.8: Composite Sustainability Changes Due to Improvement Options

Table 6.1: Estimated Costs for Six Improvement Options

Option	Description	Estimated Cost	Source
1	Low-Flow Fixtures	$120	Build-up Estimate
2	Pool Cover	$500	Vendor Estimate
3	Crawl Space Insulation	$360	Build-up Estimate
4	Hot Water Heater Jacket	$15	Wilson & Morrill 1994
5	Compact Fluorescent Light Bulbs	$120	Build-up Estimate
6	Gazebo	$1350	Build-up Estimate

Prioritization of Potential Improvement Options: Considering the options individually, Table 6.2 shows a prioritization of options based on composite sustainability change shown in Figure 6.5. Within the feasibility constraint discussed in the preceding section, the first five options can be implemented together to improve the facility's sustainability. The next section explores the properties of the sustainability evaluation process in terms of its sensitivity, the mathematical properties of improvement options, and other aspects of model performance.

6.3. Analysis of Model Performance

To analyze the performance of the model, three separate strategies were used: comparison of the model's ranking of alternatives with expected ranking, sensitivity analysis to explore boundary behavior of the model, and analysis of the mathematical properties of vectors within the three-dimensional sustainability space. This analysis begins with a discussion of the assumptions and stipulations of the facility sustainability model

Table 6.2: Prioritization of Improvement Options

Priority	Option	Sustainability Change
1	Pool Cover	+0.06698
2	Crawl Space Insulation	+0.03392
3	Hot Water Heater Jacket	+0.01937
4	Compact Fluorescent Light Bulbs	+0.01934
5	Low-Flow Fixtures	+0.01451
6	Gazebo	-0.00212

and the process used to apply it (Section 6.3.1). Next, each improvement option considered in the case study is examined individually to identify its impacts on the flows and internal characteristics of the case study facility. These individual impacts are used to identify an expected prioritization of options based on heuristic knowledge from the literature. This expected prioritization is compared to the model's prioritization (Section 6.3.2) as the first test of model performance. A sensitivity analysis of the model provides a second perspective, based on comparing the model's outputs for various scenarios with expected differences in sustainability (Section 6.3.3). A mathematical analysis is provided in Section 6.3.4 to examine the additivity and commutativity of options when considered in combinations within the three-dimensional decision space.

6.3.1 Research Assumptions and Stipulations

Various assumptions and stipulations are inherent in the construction of the model and the process used to apply it. In the context of this research, an assumption is defined as a statement accepted as true that serves as a foundation of the model (after AHCD 1993). A stipulation is defined as something specified as a condition for modeling convenience (ibid.). This section discusses four assumptions and two stipulations of the research that were used in building the model and process for prioritizing improvement options.

Assumption 1 – More Options than Resources: The first assumption of the research is that from the perspective of the built facility decision maker, more options exist than resources available to implement them. This assumption is appropriate given the very large set of possible actions a decision maker could specify for a facility, both sustainable and unsustainable. Even within the set of heuristics to increase built facility sustainability, over 4000 options that could be undertaken were identified in a recent study, and this number appears to be growing (Jones-Crabtree et al. 1998). Given the assumption of more options than resources, using economic feasibility as a constraint is a reasonable method for pruning infeasible alternatives from the set of all possible options. Thus, Assumption 1 supports the rationale for incorporating economics as a constraint rather than a separate parameter as discussed in Section 4.2.

Assumption 2 – Relativity of Options: The second assumption of the research is that the set of options that could be applied to a built facility have different relative impacts on the overall sustainability of the whole facility system. This assumption is reasonable since the impacts of possible actions for a built facility range widely in terms of the parameters comprising sustainability, as discussed further in Section 6.3.2 for the options considered in the demonstration case. The hypothesis of this research is that a model of built facility sustainability can be constructed which has the capability to prioritize facility improvement options. An ordinal or ranking model of the sustainability of options will serve to test this hypothesis, and therefore this research has been limited to developing an ordinal, not interval or cardinal, scale of facility sustainability. A further implication of this assumption is that specifying an absolute zero for facility sustainability is unnecessary given the scope of this research, since the baseline facility state serves as a reference point for performing relative comparisons of improvement options.

Assumption 3 – Scaling and Combining Sustainability Parameters: The third assumption of the research is that each of the three sustainability parameters identified in Chapter 4 can be represented along a scale or continuum of values. This assumption is reasonable because each of the parameters is defined in such a way in Chapter 4 as to have upper and lower values as well as a threshold state to distinguish between them. A corollary to this assumption is that the three parameter scales can be combined into a three-dimensional decision space representing sustainability, the orthogonality of which implies independence and non-conditionality of the parameters (Duke 1999). This corollary assumption is reasonable in conjunction with the second assumption of relativity of options. Given that the objective of the model is to provide relative comparisons of improvement options, any dependence or conditionality that exists among the parameters will not change the ordering of options since it will be equally applied to all options in the application of the model (ibid.). The assumption of orthogonality of scales also increases the utility of the model for visualization of options (ibid.). Since proof of independence and non-condtionality are only required for interval or cardinal scaling of options (ibid.) and constructing these kinds of scales are outside the scope of this research (see Section 1.2.2), mathematical proof of orthogonality has been left for future research.

Assumption 4 – Relative Weighting of Parameters: The model's fourth assumption is that the three parameters of sustainability are equally weighted with respect to one another. This assumption is reasonable given the role of the model as a decision support tool, as well as in the absence of any conclusive evidence that the parameters should not be equally weighted. While proof of equal weighting of parameters has been left to future research, note that the three-dimensional representation of sustainability could easily be modified to accommodate alternative weighting configurations by simply stretching or compressing the scales of the axes to increase or decrease the relative influence of the parameters (Duke 1999, Vanegas 1998, Baker 1997). Further implications of the scaling of parameters are discussed in Section 7.2.2.

Stipulation 1 – Boundaries of the Three-dimensional Sustainability Space: The first stipulation of the research is with respect to the decision of how to bound the three-dimensional sustainability space. For the model developed in this research, the limits of each parameter are stipulated to be [-1, +1], for the purposes of creating a consistent scale among the facility system and its set of affiliate systems. By stipulating this consistent scale, the model could be constructed in such a way that the parameter values for all affiliate systems can be substituted directly into the calculations for extra-system impacts as discussed in Section 5.2.3. The incorporation of the hyperbolic tangent squashing function (Eberhart & Dobbins 1990; Wasserman 1992) provides a valid mechanism for achieving this scale.

Stipulation 2 – Time Frame of Sustainability Calculations: The second stipulation of the research is with respect to choosing a consistent period of time over which to calculate changes to the facility state and the state of affiliate systems. Since all calculations of extra-system impacts are based on resource flows across the system boundary, a consistent time period must be selected to convert flow values (in units of quantity per unit time) into quantities (Merritt et al. 1996). For the purpose of this research, the time increment for all model calculations is one year, to accommodate seasonal fluctuations in flow that may occur on shorter time frames. A one-year time increment is also useful in terms of the annual fiscal and resource allocation cycles that characterize decision making for many types of facilities (Gregory & Pearce 1999). As such, the model's calculation of sustainability reflects changes to the facility's sustainability for a one year discrete increment of time. Section 7.2.7 discusses further implications of this choice of time frame in terms of how initial material impacts are amortized in the calculations of option sustainability, as well as how this property of the model can be expanded to calculate life cycle sustainability comparisons in future research.

To conclude this examination of assumptions and stipulations, recall that the objective of this research was to provide decision makers with a prioritization of self-selected options, according to the relative sustainability of those options in the context of their use. This is *not* to say that the set of options considered is or ought to be all-inclusive, or that the top-priority option is optimal. Since in application of the model, the decision maker selects desirable or appropriate options, it is possible that the *most* sustainable options for the situation in question is not even included in the set of options considered. Thus, the prioritization calculated by the model, while accurate in terms of relative sustainability of options considered, is only as good as the choice of the options themselves.

6.3.2 Actual vs. Expected Prioritization of Improvement Options

To determine an expected prioritization of the set of six improvement options, the changes in each of the salient variables for the parameter functions are discussed in the following subsections. The resulting prioritization is compared to the prioritization developed using the model (Section 6.2) to assess the performance of the model.

Option 1: The first option involved installing low flow showerheads on three showers in the facility, and flow-reducing toilet dams on four toilets (HOK 1994). These retrofits were estimated to reduce the flow of water and wastewater by four and three gallons per capita per day, respectively (Metcalf & Eddy 1991). Additional savings was estimated in terms of natural gas used to heat water for showers (HOK 1994), as detailed in Appendix D. This option was expected to increase stakeholder satisfaction with respect to operating costs, while not impacting any other item on the stakeholder satisfaction scale.

Option 2: The second option involved purchasing a solar cover for the facility's pool, resulting in reduced water consumption via evaporation, less natural gas consumption due to reduced heat loss and therefore lower water heating requirements, and less chlorine use due to reduced evaporation and debris accumulation (Sustainability Project 1996). The pool cover was expected to increase stakeholder satisfaction with respect to both operating expense and ease of operation and maintenance, since the cover would also reduce the amount of debris accumulating in the pool (ibid.). However, the cover is made from non-renewable petroleum resources and was assumed to embody a relatively large amount of energy and raw materials in its manufacture (Dadd 1990).

Option 3: The third option involved insulating the crawl space beneath the facility with fiberglass insulation (Building Science Corporation 1996). This option would result in savings in the energy consumed both to heat and cool the facility, including natural gas and electricity consumption (ibid.). It would result in improved stakeholder satisfaction by addressing both the comfortable surface temperature and operating expense items in the satisfaction scale (ibid.). The insulation material, while embodying significant amounts of energy in its manufacture, is manufactured from recycled or otherwise recovered raw materials and thus avoids significant depletion of other resource bases (Southface Energy Institute 1997).

Option 4: The fourth option involved installing an insulating jacket around the natural gas hot water heater in the facility (Georgia Office of Energy Resources 1994). It resulted in a reduction in natural gas consumption by reducing heat loss of stored heated water in the hot water tank (ibid.). This option improved the operating expense item on the stakeholder satisfaction scale (Wilson & Morrill 1996). It requires the consumption of energy, water, and nonrenewable resources in its manufacture, but has minimal direct negative impacts to natural ecosystems (ibid.).

Option 5: The fifth option involved replacing eight incandescent light bulbs in the facility with state-of-the-art compact fluorescent bulbs (HOK 1994). This option was assumed to save 7.5% of the total lighting energy in the home (Wilson & Morrill 1994). While additional savings would likely result due to a reduction in cooling load, this effect was assumed to be negligible. This option affected the operational expense item on the stakeholder satisfaction scale. The bulbs have a relatively high amount of embodied energy and consume nonrenewable resources (ibid.).

Option 6: The final option was to install a gazebo in the rear of the facility, in an area currently consisting of lawn. This option required the influx of raw materials from source systems, including #2 Treated Yellow Pine, steel fasteners, concrete, asphalt shingles, plywood, and wood sealer/stain (based on a structural design by the investigator). It was estimated to increase the volume of solid waste out of the facility system, as well as to convert a portion of the intra-system land use from lawn to hardscape with container plants as described in Appendix D. This item resulted in no changes to the stakeholder satisfaction scale, since it did not address any specific items on the scale.

Expected Prioritization vs. Actual Prioritization: The impacts of each of the six options are shown qualitatively in Table 6.3. Based on the estimated changes described in the previous sections, the expected ranking of items is listed in column 12 of the table, based on a simple summation of impacts (i.e., each "+" gets one point, each "-" gets –1 point, and each "0" gets 0 points). Column 13 of the table indicates the prioritization resulting from application of the model (Section 6.2), and Column 14 indicates matches between the expected and actual prioritizations.

The expected prioritization in Table 6.3 was developed by inspection of the total numbers of increases and decreases in the significant factors listed for each option, without regard to the magnitude of increases or decreases. The prioritization developed from applying the model (Section 6.2) corresponds reasonably well to the expected prioritization based on heuristic knowledge, particularly for options representing the most extreme increases or decreases in sustainability as shown in Figure 6.8 (previous section). Discrepancies between the expected and actual prioritization are likely due to differences in the magnitude of flow changes for each option, which is not reflected in the plus-zero-minus impact ratings shown in Table 6.3.

6.3.3 Sensitivity Analysis

The second strategy for evaluating the performance of the model was to undertake a sensitivity analysis of the performance of the model demonstrated in Section 6.2. The model's sensitivity was tested by examining the set of six options over two ranges of conditions: different conditions for influx of raw materials to implement the options, and different facility locations.

Based on separating the components comprising the composite index of sustainability as shown in Figure 6.9, the relative magnitude of stakeholder satisfaction clearly dominates the composite value of sustainability. Second to this factor, intra-system ecosystem impact dominates changes among the remaining factors. As described in Appendix D, Intra-System Resource Base Impact was negligible for any of the improvement options, and thus had a value of zero for all improvement options. Compared to the two dominating factors of Stakeholder Satisfaction and Intra-System Ecosystem Impacts, the remaining variables of Extra-System Resource Base Impact and Extra-System Ecosystem Impact are relatively small. Nonetheless, these variables provide the capacity to distinguish among the improvement options as described in Section 6.2.

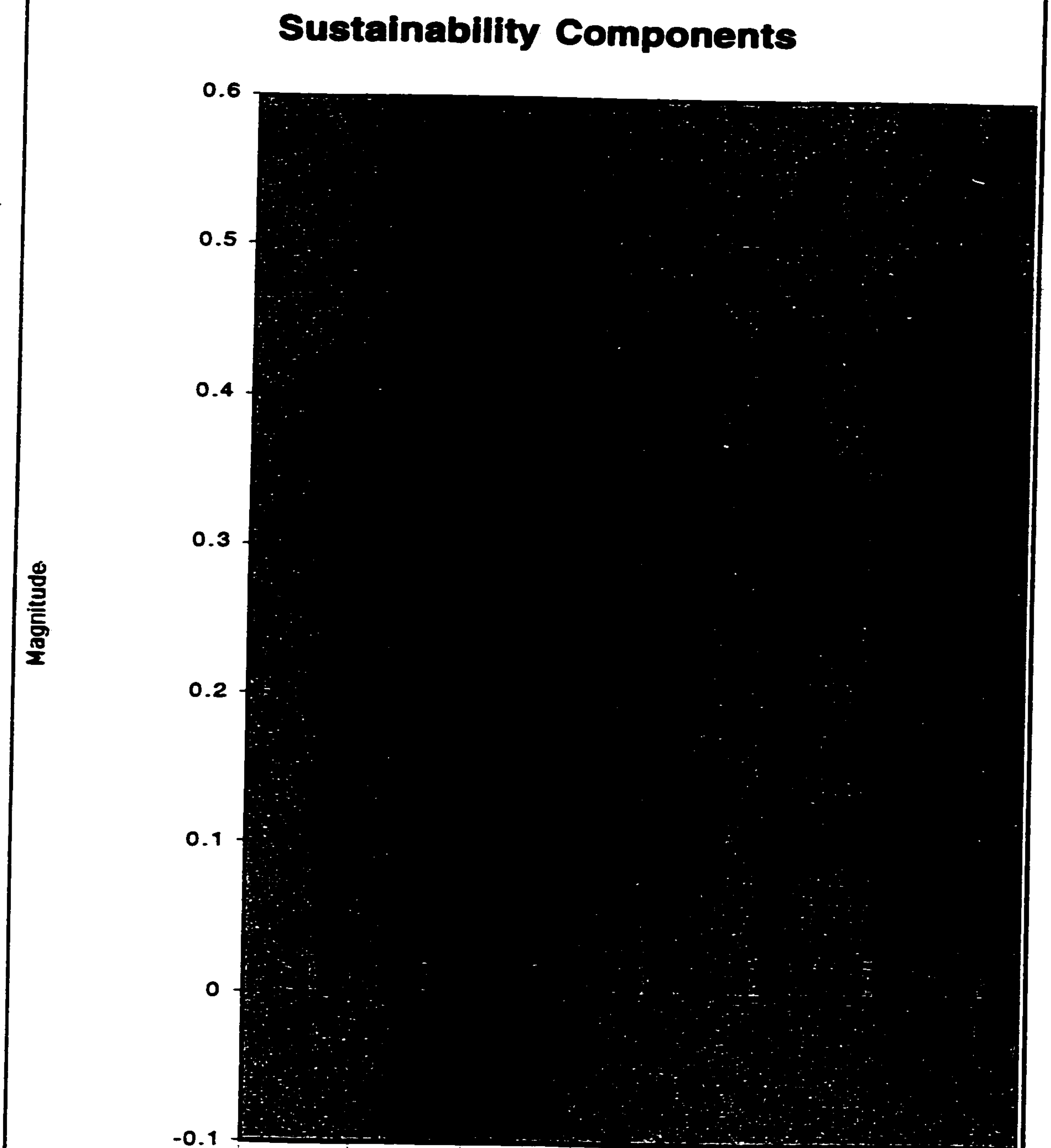
Option	Water Consumption (Reduction is good)	Power Consumption (Reduction is Good)	Natural Gas Consumption (Reduction is Good)	Solid Waste Generation (Reduction is Good)	Building Consumable Consumption (Reduction is Good)	Building Durables Consumption (Reduction is Good)	Stakeholder Satisfaction (Increase is Good)	Internal Resource Base Impacts (Positive Change is Good)	Internal Ecosystem Impacts (Positive Change is Good)	TOTAL	Expected Prioritization	Model Prioritization	MATCHES
1 - LF Fixtures	+	0	+	0	0	-	+	0	0	2	2/3	5	
2 - Pool Cover	+	0	+	0	+	-	+	0	0	4	1	1	
3 - Crawl Space	0	+	+	0	0	-	+	0	0	2	2/3	2	
4 - HWH Jacket	0	0	+	0	0	-	+	0	0	1	4/5	3	
5 - CF Light Bulbs	0	+	0	0	0	-	+	0	0	1	4/5	4	
6 - Gazebo	0	0	0	-	-	-	0	0	-	- 4	6	6	

Legend:		
	+	Change for better
	-	Change for worse
	0	No/negligible change

Table 6.3: Impacts and Comparative Prioritization of Improvement Options

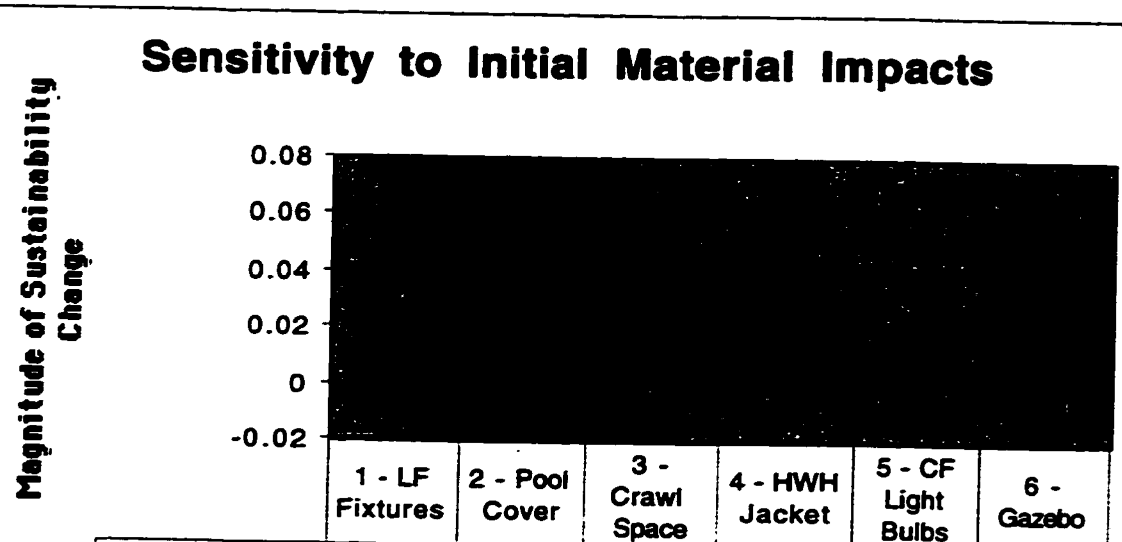
Sensitivity to Initial Material Impacts: The first sensitivity comparison considers possible differences between the first time period, when importing building durables into the system affects sustainability, and subsequent time periods that do not count this influx. This comparison is important to determine how significant are the raw materials used to implement the improvement options versus the potential savings in subsequent time periods. Figure 6.10 shows the composite sustainability ratings for the six options in the case study location (Atlanta) during the first and second years of the projected scenarios. The first year includes the impacts of importing new materials to implement the changes (initial material impacts), while the second year includes only changes to typical cross-boundary flows such as water, electricity, and natural gas. Since more matter is consumed in the first year, the composite sustainability should be less in the first year than in the second year. Figure 6.10 illustrates that the findings of the sensitivity analysis support this expectation.

Sensitivity to Location: The second sensitivity comparison considers possible differences between locations of the facility. This comparison is important to determine how significant are the location capacity factors included to incorporate context into the model. Figure 6.11 shows the composite sustainability ratings for the six options in three locations: the Atlanta case (assumed to be relatively neutral with respect to location capacities); an impoverished location (with all resource base and ecosystem location capacities = -1); and a pristine location (with all resource base and ecosystem location capacities = +1). Based on the assumptions of the model, consumptive options should have a lower sustainability in impoverished locations than in pristine locations. While no difference is evident for the first five improvement options, the most consumptive option (6 – Gazebo) in Figure 6.11 supports this expectation.



	0 - Baseline	1 - LF Fixtures	2 - Pool Cover	3 - Crawl Space	4 - HWH Jacket	5 - CF Light Bulbs	6 - Gazebo
Extra-System RBI	-0.000133424	-0.000172742	-0.000632975	-0.000132299	-0.000137175	-0.000165853	-0.000961481
Intra- System RBI	0	0	0	0	0	0	0
Extra-System EI	-6.59E-04	-6.48E-04	-1.32E-03	-6.33E-04	-6.57E-04	-6.71E-04	-1.10E-03
Intra- System EI	0.023207727	0.023207727	0.023207727	0.023207727	0.023207727	0.023207727	0.021474394
Stakeholder Satisfaction	0.410958904	0.431506849	0.506849315	0.45890411	0.438356164	0.438356164	0.410958904

Figure 6.9: Component Magnitude Comparison for Improvement Options



	1 - LF Fixtures	2 - Pool Cover	3 - Crawl Space	4 - HWH Jacket	5 - CF Light Bulbs	6 - Gazebo
■ Atlanta Year 1	0.01451	0.06698	0.03392	0.01937	0.01934	-0.0021
■ Atlanta Year 2	0.01454	0.06781	0.03393	0.01938	0.01939	-0.0012

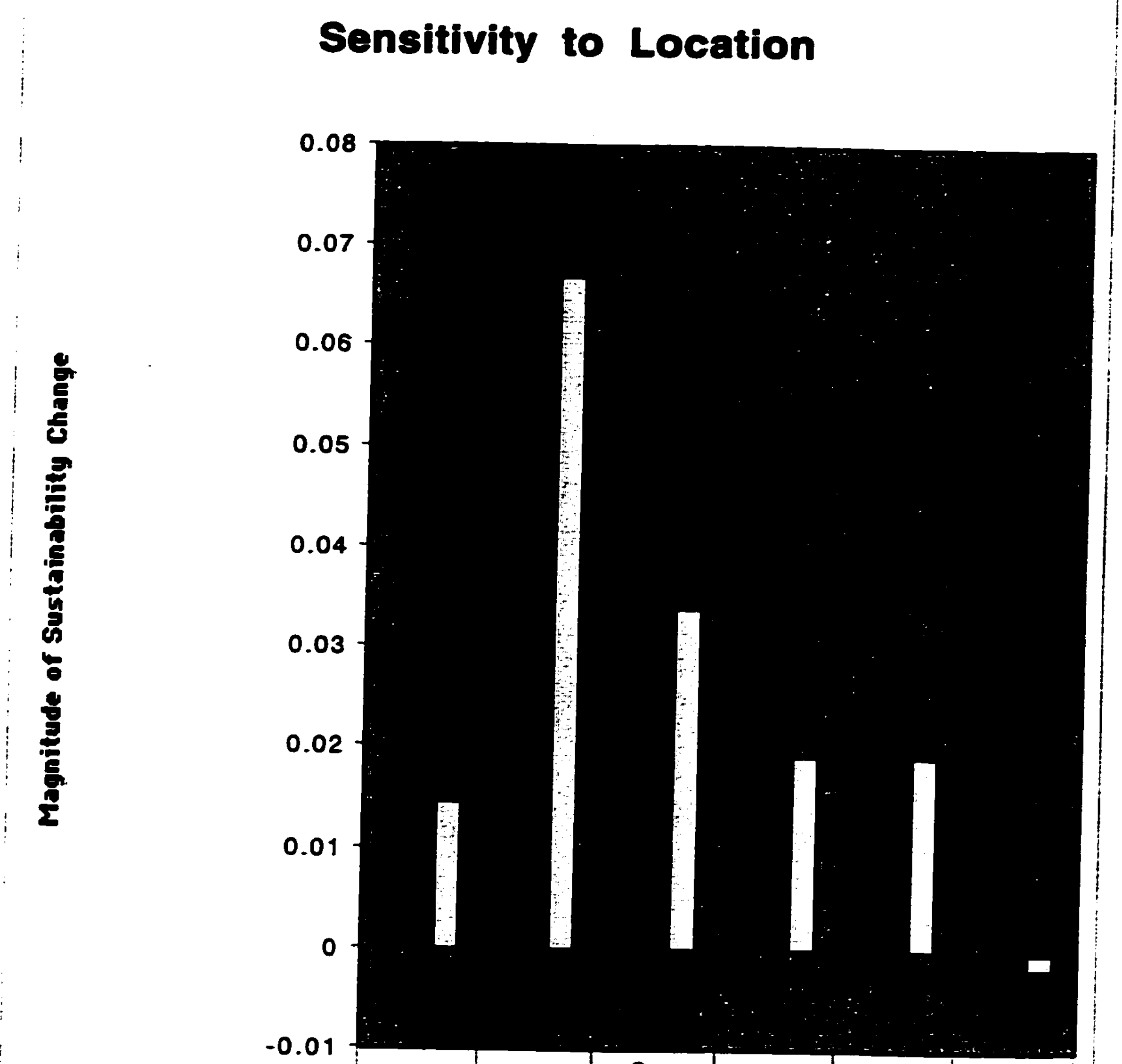
Figure 6.10: Composite Sustainability Ratings for Initial Material Impacts

In all of these scenarios, stakeholder satisfaction and Intra-System impacts are assumed to remain the same. Since these factors dominate composite sustainability as shown in Figure 6.9, the relatively small differences among scenarios in the sensitivity analysis are not surprising. Figure 6.12 shows component comparison of the changes to Extra-System Resource Base Impacts for the locational significance assessment, providing additional support for the conclusion that the model is sensitive to location. The gazebo option does not vary by location in year 2, since its influx of materials (wood stain/sealer) is assumed to come from the same source no matter where the facility is located.

6.3.4 Arithmetic Properties of Vectors Within Sustainability Space

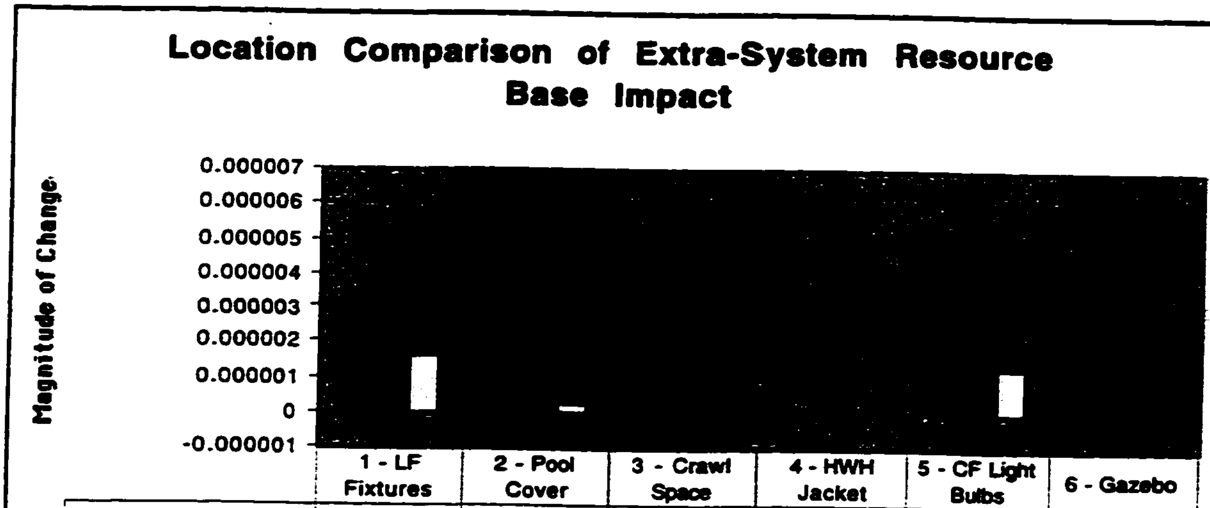
In order to assess the validity of *combining* improvement options when ranking using the composite sustainability index (Equation 22), two properties of the vector representation must be proved: additivity and commutativity of options in combination. Note that these properties are not required when comparing and prioritizing improvement options on an individual basis, and are not problematic when comparing sequences of discrete items within the three-dimensional space. The following subsections provide proofs and discussions of these two properties.

Additivity of Options: In assessing the mathematical properties of the model for ranking combinations of options, the first property that must be verified is additivity – in other words, does the sustainability of the facility after implementing a set of changes equal the sum of the changes in sustainability plus the baseline state of sustainability? To verify this property, the options examined in the case study are shown in Table 6.4 in terms of their individual changes in sustainability parameters from the baseline state. If options are additive, then the outcome of implementing all options together should equal the sum of the changes resulting from implementing each option separately.



	1 - LF Fixtures	2 - Pool Cover	3 - Crawl Space	4 - HWH Jacket	5 - CF Light Bulbs	6 - Gazebo
■ Atlanta Year 1	0.01451	0.06698	0.03392	0.01937	0.01934	-0.0021
■ Impoverished Year 1	0.0145	0.06698	0.03392	0.01936	0.01934	-0.0025
□ Pristine Year 1	0.01452	0.067	0.03393	0.01939	0.01935	-0.0018

Figure 6.11: Composite Sustainability Ratings for Different Locations



	1 - LF Fixtures	2 - Pool Cover	3 - Crawl Space	4 - HWH Jacket	5 - CF Light Bulbs	6 - Gazebo
■ Atlanta - Year 2	2.6815E-06	4.4841E-07	4.4953E-06	9.4826E-08	3.5259E-06	-3.371E-08
■ Impoverished Year 2	4.7232E-06	6.0507E-07	6.5687E-06	9.4826E-08	4.9556E-06	-3.371E-08
□ Pristine Year 2	1.6607E-06	3.0716E-07	1.3307E-07	9.4826E-08	1.3333E-06	-3.371E-08

Figure 6.12: Component Sustainability Ratings for Different Locations

Table 6.4: Parameter-based Sustainability Changes Due to Improvement Options

Case	Total SS	Total RBI	Total EI	SS Change	RBI Change	EI Change
0 - Baseline	0.4109589	-0.0002334	2.25E-02			
1 - LF Fixtures	0.4315068	-0.0002727	2.26E-02	2.055E-02	-3.932E-05	1.098E-05
2 - Pool Cover	0.5068493	-0.000733	2.19E-02	9.589E-02	-4.996E-04	-6.601E-04
3 - Crawl Space	0.4589041	-0.0002323	2.26E-02	4.795E-02	1.125E-06	2.578E-05
4 - HWH Jacket	0.4383562	-0.0002372	2.26E-02	2.740E-02	-3.751E-06	1.936E-06
5 - CF Light Bulbs	0.4383562	-0.0002659	2.25E-02	2.740E-02	-3.243E-05	-1.173E-05
6 - Gazebo	0.4109589	-0.0010615	2.04E-02	0.000E+00	-8.281E-04	-2.171E-03

Net RBI after all changes = Baseline + Sum (RBI Change)I = -1.64E-03
Net EI after all changes = Baseline + Sum (EI Change)I = 1.97E-02
Net SS after all changes = Baseline + Sum (SS Change) = 6.301E-01

Table 6.5 shows parameter changes resulting from a model run with all of the options incorporated into the initial model variables. The results confirm that the model is additive in terms of Resource Base Impact and Ecosystem Impact. In terms of Stakeholder Satisfaction, Table 6.4 shows what would be the cumulative value for that parameter if all improvement options were implemented. However, the cumulative value is obscured due to the assignment of [-1, 0, +1] as the only possible values for the Stakeholder Satisfaction scale items. Due to the way in which Stakeholder Satisfaction was incremented when forecasting future sustainability states, assuming that the values for this scale are additive could result in a net value of greater than one, violating the definition of the scale as constructed in Chapter 5. While the resolution of the scale is adequate for ranked comparison of improvement options, it currently lacks sufficient resolution to be meaningful in an additive sense. However, Stakeholder Satisfaction can be assessed in a meaningful way for combinations of options if the Stakeholder Satisfaction scale is completed *separately* for each combination of options rather than calculating a value for option combinations by summing the Stakeholder Satisfaction for each option individually.

Commutativity of Options: Given that options are additive, at least in terms of their impacts on Resource Bases and Ecosystems, the second mathematical property that should be maintained is the commutativity of options. In other words, sets of options implemented in different orders should result in the same final sustainability. Based on the assumptions of the model as described in Section 6.3.1, this property follows from the way in which time is considered in the model. Since options are additive, the order in which they are implemented within a single evaluation period is irrelevant, because the objective functions of the model are only evaluated for cumulative variable values at the end of each evaluation period. If options were implemented in different orders over several evaluation periods, the interim objective function outputs would be different due to sensitivity of the model to initial material impacts as described the previous section.

Table 6.5: Ecosystem and Resource Base Impacts for All Options Combined

Combined Options

Fresh water consumed	122295	gal	-0.20	-1.40E-05	-0.20	-1.40E-05
Waste water disposed	122295	gal	-0.20	-1.40E-05	-0.05	-3.49E-06
Electricity consumed	23715	kWh	-0.50	-4.11E-04	-0.10	-8.22E-05
Natural gas consumed	2741.5	Therms	-0.50	-8.25E-05	-0.05	-8.25E-06
HVAC filters	3	each	-0.10	-3.00E-05	-0.20	-6.00E-05
Incandescent light bulbs	0	each	-0.30	0.00E+00	-0.30	0.00E+00
Pesticide	1	gal	-0.70	-5.83E-07	-0.30	-2.50E-07
Chlorine	2.5	gal	-0.70	-5.87E-07	-0.45	-3.78E-07
Flowers - potted, annual	5	flats	0.05	5.00E-05	0.05	5.00E-05
Gasoline (for lawn mower)	15	gal	-0.60	-4.50E-07	-0.35	-2.63E-07
Low-flow showerheads	3	each	0.00	0.00E+00	-0.30	-1.80E-05
Toilet dams	4	each	0.00	0.00E+00	-0.30	-2.40E-05
Pool cover	1	each	-0.40	-6.67E-04	-0.30	-5.00E-04
Fiberglass Insulation	12	rolls	-0.30	-4.04E-06	-0.25	-3.37E-06
Hot Water Heater Jacket	1	each	-0.30	-4.62E-06	-0.25	-3.85E-06
Compact Fluorescent bulbs	8	each	-0.30	-2.70E-05	-0.40	-3.60E-05
#2 Treated Yellow Pine	500	bf	-0.15	-1.09E-07	-0.20	-1.45E-07
Fasteners	10	lbs	-0.40	-6.67E-08	-0.35	-5.83E-08
Sack-crete	16	bags	-0.30	-4.80E-05	-0.35	-5.60E-05
Shingles - 15 yr. Asphalt	0.3	square	-0.65	-1.95E-06	-0.40	-1.20E-06
Plywood	256	sq ft	-0.15	-3.84E-04	-0.30	-7.68E-04
Water sealer/stain	2	gal	-0.80	-1.80E-07	-0.30	-6.74E-08
Mixed MSW disposed	60	cy	-0.50	-6.47E-05	-0.15	-1.94E-05
Bagged compostable waste	20	cy	-0.15	-5.17E-05	-0.25	-8.62E-05
			Total Share of Off-Site Ecosystem Impacts =	[illegible]	Off-Site RBI =	[illegible]
			Total Intra-System Impacts =	[illegible]	On-Site RBI =	[illegible]
			Sum =	[illegible]	Sum =	[illegible]
			Desired Sum =	1.97E-02		-1.64E-03

Values would also differ based on the number of time periods for which savings was achieved due to each particular option. For example, if a high-savings option was implemented in the first time period and a low-savings option in the second, then the net impacts would be for two time periods of high savings plus one period of low savings. Alternatively, implementing the low-savings option in the first period plus the high-savings option in the second period would by definition result in less savings overall, and thus a lower sustainability.

From this example, it can be concluded that while commutativity is preserved within small evaluation periods according to the assumptions of the model, it is not preserved when evaluating cumulatively over multiple or long time periods. The conclusion of commutativity within time periods also ignores the potential for minimized disruption and/or other impacts due to the effects of clustering improvements. These clustering effects, including savings by hiring contractors to do multiple jobs at once and other economies of scale, have been assumed to be negligible for this analysis and are reserved for further research.

6.4. Validation of the Research Product

The final aspect of the research was to validate and evaluate the research product. This section amalgamates the evidence developed in this and previous chapters to establish validity of the contributions, based on the validity evaluation questions developed in Section 3.2. Each question tests a different aspect of the research hypothesis, i.e., that it is possible to develop a model of built facility sustainability that allows decision makers to prioritize facility improvement options according to their relative influence on facility sustainability.

6.4.1 Conclusion Validity

As discussed in Chapter 3, the question to establish conclusion validity is, "Was it possible to construct a quantitative model of built facility sustainability that does what it was designed to do, i.e., prioritize improvement options in terms of their relative sustainability?" In this research, conclusion validity was established by constructing a process that uses model outputs to prioritize improvement options (Section 6.1), demonstrating the process using a case study (Section 6.2), and expanding on the case study using performance, sensitivity, and mathematical analyses (Section 6.3). The case study used measured and forecasted sets of inputs to the model for a baseline facility state and six individual improvement options that proved to be feasible within the decision making constraints established in the case study. In each of these three processes, the model did in fact generate distinguishable values for sustainability that could be used to prioritize improvement options using the process developed in Section 6.1. While the magnitude of changes were subject to the dominance of two components of composite sustainability (see Section 6.3.3), the model was able to quantitatively distinguish among the baseline facility state and various improvement alternatives described by differing sets of input variables.

6.4.2 Internal Validity

Of the classic threats to internal validity identified by Campbell & Stanley (1966), a potential threat to internal validity in this research is subjectivity in identifying the parameters and variables of sustainability. As discussed in Section 3.2.2, the question to establish internal validity is, "Do the variables used in the model really reflect the properties of a built facility that determine its sustainability?"

To support the conclusion of internal validity, multiple approaches were used to corroborate the choice of parameters, including analysis of the built environment sustainability literature, a search of the theoretical sustainability literature to identify parameters based on fundamental thermodynamic, biological, and anthropocentric constraints, and content analysis of published definitions of sustainability. Based on corroboration among the results of these strategies (discussed further in Chapter 4), the selection of variables for the model of facility sustainability is supported in terms of internal validity. By using separate strategies to arrive at the same outcome, potential threats to internal validity have been alleviated, and therefore internal validity is demonstrated according to established methods for qualitative research (Yin 1989; Guba & Lincoln 1981).

6.4.3 Construct Validity

The question of construct validity from Chapter 3 was, "Does the prioritization of options generated by the model make sense in terms of what is known about built environment sustainability?" To establish construct validity, three conditions were discussed in Chapter 3:

1) The construct must be set with in a semantic net that shows how the construct relates to other constructs.
2) Operationalizations of the construct should match what one would expect based on knowledge of theory.
3) Data from the research should support the theoretical view of the relations among constructs.

The hierarchically represented outcomes of the content analysis in Chapter 4 and Appendix B provide a solution to the first condition. The content analysis also served as a way to establish translation validity between the concept of sustainability as understood by experts published in the literature, and the concept as captured in the sustainability construct used in this research.

The second condition was met by establishing a solid chain of evidence to support the derivation of the construct from associated theory, as described in Section 4.1 and Appendix A. This strategy is particularly appropriate for naturalistic research (Yin 1989; Guba & Lincoln 1981). Findings from the case study and subsequent performance analyses reflected expected relationships illustrated in the literature review and the content analysis (See Section 6.3).

The third condition was addressed in Chapter 6 by selecting improvement options to test hypotheses based on current theoretical perspectives in the literature. Predictive validity was established by the capability of the model to predict sustainability changes over different time periods as described in the sensitivity analysis (Section 6.3.3). The behavior of the model in this case shows that it can predict the relative changes to sustainability resulting from different combinations of input variables as expected. In terms of concurrent validity, the model was able to distinguish among the different improvement options not only according to composite sustainability comparison, but also using comparison of the various sub-components of composite sustainability as discussed in Section 6.3. This ability to achieve similar results between composite and sub-component sustainability also provides evidence to support convergent validity of the model.

Discriminant validity was illustrated in Chapter 6 by showing that the gazebo option, selected on the request of the facility decision maker and not on the basis of improving sustainability, resulted in a negative correlation with the sustainability of the other options (see Table 6.5). This option was chosen for consideration based on an operationalization of the decision maker's preferences not corresponding to sustainability, as evidenced by the fact that it has no change in Stakeholder Satisfaction as measured by the satisfaction scale. Thus, this option corroborates the conclusion of discriminant validity, and provides a final piece of evidence to support construct validity.

6.4.4 External Validity

The final type of validity to be established is external validity, defined in Chapter 3 as the degree to which the effects identified in a study can be generalized to other persons, places, things, or times. In terms of the hypothesis tested in this research, the question to establish external validity is, "Will the model work in other situations? If so, in what other situations will it work?" For case study work as undertaken in this research, one strategy to establish external validity is by placing the case or example demographically within the population of which it is a part, and showing where it falls along critical dimensions defining the population (Yin 1989). This strategy enables others to identify any limiting features of the specific application area that may inhibit effective application of the model in other situations. Using this strategy, external validity was established with respect to the domain of sustainability on a global scale in Section 4.3.1 (see Figure 4.9), and on a technological systems scale in Section 4.3.2 (see Figure 4.15).In terms of theoretical sustainability, the parameters of technological sustainability were linked to the construct for global sustainability in Sections 4.1.3 and 4.3.2, showing how they relate to the parameters that apply on a global scale. Likewise, in Chapter 5, the parameters for built environment sustainability were linked directly to the parameters for technological system sustainability, again providing an audit trail for establishing external validity with respect to system type.

With respect to the demonstration case study in Chapter 6, external validity was established by placing the demonstration case demographically within the population of which it is a part, and showing where it falls along critical dimensions defining the population (see Sections 1.2.2 and 6.2.1). The sensitivity analysis also provided evidence to corroborate external validity in its examination of model performance in different locations and under different conditions. Implications and limits of applicability of the research findings and model are discussed further in Chapter 7, along with recommendations for future research to extend the model's domain of applicability.

6.5. Summary: Process for Applying the Facility Sustainability Model

This chapter demonstrated how to use the quantitative model of facility sustainability developed in Chapter 5 to meet the objective of the research: to provide a method for facility decision makers to prioritize potential improvement options in terms of their impact on the sustainability of a facility system. The chapter began by defining a process for using the model to establish option priorities, in terms of Simon's classic model of decision making (Simon 1986). The process was then expanded into a detailed, step-by-step description to guide implementation of the model, including three possible methods for actual prioritization: the composite sustainability index, direct examination of sustainability changes within the three-dimensional sustainability space, and component-by-component examination of options. A case study was presented to illustrate how the process works in the context of a real facility, followed by an analysis of the performance of the model and process in terms of expected vs. actual prioritization of options in the case study, a sensitivity analysis of the model in terms of time and location changes, and an examination of the mathematical properties of vectors within the sustainability decision space. The chapter concluded with an evaluation of the research findings and contributions in terms of the validity questions posed in Chapter 3. The final task of the research is to characterize the contributions, impacts, and benefits of the work and discuss conclusions, lessons learned, and areas for future research. Chapter 7 explores these aspects of the research.

CHAPTER VII

CONTRIBUTIONS, CONCLUSIONS, AND FUTURE RESEARCH

The previous six chapters of this dissertation articulated the problem of prioritizing improvement options to increase built facility sustainability, and described the research used to generate a solution to this problem. The outcome of the research is a quantitative model of built facility sustainability and a method for applying it in the context of a specific facility to prioritize improvement options. The purpose of this final chapter of the dissertation is to summarize this research outcome, describe its contributions to the knowledge base in terms of the scope of work described in Chapter 1 and the point of departure established in Chapter 2, and examine the potential impacts and benefits of the work. The dissertation concludes with a set of lessons learned from the research, an examination of areas for future research, and an overview of the research findings and outcomes.

7.1. Contributions, Benefits, and Impacts of the Research

The primary means of evaluating the success of the research is to examine how its contributions have expanded the body of knowledge. To evaluate the research, the following sections summarize the point of departure for the work, characterize the contributions resulting from the work and demonstrate how they have advanced the state of knowledge, and describe the benefits and impacts of the research contributions.

7.1.1 Point of Departure for the Research

The point of departure for the research was a widely varying set of existing heuristics, guidelines, models and frameworks, and assessment and evaluation tools based on divergent implicit theories of sustainability and how it applies to built facilities. At this point of departure, there was a strong need to find a method to evaluate and prioritize improvement options for specific facilities. As discussed in Chapters 1 and 2, many opportunities exist to improve facility sustainability, but prior to this research, no way existed to prioritize those opportunities according to their effects on facility sustainability. The hypothesis of this research was that it is possible to construct a model of built facility sustainability that can be used to prioritize improvement options according to their relative effects on the sustainability of the facility in its specific context.

As described in Chapter 1, the scope of this research is bounded by the intersection of three different domains of knowledge: built environment knowledge, sustainability knowledge, and decision making knowledge. Chapter 2 extensively explored the literature representing the intersection of sustainability and the built environment to establish a point of departure for this research. Based on the findings of Chapter 2 (see Section 2.6), no existing work was found that is comparable to the contribution of this research, namely a model of built facility sustainability that can be used to prioritize improvement options in a context-sensitive fashion for a given facility. However, the contribution of this research draws upon and synthesizes the work of others within each of the individual domains and their intersections with each other, as shown in Figure 7.1. This work goes beyond existing knowledge by integrating and expanding upon elements of each of the domains into a holistic method for prioritizing facility improvement options in terms of their relative sustainability.

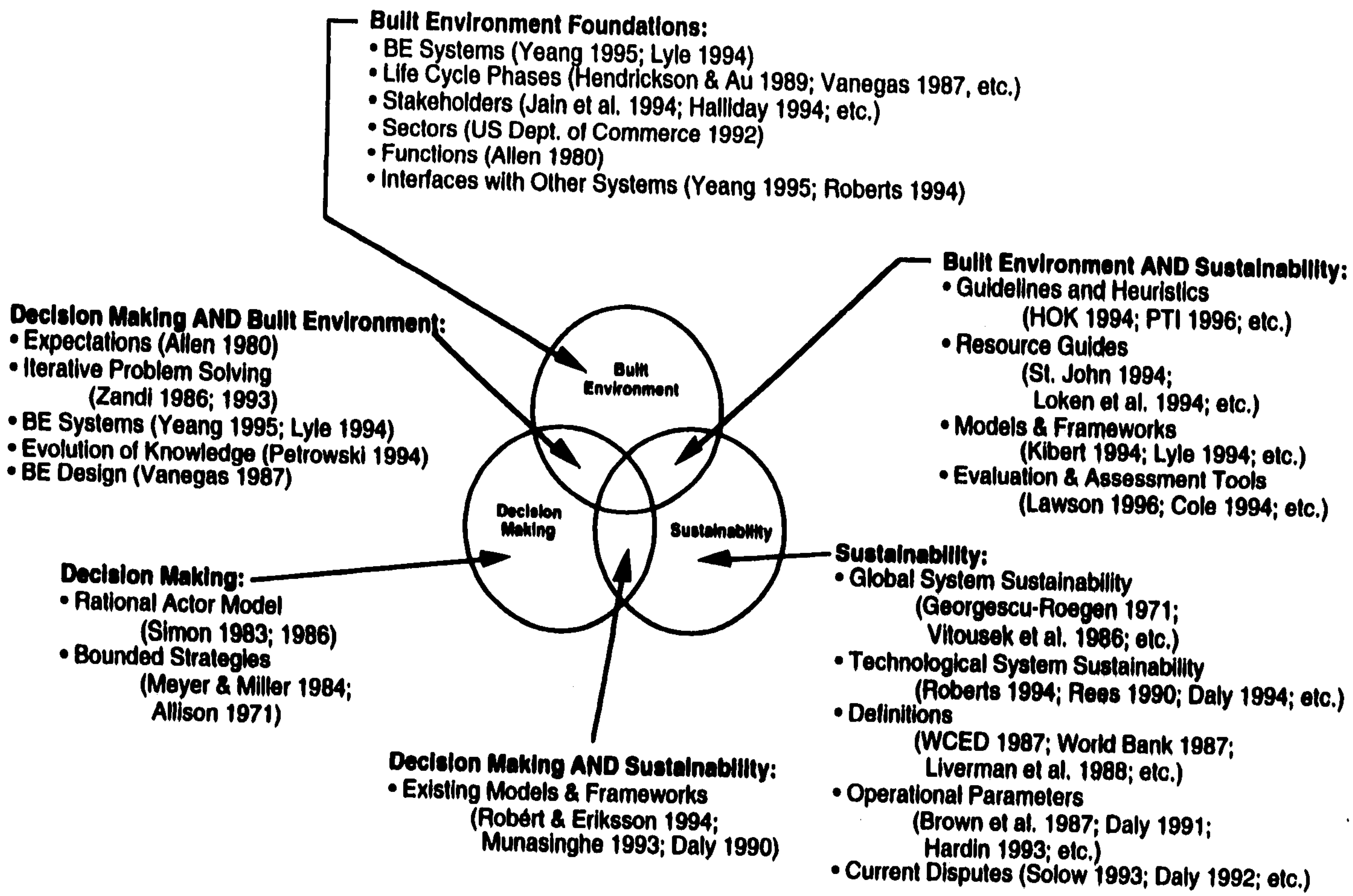


Figure 7.1: Foundations for the Research Contribution

7.1.2 Contribution of the Research

The total contribution of the research, developed to test the research hypothesis, is a completely new and unique solution to the problem of prioritizing improvement options in terms of how they impact the sustainability of a built facility. This total contribution is an integration of the following four individual contributions:

- A construct of sustainability for systems, expressed in terms of three key parameters: Stakeholder Satisfaction, Resource Base Impact, and Ecosystem Impact
- A set of measurable variables that operationalize these three sustainability parameters in terms of built facility systems
- A quantitative model of built facility sustainability that mathematically combines the measurable variables into equations for the three parameters of sustainability
- A process for applying the quantitative model using the construct of sustainability to prioritize facility improvement options

The component contributions build upon one another to yield the integrated method for prioritizing improvement options that is the total contribution of this research. Table 7.1 summarizes the component contributions, the role they play in supporting the total research contribution used to test the research hypothesis, and their intellectual merit and impacts. Table 7.1 also lists the location in the dissertation where each contribution is developed. In the context of this research, intellectual merit means the degree to which the state of knowledge has been advanced beyond the point of departure in a meaningful and valid way. Impact means the way(s) the contribution can change how things are done in the

Table 7.1: Component Contributions of the Research

	CONTRIBUTION	ROLE	INTELLECTUAL MERIT	IMPACT	SECTION
A	Construct of Sustainability for Systems	Establishes the three parameters of sustainability; shows how they can be combined into a three-dimensional decision space	Collapses the perspectives identified in a review of the sustainability literature and 83 different definitions of the concept into three basic parameters that can be used to define the sustainability of systems	Provides an easy-to-understand representation of the complex concept of sustainability that unifies many disparate perspectives and facilitates comprehension of the concept	Chapter 4 Appendix A Appendix B
B	Set of Measurable Variables to Define the Sustainability Parameters for Built Facility Systems	Defines the three parameters in terms of measurable variables relevant to built facilities	Derives a set of measurable facility variables that together define the sustainability of built facilities and resolve disparate perspectives in the built facility sustainability literature	Stakeholders now know what kinds of data to collect and how to collect it in order to evaluate the sustainability of built facilities	Chapter 5 - Sections 5.1 and 5.3
C	Quantitative Model of Built Facility Sustainability	Mathematically combines built facility variables into operational equations for each sustainability parameter	Completely new; this model fills a gap in which there are no competing models, and consists of quantitative equations for evaluating the three sustainability parameters in terms of measurable built facility variables	Stakeholders now have a quantitative means to combine their collected data into a measure or metric of sustainability for a given facility state	Chapter 5 - Section 5.2 Section 5.4
D	Process for Using the Model to Prioritize Improvement Options	Specifies a method for representing the three parameters in three-dimensional space, and using the difference between benchmark and post-option states of the facility to prioritize the set of improvement options	Draws upon classical decision theory and problem solving methods to create a new process for prioritizing options in terms of sustainability parameter values in a three-dimensional decision space	Stakeholders now have a demonstrated process to use the measure of sustainability for different facility states to prioritize potential improvement options in terms of their relative sustainability impacts	Chapter 6 Appendix C Appendix D

applicable domain of interest. Together, the role, merit, and impacts of each of the individual contributions support the overall merit and impact of the total contribution of this research.

Figure 7.2 shows how each of the four individual contributions fits within the scope of the research defined in Chapter 1. Advances beyond the state of knowledge were necessary in the domain of sustainability as well as in the intersection of sustainability and the built environment in order to achieve the goal of the research: developing a way for facility decision makers to prioritize improvement options in terms of their sustainability. The individual contributions build upon each other progressively to achieve the total research contribution: a facility sustainability model and a process for applying it to prioritize improvement options in terms of their impact on the sustainability of a facility.

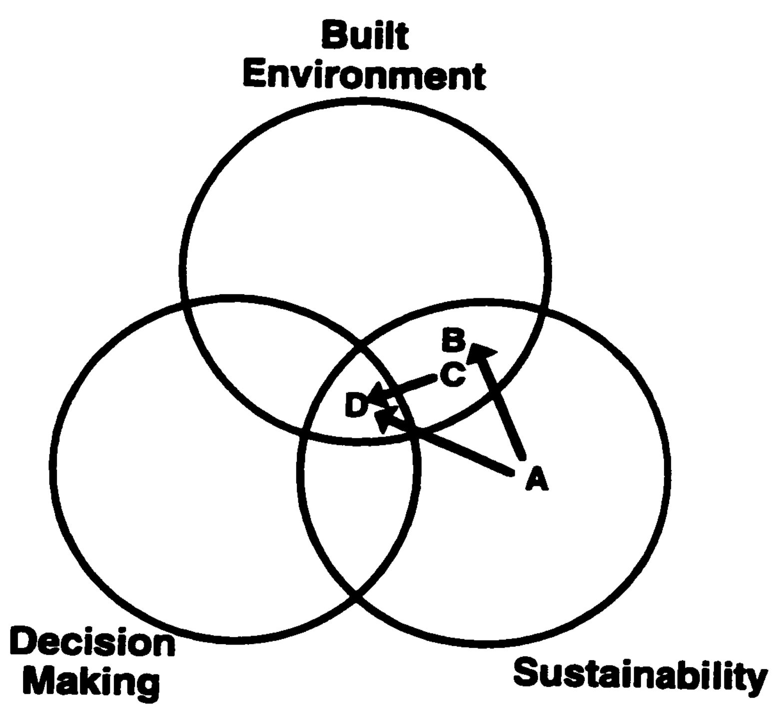


Figure 7.2: Component Contributions with Respect to the Scope of the Research

7.1.3 Specific Impacts and Benefits of the Research

Table 7.1 shows overall impacts that may stem from the individual contributions of this research. As a whole, however, the primary contribution of the work—the prioritization model of built facility sustainability—has the potential to benefit stakeholders both internal and external to the facility itself (see Chapter 1, Figure 1.3).

Internal Stakeholders: First, facility owners/decision makers will benefit from having a tool to assist them in making their facilities more sustainable, leading to competitive advantages, reduced liability and operational cost, and increased user satisfaction (Browning 1996; Kinlaw 1992, Schmidheiny 1992). The prioritization model provides a consistent, quantitative basis for comparatively evaluating alternative courses of action that derives from real facility data, and thereby will enable facility decision makers to have confidence in and justify their recommendations in terms of that data.

Along with its role as a prioritization decision support tool, the model's operationalization of sustainability for built facilities can also assist with diagnosing the features of built facilities that contribute to or detract from their sustainability. As a result, stakeholders' awareness of the impacts their facilities have on the rest of the world, along with a better understanding of the links between their buildings and the affiliate systems that support them, can lead to more sustainable solutions on the part of owners with respect to their facilities.

As more decision makers begin to monitor and archive the data necessary to apply the model and prioritization process to their decisions, better understanding of the relationship between sustainability and economic costs and benefits will emerge. This understanding will provide evidence to support the economic benefits of sustainability, encouraging more owners to adopt it as a driver of problem-solving.

With increasing numbers of owners seeking to increase the sustainability of their improvement choices, the impacts on the built environment will be significant. As shown in

Chapter 6, the impacts of a single action by a single owner may be relatively small, but the potential for cumulative impacts as a result of widespread change is significant. Incorporating sustainability into all phases of the facility life cycle has the potential to change the form, function, and performance of the built environment in the future, with benefits in terms of increased satisfaction for both users and other stakeholders of built facilities.

External Stakeholders: The model also has the potential to influence the behavior of source and sink facilities by encouraging owners to contact the operators of these facilities and learn more about their processes. An increased demand for sustainability information on the part of users of the model could help drive the widespread adoption of ecolabels and sustainability certification for building materials, systems, and facilities. Increased awareness of sustainability on the part of source and sink system operators could be a resulting impact of these types of documentation requirements. To maintain a competitive advantage, this awareness could drive source or sink system operators toward achieving a greater level of sustainability for their own facilities.

As illustrated throughout the dissertation, the dependencies and relationships between nearly all systems on Earth may lead to significant ripple effects throughout the network of systems with only small changes in individual systems. Due to the potentially positive and beneficial impacts sustainability improvement could initiate, the next step is to explore ways in which the model could be improved in future research and development.

7.2. Conclusions: Lessons Learned and Future Research

As a result of applying the model in the context of the case study and performance analysis, significant lessons were learned about how the model works with respect to prioritizing improvement options. The following subsections describe seven notable lessons learned as a result of this research, along with recommendations for future research associated with each lesson.

7.2.1 Implications of the Ordering Method for Improvement Options

Using Equation 22 to combine the parameter functions into a single composite index of sustainability enables decision makers to compare different options in terms of the overall objective of increasing sustainability. It provides a basis for examining the options by focusing only on their contribution to moving the facility further into the octant of sustainability as described in Chapter 4. Equation 22 provides one valid basis for ranking alternatives in terms of a single composite numerical index (Duke 1999, Griffin 1999) and is based on two hypotheses discussed in Section 6.3.1:

- The axes comprising the three-dimensional space are orthogonal
- Values along each axis are scaled in such a way as to represent an equal weighting among the three sustainability parameters in the decision process

One implication of these hypotheses is that prioritization using the composite index of sustainability is exactly equivalent to the result one would obtain from performing multi-attribute decision tree prioritization using the three parameters of sustainability with equal weightings (Gregory 1999). Compared to the composite index, the three-dimensional sustainability space representation gives considerably more information about how improvement options change facility sustainability.

By examining the change vectors within the three-dimensional space, one can see both the magnitudes and directions of change caused by implementing improvement options. Due to the way in which the composite sustainability index is calculated, this information is amalgamated into a single number that hides the richness of the sustainability implications of change. For example, an option that reflects an extremely positive change along one axis and slightly negative changes along the other two will receive a higher ranking using the composite sustainability index than an option with small, positive changes in all three axes. Using the three-dimensional decision space to compare the options would reveal that the first change (with two parameters becoming less sustainable) is an improvement in some sense, but is not moving the facility in the desired direction, i.e., more positive within the octant of sustainability. Thus, the decision maker might choose the second option over the first, since it results in positive movement in the direction of the octant of sustainability, i.e., positive changes along all three axes.

While the composite index of sustainability is a useful method for prioritizing improvement options, it may disguise the issue of overall direction of change. Direct examination of change vectors within the three-dimensional sustainability space, on the other hand, reveals both direction and magnitude of change, and therefore allows both of these factors to be considered independently in decision making. Thus, the primary lesson learned is that the method for ordering the improvement options (composite index vs. visualizing changes in three-dimensional sustainability space) may make a difference in how a decision maker chooses to prioritize options, and decision makers should consider using the three-dimensional decision space to examine options in terms of *both* their direction and magnitude.

Future research to improve the utility of the three-dimensional sustainability space should include development of integrated graphical software to automate the plotting of points within the space and to allow the decision maker to manipulate the space (e.g., by rescaling or rotating the axial system) to facilitate examination and comparison of vectors within the space. Additional research could focus on providing mechanisms to graphically represent constraint conditions within the space, and to use the three-dimensional space itself as a map to identify areas in which technologies or strategies are needed to flesh out the set of options available to facility decision makers.

7.2.2 Implications of Relative Influence of Individual Parameters

The relative influence of the sustainability parameters SS, RBI, and EI should be balanced to assure that one parameter's scale does not inadvertently overwhelm the others. For example, in Figure 6.9, the scaling of the SS parameter is so large compared to the other parameters that they appear insignificant during visual comparison. Yet these parameters may be essential to characterize the distinctions among options, and prove to be important to their ranking. In the demonstration presented in Chapter 6, the dominating parameter was Stakeholder Satisfaction. Intra-System Ecosystem Impact also proved to be secondarily dominant in the ranking of options.

Note that the scaling of SS with respect to RBI and EI may be an accurate reflection of how decisions are actually made in the built environment. This relative scaling makes sense in terms of how each of the parameter equations was constructed, and it is reasonable given that individual changes within the built environment have a much larger relative impact on the stakeholders of the system than they do with respect to global ecosystems and resource bases. For example, using a low flow showerhead may make a significant difference to a stakeholder who derives a significant degree of satisfaction from taking showers, whereas the few gallons of water and therms of natural gas saved by the showerhead are relatively small compared to the total quantity of available water and natural gas provided by affiliate systems. If the stakeholder is unhappy with the performance of the low flow showerhead, he or she may not continue to use it and switch back to the old showerhead, negating resource savings and reduced ecosystem impacts from making the change. Thus, in terms of how facility decision makers actually make decisions, the relatively large scale of the Stakeholder Satisfaction parameter is appropriate, since the ultimate governor of rational facility decisions is how well a given change will meet the needs and aspirations of the people making the change.

A second reason that the SS scale dominated to such a large degree is that the six options considered in the demonstration case caused a relatively small variation in the other parameters. To achieve a better spread of options in terms of sustainability, options should be considered that demonstrate greater variation across all variables. Future research could also include reexamination of the instrument used to generate values for the dominant parameter, Stakeholder Satisfaction (see Section 7.3.5 for further discussion), or additional mathematical experimentation to determine the optimal scale configuration of the axes to provide the most useful method for comparing points within the space, especially for improvement options that result in small parameter variations.

7.2.3 Implications of Measurement Accuracy

Given the algorithms and estimates used in this model to measure the total input/output of the source/sink systems, measurement error in these values may be on the same order of magnitude as the measurements of the changes in flows caused by the improvement options selected. This measurement error may be sufficiently large enough to overwhelm the changes in flows themselves. For example, the error in measuring the total source/sink flows of a wastewater treatment plant may be sufficiently great to overwhelm the small changes of a single improvement (e.g., switching to a low-flow showerhead) in a single home. This error results from insufficient accuracy in the measurement technique, *not* insignificance of the change resulting from the improvement option. However, since the issue is not the accuracy of the measurements but rather the ability to prioritize improvement options, any error resulting from measuring large scale flow quantities will cancel out in the comparison of *relative* sustainability of the options with respect to the baseline state of facility sustainability. Thus, while users of the model and process must actively guard against potential measurement pitfalls, measurement error in and of itself does not degrade the value of the model for setting priorities.

Future research with respect to issues of measurement accuracy should focus on expanding and refining the set of data to serve as a basis for model calculations, as well as improving the accuracy of estimates and instruments to measure model flows and impacts. More rigorous archiving of data relevant to facility sustainability (see Section 7.2.5) will also help to reduce estimation error in the application of the model.

7.2.4 Implications of the Choice of Feasibility Constraints

The choice of feasibility constraints plays a role in how combinations of options may be ranked. When considering combinations of options, the mathematical property of additivity is a requirement, as discussed in Section 6.3. Under conditions where the sustainability of improvement options is additive (see Section 6.3.4), a decision maker may opt for a combination of lower-ranked options instead of the highest-ranked item, if their combined sustainability is greater than the sustainability of the highest-ranked option alone. When feasibility constraints such as cost limit the degree to which options can be combined, consideration of all combinations of options is recommended to identify any feasible combinations of options that may be higher ranked than individual options.

In the case study considered in Section 6.2, the feasibility constraint did not restrict the choice of options that could be implemented individually. For the case study, more strict economic feasibility constraints (e.g., a budget of less than $1350) could have rendered infeasible more combinations of options, resulting in ranking of a subset of options that may differ from the initial ranking.

For example, the decision maker in the case study could essentially choose between either the gazebo or options 1 through 5 together, given a budget of $1350. With a lower feasibility threshold, the gazebo would have been pruned as infeasible, and only some combinations of options 1 through 5 might have been affordable. With options pruned due to infeasibility, the rankings of improvement items will be different than in the unconstrained case since some options or combinations of options are no longer part of the analysis.

Future research to address the issue of feasibility constraints should include adaptation of classical preference elicitation techniques (e.g., Simon 1983, Tversky 1967) into a formal mechanism for articulating decision constraints, particularly in situations where constraints are not independent of the options considered. For example, the economic feasibility constraint in the example was generated based on the homeowner's willingness to pay for the most expensive option by itself. Had this option not been part of the set of alternatives considered, the homeowner may have had a lower threshold of economic feasibility. Decision framing, the way the problem is posed to the decision maker, and the presence or absence of a formal decision making process or framework will all influence the kinds of decision constraints that are relevant for a particular situation (Zandi 1993, White et al. 1984, Sprague & Carlson 1982, Sharda et al. 1988, Nelson & Quick 1994, Volkema 1990). Future research should include replication of the model application in the context of different decision environments to evaluate the effect of the decision environment on feasibility of options.

7.2.5 Implications of Data Availability

Based on the data collection experience associated with the case study in this research, lack of data may be a constraint to application of the model in current practice. Finding a willing decision maker with reasonably complete historical consumption records (e.g., electric bills, gas bills, etc.) was challenging. Even with the existing records of the decision maker in the case study, some interpolation and estimation of quantities was necessary (see Appendix D). The estimation of source and sink properties, along with changes in flows due to improvement options, were additional challenges in the demonstration (see Section 7.2.3 for a discussion of the implications of this challenge). While the model could be successfully applied in the demonstration case, more consistent monitoring of data by stakeholders, more complete sets of default parameters, and more detailed impact estimation algorithms will improve the usability and usefulness of the model in future cases.

Since usability was a primary goal for the research product, the data considered in the case study was limited to information that could be collected using existing documentation maintained by a facility owner, such as utility bills, store receipts, and simple quantity estimates. By virtue of identifying the kinds of information important for sustainability assessment, the research contributed a framework of data requirements for stakeholders to begin documenting the critical flows and impacts of their facilities. With increased awareness and ongoing monitoring of relevant source, sink, flow, and other data, future researchers in this area may be able to draw upon a much larger and more interesting set of source data to refine the model developed in this work.

7.2.6 Implications of the Stakeholder Satisfaction Scale

The assumptions associated with the stakeholder satisfaction scale were challenged in the application of the model to prioritize improvement opportunities. The intent of the stakeholder scale was to provide a consistent set of criteria against which to evaluate the impacts of changes in the facility on the stakeholders who inhabit it. The criteria used to comprise the scale were obtained by a search of the literature, and served as a starting point for measuring the relative satisfaction of stakeholders under various states of their facility. Inherent in the construction of the scale was the assumption that a three-category Likert scale (Not Met, Met, Exceeded) would provide sufficient resolution to distinguish among stakeholder satisfaction for different options. Additionally, the scale is constructed in such a way that although the criteria can be weighted by decision makers, the weighted criteria themselves are assumed to be additive and linear with respect to one another. While the weighted items within the scale are indeed additive, the Likert ratings of each criteria are *not* additive, and this feature of the scale proved to disrupt the additivity of options within the three-dimensional decision space as discussed in Section 6.3.4.

The scale may be limited in its applicability to facilities with different or more specific stakeholder expectations, but since it can be customized simply by changing the set of expectations to more closely match the needs of a particular situation, the basic structure of the scale remains useful. Note that while the set of expectations can be modified to customize the instrument for specific situations, the set must remain constant *within* a given analysis in order for the comparison of options within that analysis to be valid.

As constructed, the scale is useful as long as it can distinguish among facility states. For all but the gazebo option in the case study, the Stakeholder Satisfaction Scale provided this capability in the case study. Given that the scale was unable to capture any added stakeholder benefits from installing the gazebo, additional consideration should be given to further testing and refining the scale in future research, to either enable to scale to capture real differences among options, or to conclusively identify situations in which there is truly no difference among options in terms of stakeholder satisfaction.

7.2.7 Implications of Unit Time

Finally, as discussed in Section 6.3.1, one of the stipulations of the model is that all flows should be evaluated over a unit time period of one year, to account for seasonal flow fluctuations when converting flows to quantities of resources. This unit of time was selected not only to normalize seasonal fluctuations, but also to match typical decision and resource allocation cycles in built facility decision making (Gregory & Pearce 1999). As such, it provides one possible discrete time increment for accounting for changes in facility sustainability.

The model is constructed in such a way that it can be applied for many time periods sequentially to estimate changes in sustainability over the life cycle of the facility, its components, or some other desired life cycle. With repeated application of the model for sequential time periods, a sustainability path could actually be plotted using multiple vectors within the three-dimensional sustainability space for each option over multiple time periods. While application of the model in this way was outside the scope of the research, the sensitivity analysis did explore some of the implications of time in its consideration of Year 1 vs. Year 2 impacts of the improvement options (see Section 6.3.3).

One important consideration in future applications of the model is how initial, one-time impacts (e.g., resources embodied in the product, energy required for installation, etc.) should be amortized over the life cycle of the facility. Since the focus of this research was to prioritize options with respect to one another, all initial impacts were lumped together into the one-year time period being considered in the case study, providing one possible basis for comparison. In the case of this research, the one-time-period accounting for impacts was a reasonable approach, since the initial impacts of each improvement option in terms of resource base and ecosystem impacts would truly be felt at the point in time when the option was implemented.

An alternate approach would have been to spread out the initial impacts of each option over its anticipated life cycle, resulting in a lower set of impacts in the first time period and possibly changing the prioritization of options generated using the aforementioned method. Future research should focus on identifying the possible costs and benefits of these and other amortization schemes, to provide a basis for selecting the most appropriate amortization scheme for the facility being analyzed.

7.3. Summary: Research Findings and Outcomes

As stated in Chapter 1, one primary question has served as the driver for this research: how can decision makers compare the relative sustainability of facility improvement options? This research focused on developing a method to evaluate the sustainability of built facilities to provide a basis for comparative prioritization, in the context of testing the research hypothesis: it is possible to construct a model of built facility sustainability that can be used to prioritize improvement options in the context of their use. The contribution of the research, a quantitative model of facility sustainability and a process for applying it to prioritize improvement options, supports the truth of the hypothesis by virtue of its existence.

This research developed an answer to this question of how sustainability should be defined in the context of built facility systems, beginning with defining sustainability in the generalized context of global and technological systems. Using two parallel techniques for operationalization, Chapter 4 showed that the critical parameters of sustainability are influenced by how humans consume resources and affect natural ecosystems in the process of satisfying their needs and aspirations. From the findings of Chapter 4, this research defines sustainability as a system state in which no internal (intra-system) or external (extra-system) constraints are violated that would threaten the stability of the system into the foreseeable future. Given this definition, a sustainable system is one in which the following constraints are met:

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

Based on the primary parameters identified in the research (Stakeholder Satisfaction, Resource Base Impact, and Ecosystem Impact), Chapters 5 and 6 showed that evaluating sustainability means defining an appropriate scale of analysis for the problem at hand, then focusing on how system activities within that scale influence the other systems to which it is interconnected.

In terms of the built environment, Chapter 5 described how a useful scale of analysis was at the level of whole facilities and the site on which they exist, since this is the scale at which salient properties of the system as a whole begin to emerge. By focusing at this scale, Chapter 5 defined two distinct entities for which sustainability must be evaluated: the system itself (intra-system entities), and the context of the system (extra-system entities). As shown in Chapters 5 and 6, only two ways exist for a system defined as such to impact sustainability: by changing the nature of the *system within its boundaries* (i.e., intra-system impacts), and by changing the nature of the *context* by virtue of the flows of matter and energy across the system boundary (i.e., extra-system impacts).

Given the definition of a system described in Chapter 5, the primary operational parameters of sustainability (Stakeholder Satisfaction, Resource Base Impact, and Ecosystem Impact) were expanded into functions of variables that have meaning to built facility decision makers. These variables can be expressed on a purely abstract level (as in Chapter 4), as well as on a level at which real decision makers can understand and measure them. Chapter 5 broke down the parameters of sustainability into hierarchical levels of variables, to a level of detail for which decision makers can operationally evaluate them.

Chapter 6 demonstrated how to use the operational objective function of facility sustainability to prioritize improvement opportunities to increase the sustainability of facility systems. Establishing a baseline state of sustainability at the point of analysis gives decision makers a benchmark against which to compare predicted sustainability after implementing improvement opportunities. The improvement opportunities are controlled by variables both internal and external to the system, and their sustainability varies based on changes to the variables described in Chapter 6. The relative magnitude of change in sustainability provides a basis for ordering improvement opportunities to increase facility sustainability, thus providing a solution that meets the goals and objectives of this research.

With respect to its mathematical formulations, the model developed in this research provides a first-generation quantitative model of the relationships among variables contributing to the sustainability of built facilities. Since no other models with the capability for prioritization exist to provide a point of comparison, this model is a ground-breaking first step in the evolution of sustainability theory for the built environment. By providing an operationalized construct of sustainability for built facilities in the form of a quantitative model, the research provides a major contribution to the body of sustainability knowledge and establishes a new point of departure for future work.

APPENDIX A:

A REVIEW OF PERSPECTIVES ON THEORETICAL SUSTAINABILITY

In setting the stage to operationalize sustainability as undertaken in Chapters 4 and 5, an important precursor is to examine the general literature on sustainability as it has evolved outside the domain of the built environment. Toward this end, Appendix A presents an overview of significant initiatives in the literature that apply sustainability to a variety of different kinds of systems. The overview evolves in terms of a series of questions about sustainability, including who or what is being sustained, who or what is doing the sustaining, and for how long should sustainability be achieved, in terms of existing work in the general literature. The following sections develop answers for these questions at both the global and technological systems scales, based on work in the existing body of sustainability knowledge. The appendix concludes with an overview of the important points of the reviewed literature, to provide perspective on how some authors in the general literature have answered the question, "How should sustainability be achieved?"

A.1 Sustainability at a Global Level

The first critical barrier which has thus far impeded understanding and implementation of sustainability in practice is the difficulty in reaching consensus on what sustainability means at a global level, why it is important (if at all), and how it should be defined and operationalized. Even theoretical sustainabilitists have trouble coming to consensus on which variables are important and how those parameters should shape human decisions and subsequent actions. The following sections provide an overview of meta-level issues and trends in the theoretical sustainability literature to provide perspective for the development and validation of a definition of sustainability at a technological level in Chapter 4.

A.1.1 The Meaning of Global Sustainability

The concept of sustainability was first accorded widespread public recognition as a result of the 1992 Earth Summit in Rio de Janeiro, within the context of sustainable development. The United Nations World Commission on Environment and Development coined a definition of sustainable development in their report presented at the Summit which is probably the most well-known in all of the sustainability literature: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (WCED 1987, p. 43).

The work of the Commission, developed in response to a growing recognition of global environmental problems brought on by human development activities, spurred a fresh interest in sustainability among theoreticians in fields as diverse as economics, ecology, and sociology, as well as among practitioners in domains ranging from manufacturing to building construction to agriculture. The resulting evolution of meanings of the concept exhibits sometimes conflicting diversity, of which one analyst said (Pezzey 1989, p. 3f):

> This diversity of approach has one big advantage: nearly everyone can agree that 'sustainable development' is a good thing...but the same diversity gives rise to numerous inconsistencies, and 'it may only be a matter of time before the metaphor of sustainability becomes so abused as to be meaningless'. (quoting O'Riordan 1988, p. 30).

In order to determine a sound and useful understanding of sustainability with respect to any particular domain of application, a beginning step is to examine more closely the fundamental ideas underlying the concept at a global level.

The first step in understanding sustainability is to examine its grammatical roots: the infinitive "to sustain", and the suffix "-ability". The American Heritage College Dictionary defines sustain: "to keep in existence; to maintain" (3rd ed. 1993). Likewise, the suffix "-ability" connotes "ability, inclination, or suitability for a specified action or condition" (ibid.). Thus, the term sustainability could be defined as "the suitability or inclination to be kept in existence or maintained." This definition of sustainability leads to the questions, "What or who is being sustained?" and "By what or whom?" Other operational questions logically follow: "How?" and "For how long?" The next sections provide some possible answers from the theoretical sustainability literature by comparing and contrasting three global definitions of the concept: the Rio definition (WCED 1987), Liverman et al.'s working definition (1988), and a definition by Brown et al. (1987).

A.1.2 Who or What is Being Sustained at a Global Level?

The concept of sustainable development as delineated in Rio brought to attention the unpleasant idea that human activities as they are currently taking place are likely to ultimately result in misery or the possible demise of the human species on Earth if certain trends of human behavior continue. In particular, the World Commission on Environment and Development (hereafter the Commission) identified the issues of inter-generational equity (fairness to future generations) and intra-generational equity (fairness among the generation currently inhabiting Earth) as being critical to ensuring the continued survival of the human species.

The Commission's definition of sustainability (see Section A.1.1) is similar to many of the definitions in the theoretical sustainability literature in that it takes a distinctly anthropocentric or human-centered view of sustainability. In other words, the answer to the question of who or what is to be sustained according to the Commission is *humans*. While the assumptions underlying the Commission's proposed mechanisms to implement sustainable development have been called into question by other authorities on development and sustainability (e.g., Jacob 1994; Daly 1990), the basic principles of sustainability as it applies to human development which were identified by the Commission remain uncontested:

- Equity in the use of natural resources, both intra- and inter-generational
- Reduction of the negative impacts of human activity on the natural environment
- Providing the mechanism for humans to meet their needs and aspirations, both now and into the foreseeable future.

These principles reflect the most basic conception of sustainability as it applies to development activities, and are generalizable to other human actions as well. A useful working definition of sustainability has been proposed by Liverman et al. (1988, p. 133) which captures the essence of sustainability from an anthropocentric viewpoint:

> [T]he indefinite survival of the human species (with a quality of life beyond mere biological survival) through the maintenance of basic life support systems (air, water, land, biota) and the existence of infrastructure and institutions which distribute and protect the components of these systems.

This definition provides an explicit answer to the question of who or what is being sustained: the human species. By designating the beneficiary of sustainability as the human species, not humans as individuals, the definition fails to provide a definite mechanism for making tradeoffs between the survival of individual humans or groups of humans and the net survival of the species. Brown et al. (1987, p. 717) provide an alternative perspective on the question:

> In the narrowest sense, global sustainability means the indefinite survival of the human species across all the regions of the world. A broader sense of the meaning specifies that virtually all humans, once born, live to adulthood and that their lives have quality beyond mere biological survival. Finally, the broadest sense of global sustainability includes the persistence of all components of the biosphere, even those with no apparent benefit to humanity.

This definition highlights three potential sets of possible beneficiaries of sustainability (Figure A.1): (1) humans as a species; (2) all individual humans; or (3) all individual living beings. Which level is specified as a constraint of sustainability has a drastic impact on the types of permissible actions and priorities that can take place without damaging the sustainability of the global system. For example, if sustainability of the human species is the desired constraint, severely destructive activities such as nuclear war might be permissible if provisions were made for the ongoing survival and prosperity of a sufficient genetic pool of humans. From the perspective of the third level – sustaining all individual living beings – nuclear holocaust would be unsustainable without question. This admittedly extreme example shows that the question of who or what is to be sustained is critical to determining an appropriate operationalization of sustainability.

The level of sustainability to be sought in human action cannot be arbitrarily specified without an understanding of the context of the analysis. The scope of influence on living beings as individuals or as species is highly dependent on the nature of the actions to be taken, as well as highly unpredictable. For example, a government deciding to construct a dam to provide flood control for human development may have to make a tradeoff between meeting the safety needs of the humans who will benefit from the dam, and an endangered species of fish or plant whose complete existence will be wiped out by the reservoir which builds up behind it. From the perspective of this research, the kinds of decisions with which to be concerned are unlikely to require immediate tradeoffs between human lives and the survival of non-human species. Instead, the potential impacts of choices in the built environment on long-term survival of both human and non-human species are the primary focus of the work.

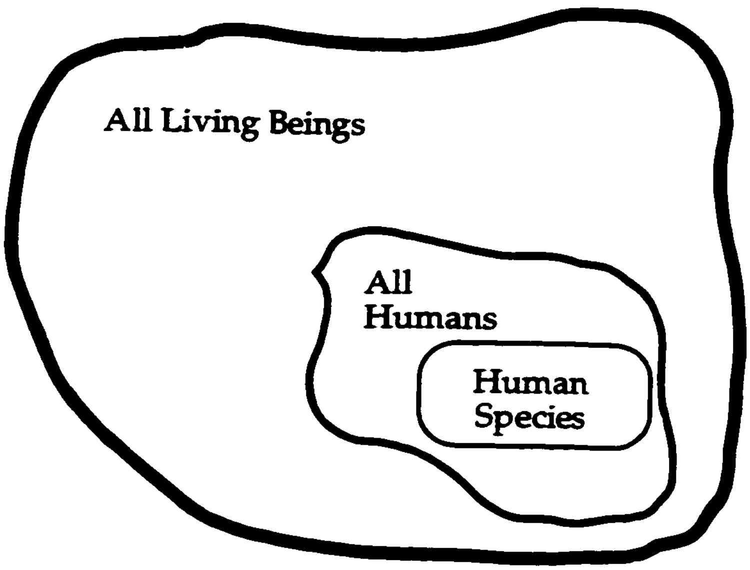


Figure A.1: Possible Sets of Beneficiaries of Sustainability

It is important to reemphasize at this point that at a global level of sustainability analysis, decision-makers are not interested in sustaining any particular human *activity or artifact*, but rather humans themselves and biological life as a whole. In the rest of this dissertation, the concept of sustaining the built environment means sustaining that environment to meet human needs and aspirations, without endangering other life both now and in the future. If the specific built system under consideration does not meet human needs or aspirations, or if it endangers other life, then it should not be sustained in and of itself.

A.1.3 Who or What is Doing the Sustaining at a Global Level?

The working definition by Liverman et al. (1988) provides a more discrete approach to sustainability than the Rio definition in several ways. First, it emphasizes that the primary goal of sustainability should be human survival into the indefinite future, at a state beyond mere biological survival. Secondly, it identifies two basic mechanisms for achieving this goal:

1) Maintaining basic life support systems (air, water, land, biota)
2) Creating and maintaining human infrastructure and institutions to distribute and protect the resources generated by the life support systems.

But it fails to explicitly say who should be undertaking these activities. Obviously natural ecosystems must play a role: they comprise those basic life support systems, and intrinsically have the ability to regenerate and maintain themselves within certain *limits* of harvest, pollution, or other stress.

These limits of ecosystems imply a second role to be played, presumably by humans. While in anthropocentric definitions of sustainability, humans are the explicit beneficiaries of the sustaining action, someone or ones in fact have to be actively policing the distribution of resources to meet human needs in a way that ensures that the limits of natural ecosystems are not exceeded or otherwise transgressed. Liverman et al. capture this requirement in the second half of their definition, without going into the politics of who should do the policing or sustaining. Clearly, however, since humans are the beneficiaries of anthropocentric sustainability, they also should have some responsibility for enacting and maintaining that sustainability.

Thus, the question becomes, to which humans fall the responsibility of ensuring that our natural life support systems are used fairly and not abused? Should such responsibilities be distributed evenly over all humans and left to the altruistic whims of each? Garrett Hardin, in his famous essay "Tragedy of the Commons," has illustrated the perilous and fallible nature of this scheme for sustaining (1968).

Perhaps a more useful question, certainly from the perspective of this work, is who is actively interested and willing to take on the responsibility for sustainability? The answer to this question varies widely from application to application, and the answers to this question from the perspective of the building industry are examined more closely in Chapter 1. To summarize, stakeholders from all facets of the built environment are interested in sustainability for reasons ranging from potential profit to a simple conviction that it's the right thing to do. These stakeholders include users, owners, designers, and constructors of the built environment, as well as the academic and research community that supports its continued evolution. From the perspective of this research, it is these sets of stakeholders who will be doing the sustaining with respect to the built environment.

A.1.4 For How Long Should Sustainability Be Achieved at a Global Level?

The next question to be answered is "For how long?" In answering this question at a global level, the important objective is sustaining the lives of humans and other living things as species (or individuals, depending on which of Brown's three perspectives is chosen), not sustaining specific artifacts or processes. It is meaningless to speak of sustaining a technology in and of itself; for example, buildings have a finite lifespan just like individual organisms and cells, and cannot be sustained indefinitely. At a global level, each technology or technological component serves its specific purpose to further the survival of the human species as a whole (e.g., Yeang 1993).

In terms of the global Earth system, the technologies humans create are all subject to the greater purpose of sustaining the global system in which we reside, and each must be considered in the context of the roles it plays in achieving that purpose. Typical answers from the literature to the question of "For how long?" in the case of the global Earth system include "future generations" (e.g., WCED 1987, Howe 1979, Lele 1990, Tietenberg 1984), "500-year planning" (Tonn 1989), and "indefinitely" (Pearce 1988, Liverman et al. 1988, Brown et al. 1987).

In the case of this dissertation, the answer to this question is considered to be "into the foreseeable future", where under predictable conditions the indefinite time frame applies. Under unforeseen conditions, reevaluation will be necessary to establish new strategies for sustainability that take the new conditions into account in striving to plan for an indefinite period of time. Having answered these three underlying questions for sustainability at a global scale, the next step is to examine the same set of questions at a technological systems scale.

A.2 Sustainability at a Technology Level

At a technology level, the objectives of sustainability focus more specifically on the measurable impacts of specific technologies. Developing an understanding of sustainability on the scale of technological systems again begins by examining the questions of "What or who is being sustained?" and "By what or whom?" followed by "For how long?" and "How should sustainability be achieved?"

A.2.1 Who or What is Being Sustained at a Technological Level?

As mentioned in Section A.1, the question of who or what is being sustained depends on the scale of analysis undertaken. At a global level, the answer to this question ranges from humans as a species, to all humans as individuals, to all life on earth. At a technological level, the direct stakeholders within the technological system of interest are of greater concern. For example, in developing strategies to increase the sustainability of a built system, decision-makers would primarily like to sustain the human and non-human *users* of that system, and secondarily sustain the other stakeholders of the system. In the case of a sustainable house, the first priority is sustaining the beings that live in the house, and second the beings that are affected by the house in its context over time and space. This second group of beings includes humans and non-humans who live in the environment around the house as well as those who are involved in supplying resources for and designing, constructing, maintaining, and deconstructing the house. Thus, the scale of concern changes from humans or beings at a species level to humans or beings as impacted by the specific technology being analyzed.

A.2.2 Who or What is Doing the Sustaining at a Technological Level?

The answer to the question of whom or what is doing the sustaining also changes at the technological scale of analysis. Whereas at a global level the answer is all global ecosystems and humans as a species, at the technological level the stakeholders who make decisions with respect to the system are the primary sustainers of the system. As mentioned in Section A.1.3, the specific sustainers for a technological system in the built environment are typically the users, owners, designers, and constructors of the built environment, as well as the academic and research community which supports its continued evolution. The specific roles of these sustaining stakeholders for the built environment are described in more detail in Chapter 1.

A.2.3 For How Long Should Sustainability Be Achieved at a Technological Level?

As mentioned in Chapter 4, it is meaningless to speak of sustaining a technology in and of itself. To answer the question of "How long?" at the technological scale, analysts need to be aware of the specific purpose played by the technology in meeting the needs and aspirations of humans and non-humans, and select a time frame based on the duration of those needs. Technologies should not necessarily be sustained if the purpose for which they were created ceases to exist or if a superior replacement is developed. One example is the typewriter – not only has the advent of word processors provided a superior replacement, but scanning technology has also largely removed the need for using typewriters to fill in forms. Thus, sustaining typewriters for their own sake is a task for historians at best, and illustrates the need to consider the context and purpose of the technology in determining how long it should be sustained.

A.3 How Should Sustainability Be Achieved?

The final task in this appendix is to provide a summary of perspectives from the general sustainability literature, as a means of answering the question: "How should sustainability be achieved?" A number of authors have provided evidence and research to support a variety of answers to this question. An overview of the various schools of thought about general sustainability begins by examining the evolution of sustainability in response to the global problems created by humanity after the Industrial Revolution.

A.3.1 From Genesis to Rio: How Humanity Got Where It Is

William Ruckelshaus, known for his role as CEO of Browning Ferris Industries, Inc. as well as twice-administrator of the US Environmental Protection Agency, has proposed three eras of sustainability consciousness: original sustainability, transitional unsustainability, and post-industrial sustainability. Original sustainability, he claims, was the "original economy of our species":

> Preindustrial peoples lived sustainably because they had to; if they did not, if they expanded their populations beyond the available resource base, then sooner or later they starved or had to migrate. The sustainability of their way of life was maintained by a particular consciousness regarding nature: the people were spiritually connected to the animals and plants on which they subsisted; they were part of the landscape, or of nature, not set apart as masters. (Ruckleshaus 1989, p. 9)

As population increased and people began to conglomerate into cities, concurrently developing technology began to provide the means for mastery of nature, spurred on by the requirement for increased efficiency of agricultural and industrial production to support urban populations. This mastery of nature paradigm was further embedded into Western culture by the predominant religious paradigm of Judeo-Christian belief, namely that the Earth and its creatures have been given to humanity as a gift from God, which it is our responsibility to subdue:

> God created man in the image of himself...male and female he created them. God blessed them, saying to them, 'Be fruitful, multiply, fill the earth and subdue it. Be masters of the fish of the sea, the birds of heaven and all the living creatures that move on earth.' (Genesis 1:27-28, NJV 1985).

The resulting paradigm of transitional unsustainability remains dominant today and is marked by an objective of economic development at any environmental cost and a belief, spoken or unspoken, that technology will inevitably provide the means to continue development without respect for environmental constraints As Ruckleshaus puts it, "Advanced technology gives impetus to the basic assumption that there is essentially no limit to humanity's power over nature." (ibid., p. 9) Environmentalism, to the degree to which it is a part of the current paradigm, is "ameliorative and corrective -- not a restructuring force" (ibid.).

The growing evidence of global environmental decline, despite diverse initiatives of such ameliorative environmentalism on various scales, was the impetus for the now-famous 1987 gathering of the United Nations World Commission on Environment and Development in Rio de Janeiro. This Commission, chaired by Norwegian Prime Minister Gro Harlem Brundtland, conducted public hearings on five continents during the mid-1980s to investigate underlying drivers for the growing states of worldwide environmental and economic crisis. The outcome of the Commission's work was the report *Our Common Future* (WCED 1987), which has made popular the concept of sustainable development in many fields of study and laid the political groundwork for serious consideration of large-scale change in how humans interact with the Earth and with each other.

Brundtland's Commission proposed what is probably the most widely known definition of sustainable development, discussed further in the first part of this appendix: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (p. 43). Brundtland later went on to revise this original definition, changing the idea of meeting human needs to needs and aspirations, thereby including the concept that it should be the role of development to provide more than just basic biotic survival for humans but rather afford them the opportunity to achieve some higher quality of life (Brundtland 1989, p. 12).

Herman Daly, known most widely as the father of steady-state economics, has identified an important role to be played in implementing sustainability in his critique of the Brundtland definition of sustainability:

> ...one should not be too harsh on Mrs. Brundtland. She has after all provided a political opening for the proper concept of sustainable development to evolve, and that is quite an accomplishment. Others, unencumbered by the political necessity of holding together contradictory factions, must take up the challenge of giving the basic idea of sustainable development a logically consistent and operational content. (Daly 1990, p. 6)

Daly points out that one of the most striking problems with the Brundtland Report is its inherent but understated acceptance of the fallacious assumption that sustainable growth is possible, desirable, and even essential over an extended period of time, perhaps even into the foreseeable future, to ensure ultimate sustainability (Daly 1990). The Brundtland Report acknowledges the extensive disparity in the present between the haves and the have-nots, and espouses what Daly calls "a bad oxymoron", sustainable growth, as the solution to bringing the world's poor up to a reasonable standard of living. In an earlier article, Daly uses a striking analogy for the economy as an efficient mechanism for allocation, but not for determining the optimal scale of economic activities:

> A boat that tries to carry too much weight will still sink even if that weight is optimally allocated. Allocation is one thing; scale is something else. We must deal with both, lest even the efficiently allocated weight of the economy sink the environment. (Daly 1989, p.9).

He goes on to say: "I will admit that if the ecosystem can grow indefinitely, then so can the aggregate economy. But until the diameter of the earth begins to grow at a rate equal to the rate of interest, one should not take this answer too seriously." (ibid.) With this illustration he concludes that the concept of sustainable growth is a literal impossibility, although a redistribution of wealth from rich to poor nations is one way to balance the economic growth of those nations in a sustainable way that does not put additional pressure on already overtaxed ecological support systems.

Garrett Hardin proposes that just this sort of growth in undeveloped nations, enabled by altruistic aid from the developed countries of the world, is likely to result in even greater population surges as the negative feedback mechanisms that currently keep the swelling Third World populations in check are removed. These Malthusian feedback mechanisms include starvation, disease, and other forms of population control which act responsively to keep population at a level that matches the capacity of the environment to sustain it. By using technology to outsmart the mechanisms, humans have given ourselves the proud but tenuous privilege of cheating Nature, of living beyond our means in a world that is only now beginning to show indisputable signs that it cannot take the strain (Hardin 1993).

This initial review of the literature shows that while many people have debated and discussed the idea of sustainability and its subset sustainable development, nonetheless the concept has remained fuzzy and there is lack of consensus on many important variables. The primary debates identified in the literature review are discussed in the following subsections.

A.3.2 Distinguishing Between Sustainability and Mechanisms for Achieving It

The first important distinction lies in differentiating between sustainability and sustainable development. Many discussions of sustainability begin by quoting the Brundtland definition of sustainable development as a point of reference for discussing the topic (e.g., Daly 1990, Robért 1994, Rees 1990, etc.). A meaning for the term sustainability is taken to be the target state to be achieved by Bruntland's proposed mechanisms of sustainable development or sustainable growth. For example, Liverman et al. (1988), in their work on measuring sustainability, create their own definition of sustainability loosely based on Brundtland's, as follows:

> [T]he indefinite survival of the human species (with a quality of life beyond mere biological survival) through the maintenance of basic life support systems (air, water, land, biota) and the existence of infrastructure and institutions which distribute and protect the components of these systems. (p. 133)

This definition is useful to distinguish between the objective (sustainability) and the mechanism for achieving it (development), a distinction which has been often confused and lies at the heart of the argument put forth by many regarding the feasibility of achieving sustainability. Few (if any) humans would contest the underlying objective of sustainability which is to ensure that they and their offspring can survive with a quality of life beyond mere biological survival on the Earth, given the resources and tools to which they are limited.

When this objective is coupled with proposed mechanisms for achieving it, however, opportunities abound for dispute and disagreement. Some examples are Brundtland's proposed mechanisms of sustainable development and sustainable growth to reduce poverty and supply intragenerational equity, or Solow's idea that humans don't have to preserve any particular ecosystem or natural resource, since all such resources are essentially substitutable or replaceable by human-constructed capital and technology. These two examples represent disputes with respect to mechanisms for achieving sustainability, which will be discussed in the following subsections.

A.3.3 Disputes With Respect to Mechanisms for Implementing Sustainability

The perspectives on how sustainability should be implemented are as diverse as the domains of those who seek to implement it. Three major disputes emerge from the literature on sustainability and sustainable development: development vs. growth; preservation vs.

substitutability of nonrenewable resources; and technology vs. limits as mechanisms for achieving sustainability.

Development vs. Growth: The first dispute in the literature about mechanisms for implementing sustainability centers around the economic paradigm that should govern human development. As shown in the overview of the literature, some sources believe that economic growth can be sustained into the foreseeable future. Other sources contend that until alternative values of economic activity are developed, economic growth is antithetical to the basic concepts of sustainability. As a speaker at a recent sustainability-related conference pointed out, "If you *really* want to increase the Gross National Product, have an accident on your way to work in your fossil-fuel powered vehicle." (Slone 1998). This comment summarizes the essence of the first dispute: existing measures of economic progress are often misdirected toward perceived growth, that is, the raw exchange of currency within an economic system.

Rather than simply accepting the goal of economic growth, other sources emphasize the need to qualify economic progress in terms of its real contributions toward meeting human needs and aspirations (e.g., Daly 1992). These sources take the perspective that economics, while a valuable indicator of many types of human development, should not be an end in and of itself for sustainable development.

Preservation vs. Substitutability of Nonrenewable Resources: The second major debate in the literature regards the sustainability of using nonrenewable resources. According to the strictest interpretation of sustainability principles, using nonrenewable resources is unsustainable since it reduces the availability of those resources for future generations to meet their own needs. Alternative perspectives take into account the potential substitutability or fungibility of natural resources, and qualify the sustainability of using depletable resources by limiting their consumption to a rate at which feasible technological substitutes can be developed (Solow 1993, El Serafy 1992). In the breakdown of paradigms presented in Section A.3.3, preservation of nonrenewables represents one end of a spectrum most often held by Ecologists, whereas fungibility of resources is more commonly embraced in the Economists' Paradigm.

Technology vs. Limits: The final debate regarding mechanisms for achieving sustainability ties closely to the previous debate regarding fungibility of nonrenewable resources. In this debate, one commonly held perspective is that future humans will manage to find technological solutions to problems created by current humans, so humans need not be overly concerned with limiting consumption of resources and generation of waste. This argument is often applied in the context of justifying unrestricted population growth, where the existence of more humans means a greater set of intellectual capabilities to solve problems (as discussed in Hardin 1993). From this perspective, restricting population growth may result in preventing the birth of the next Einstein, who would have been able to solve society's most pressing problems.

The counter to this position is the perspective of limits, where humans control their negative impacts to resource bases and ecosystems by limiting human activity to the set of behaviors where they can predict and control their impacts to natural systems. This argument is embraced by the Natural Step approach to sustainability, discussed further in the next section along with existing models and representations of sustainability that represent the existing body of work on the topic.

A.3.4 Existing Models and Representations of Sustainability, and Their Limited Usefulness

Existing strategies for achieving sustainability presented in the theoretical literature on the topic provide varying degrees of guidance for selecting problems to be addressed, and for finding solutions to those problems. In this section of the appendix, three representative models or representations of theoretical sustainability from the literature provide a perspective of the approaches to sustainability operationalization currently being developed.

One example of a strategy for sustainability that takes a prescriptive form is the Natural Step, developed by Karl-Henrik Robért of Sweden. The Natural Step consists of four prescriptive statements, developed using a unique consensus process that included some of the finest scientific minds in Europe. The four statements that make up the Natural Step are shown in Table A.1. These steps provide guidance for selecting alternatives to solve particular problems being addressed. Robért goes farther than most authorities in stating how to achieve sustainability: he recommends starting with the lowest hanging fruits on the tree of sustainability problems, to achieve a step-by-step progress toward sustainability, one natural step at a time (Holmberg & Robért 1997).

Table A.1: Natural Step System Conditions (Robért & Eriksson 1994)

Natural Step System Conditions
1) Substances from the Earth's crust must not systematically increase in nature.
2) Substances produced by society must not systematically increase in nature.
3) The physical basis for the productivity and diversity of nature must not be systematically deteriorated.
4) Basic human needs must be met with the most resource-efficient methods possible, including a just resource distribution.

But he still doesn't tell us how to determine what those low-hanging fruits are, or how far from reach they might be. A means of evaluating situations, organizations, artifacts, processes, etc., is needed to determine how best to approach them when trying to make them more sustainable. In particular, it would be useful to have a tool which can identify existing or potential problems of artifacts (built facilities in particular), and guide stakeholders in deciding in what order they should attempt to solve the problems so as to proceed on a maximally effective and efficient path to sustainability for the overall artifact. The research described in this dissertation provides such tool applicable in the domain of built facility systems.

In another popular framework or model of sustainability developed by Munasinghe (1993), sustainability issues are classified into three categories: social/political, environmental, and economic issues. These three classes of issues are arranged in the model as vertices of a triangle (Figure A.2), whose equilateral sides are intended to imply that achieving sustainability involves finding solutions which balance the importance and impacts of each of the three categories.

Munasinghe's triangle provides a good classification system for sustainability properties, and highlights issues such as social and political impacts which have often been omitted from consideration in traditional design processes, or otherwise overshadowed by variables such as time, cost, and quality. However, it provides no clues about how to actually implement sustainability for particular problems, and someone trying to apply the model to a built facility would have a difficult time using it to generate or evaluate potential solutions.

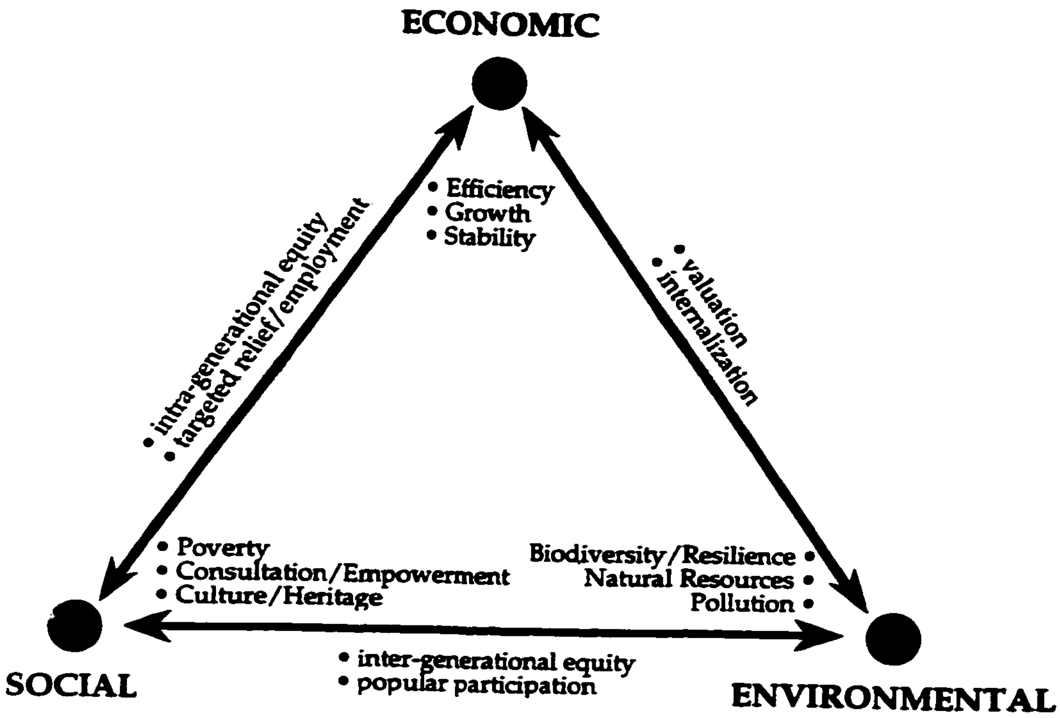


Figure A.2: Approaches to Sustainable Development (Munasinghe 1993)

Herman Daly, academic economist and author of many works on theoretical sustainability, provides another example of the state of the art in attempting to operationalize sustainability for decision making. Daly has developed a set of what he calls operational principles for sustainable development, which provide a set of rules or principles for implementing sustainability in the context of development projects. Daly's operational principles are shown in Table A.2, and serve as a framework which identifies critical variables in achieving sustainability, as well as proposing specific operational limits to those variables to define what is and is not sustainable.

Daly's operational principles are a relatively unique work in the theoretical sustainability literature. While most authorities on theoretical sustainability tend to focus on specific disagreements about particular limits or strategies for achieving sustainability (see previous section), Daly simply cuts through the layers of argument and selects limits for each relevant variable which seem reasonable based on the arguments he presents. Again, however, his principles are more useful in an evaluative sense for selecting one solution from many for a particular problem, rather than providing the means of identifying and prioritizing problems. And they are focused on a global or large regional scale, making them difficult to apply to decisions about single artifacts, buildings, or other types of projects.

Table A.2: Operational Principles of Sustainable Development
(after Daly 1990)

Sustainability Issue	Operational Principle
1a) Resource Consumption - Renewable	"[H]arvest rates should equal regeneration rates (sustained yield)"
1b) Resource Consumption - Nonrenewable	"[Limit] their rate of depletion to the rate of creation of renewable substitutes"
2) Ecosystem Impacts	"[W]aste emission rates should equal the natural assimilative capacities of the ecosystems into which the wastes are emitted"
3) Economics/Social	"[T]he scale of the economy (population times per capita resource use) must be within the carrying capacity of the region in the sense that the human scale can be maintained without resorting to capital consumption. Ultimately this will imply a limit on total scale of resource throughput, which in turn implies limits on and a tradeoff between population size and per capital resource use in the region"

Daly's operational principles are based on an explicitly stated assumption which raises some questions: "Capital, both natural and manmade, can be maintained at various levels. We want to maintain capital intact not just at any level but at the *optimal* level." (6, emphasis added). From an ethical engineering perspective, the notion of optimization requires that either (a) all relevant variables are known with a sufficient degree of confidence to ensure the inviolate safety of human life, or (b) appropriate safety factors have been developed and included to provide a reasonable margin of safety in the face of uncertainty about the values of relevant variables.

As discussed in Chapter 4, condition (a) is difficult or impossible to attain due to the global scale of many of the variables, the lack of validated and consensus-governed scientific theory, and the nondeterministic nature of human behavior which influences many if not all of the relevant variables. While many tools have been developed to assess variables of sustainability, often dispute exists over the accuracy of their output and the bases upon which their fundamental assumptions are founded. Thus, condition (b) is the basis for the approach taken to evaluating sustainability in this research, and is discussed further in Chapter 4.

A.4 Moving from Disputes to Operationalizing Sustainability

What emerges from the debates about sustainability is a ruckus not unlike monkeys chattering in trees. In fact, the developers of the Natural Step approach to operationalizing sustainability have used exactly that analogy in describing the problems inherent in the multiple debates on sustainability issues (Robért et al. 1994, p. 2):

> Up to now, much of the debate over the environment has had the character of monkey chatter amongst the withering leaves of a dying tree - the leaves representing specific, isolated problems....In the midst of all this chatter about the leaves, very few of us have been paying attention to the environment's trunk and branches. They are deteriorating as a result of processes about which there is little or no controversy; and the thousands of individual problems that are the subject of so much debate are, in fact, manifestations of systemic errors that are undermining the foundations of human society.

From an applied perspective, many of the approaches examined in this appendix fall prey to the problem of focusing on the leaves rather than the branches of the tree in that they lack a common framework for what sustainability is and what its goals are, thus missing critical elements. The purpose of Chapter 4 is to develop such a common framework based on the theoretical foundations of sustainability, which includes appropriate concepts and issues identified as being important in the previous sections. This definition and operative framework will serve as a point of departure for the development of a metric of built facility sustainability in the rest of the dissertation.

APPENDIX B:

CONTENT ANALYSIS

In seeking to corroborate the choice of variables considered as part of the operationalization of sustainability in Chapter 4, the technique of content analysis provided a way to examine a set of representative definitions from the theoretical sustainability literature. The purpose of the content analysis was to systematically identify all the variables referenced in the literature as having an impact on the sustainability of a system, and thus to ensure that the summary set of variables considered in Chapter 4 adequately portrays the concept of sustainability. This appendix describes the methodology followed in conducting the content analysis, presents the results of the analysis, and concludes with a discussion of the outcome of the analysis and its implications for the representations of sustainability developed in Chapter 4 and used throughout this dissertation.

B.1. Background

The underlying difficulty which led to the need for this content analysis is that most authors in the sustainability literature seem to have slightly different perspectives on how to define sustainability. Even those sources which purport to present an overview of perspectives on sustainability typically develop their own, slightly unique working definitions of the term (e.g., Liverman et al. 1988, Pezzey 1989), with or without unique qualifiers to shape it to their own domain of interest.

The definitions within any specific domain (e.g., ecology, economics, building construction) provide an amalgam of views nearly as varied as that existing across domains, as demonstrated in the literature review in Chapter 2 for built environment sustainability. Wide variations exist in which factors or variables are seen as essential for sustainability, and what the thresholds or objectives of those variables should be in any particular context. With much of the body of sustainability literature in domains other than ecology, little, if any, attention is paid to basic scientific mechanisms of system interaction, and much of the information in so-called applied approaches to sustainability takes a distinctly heuristic or rule-of-thumb approach rather than an analytical approach based on sound science.

This diversity of perspective in how sustainability is defined in the literature engenders a need to systematically examine that literature to determine a valid and representative definition of sustainability which incorporates consideration of all relevant variables. Toward that end, the technique of content analysis from the field of linguistics has been applied to a variety of definitions of sustainability, resulting in a classification of variables considered to be important based on the body of sustainability literature.

B.2. Content Analysis Methodology

Content analysis is a linguistic technique for "the objective, systematic and quantitative description of the manifest content of communication" (Berelson 1952, p. 18, in Krippendorff 1980). In its full form, content analysis is used to make "replicable and valid inferences from data to their context" (Krippendorff 1980, p. 21), where the data are samples of linguistic text and the context is the "surrounding conditions, antecedent, coexisting, or consequent" (ibid., p. 26). Krippendorff characterizes content analysis as an "inquiry into symbolic meaning of messages" (p. 22), and points out that messages do not generally have a single meaning as such, but are highly dependent on the perspective of the interpreter, and may vary from interpreter to interpreter.

The need met by content analysis in this research was for a tool to systematically process the large set of sustainability definitions from the literature and to extract the essential variables, objectives, and mechanisms proposed by each author to achieve sustainability. With this systematic examination of the literature, an internal corroboration of the choice of variables of sustainability in Chapter 4 can be undertaken.

Krippendorff identifies three steps in processing a body of linguistic information into analyzable form:

- Unitizing
- Sampling
- Coding

After the linguistic information has been processed, various techniques exist for analyzing the data to develop inferences or generalizations of the data. Each of these steps is discussed in detail in the following subsections.

B.2.1 Unitizing of Samples

The first step of content analysis is to determine what is to be "observed, recorded, and thereafter considered a datum" (Krippendorff 1980, p. 57). In the case of this research, each of the discrete definitions of sustainability coined by authors in the sample of definitions (see next section) is considered a sampling unit, described by Krippendorff as "those parts of observed reality or of the stream of source language expressions that are regarded independent of each other" (ibid.). The definition of sustainability used as an example in this appendix is a working definition by Liverman et al. (1988):

> [T]he indefinite survival of the human species (with a quality of life beyond mere biological survival) through the maintenance of basic life support systems (air, water, land, biota) and the existence of infrastructure and institutions which distribute and protect the components of these systems.

B.2.2 Sampling Strategy

Two existing compilations of sustainability definitions were used as the core sample for content analysis. These compilations were supplemented by definitions culled from other literature reviewed for this dissertation. The existing sets of sustainability definitions were compiled by Pezzey (1989) and DuBose (1995). Neither of these researchers claims that their compilations is exhaustive; however, both express the opinion that their sets are representative of the various perspectives on sustainability documented in the literature.

A complete listing of the definitions and sources used for this content analysis is provided as an attachment to this appendix, along with the coded information developed for each definition as described in the following section.

B.2.3 Coding of Samples

Within each sampling unit or definition of sustainability, smaller propositional units were identified, in the following form:

Variable|Objective|Mechanism

For the purposes of this analysis, a variable is a "quantity capable of assuming any of a set of values" (AHCD 1993), in which the objective for that variable is the desired value of the set of possible values. For example, one variable from the Liverman et al. definition of sustainability is "quality of human life" (1988). The objective in this definition is "beyond mere biological survival", which is a threshold of acceptability rather than a discrete value. Mechanisms are tools, strategies, or actions which are proposed by the various authors to achieve the objective values for the variables. In the Liverman et al. definition, the mechanisms for achieving quality of human life beyond mere biological survival are "maintenance of basic life support systems" and "the existence of infrastructure and institutions which distribute and protect the components of these systems".

As shown by the Liverman et al. definition, sometimes mechanisms can yield subvariables and objectives of their own. Table B.1 contains the propositional units extracted from the Liverman et al. definition of sustainability, illustrating how mechanisms can be broken down into propositional units of their own.

Table B.1: Propositional Units from the Liverman et al. definition (1988)

Variable	Objective	Mechanism
Human species	Indefinite survival	Maintenance of life support systems
Quality of human life	More than mere biological survival	Not Specified
Human survival	Quality	Maintenance of life support systems
Human survival	Quality	Existence of infrastructure and institutions which distribute and protect life support systems
Air systems	Maintenance	Protection
Water systems	Maintenance	Protection
Land systems	Maintenance	Protection
Biota	Maintenance	Protection

This example shows how the subvariables of "air systems", "water systems", "land systems", and "biota" are subject to the objective of "maintenance" as a result of the necessity of maintenance of these systems to achieve the objective of indefinite survival for the variable "human species".

B.3. Hierarchical Organization of Content Outputs

The propositional units derived from the literature can be organized into four categories: Human-Related Variables, Resource-Related Variables, Ecosystem-Related Variables, and Economic-Related Variables. A complete listing of the coded propositional units derived from the sample set of sustainability definitions is shown in Tables B.2 through B.5, sorted into the four categories.

Table B.2: Propositional Units for Human-Related Variables

Variables	Objectives	Mechanisms
Humans	Progress	Development
	"Virtually all live to adulthood, once born"	
Human individuals	Flourish	
Human species	Indefinite survival	
Human survival	Quality	Maintenance of life support systems
	Quality	Existence of infrastructure & institutions which distribute & protect life support systems
Human life	Supported at specified level of well-being	Existence of supporting ecological conditions
World's people	Stable prosperity	Nurturing and safeguarding environment
Present needs (of humans)	Met	Utilization of ecosystem or species resources
Immediate human needs	Met	
Needs and aspirations of present generations	Met	Sustainable development
Societal needs and dependencies	Met	Utilization of ecosystem or species resources
	Met	Economic exchanges
Present Humans	Optimization of economic and societal benefits	
	Don't impoverish future generations	
	Satisfaction	
	Equity	Self-reliance
		Participation
Future needs (of humans)	Ability to be met	
Long-term human needs	Met	
Needs of future generations	Ability to be met	Sustainable development
Between generations	Social Equity	
Within generations	Social Equity	Poverty alleviation
Each generation	Equal access to the resource base	
Future humans	Maintain potential for economic and social benefits	
Future generations	Should not inherit unacceptable risks of death	Potential constraints on primary freedoms of present and future generations
	No worse off than present gens	Environmental management
	Maintain options	Conserve plant and animal species
	Respect rights	Institutions and policies
	As well off as present gens	Preserve capacity
	Don't imperil welfare	
	Well-being	Leave capacity
Future options	Preserve	[Appropriate] human conduct
Human needs	Satisfaction	Sustainable development

Table B.2 (cont'd.): Propositional Units for Human-Related Variables

Variables	Objectives	Mechanisms
Human needs	Food for all	
	Health control for all	
	Appropriate technology	
	Self-reliance for all	
	Clean water for all	
	Shelter for all	
Human self-interest	Long term	
Human welfare	Maximize	Utilize available resources
	Steadily increase	
	Sustained	Sustained productive economic capacities
Initiatives (human actions)	People-centered	
Human time	Sustainability	Exact less
Human wealth	Sustainability	Exact less
Human maintenance	Sustainability	Exact less
Human participation	Sustainability	"Demand more, and provide opportunities"
Human cooperation	Sustainability	"Demand more, and provide opportunities"
Human civicness	Sustainability	"Demand more, and provide opportunities"
Transport		Environmental protection
Social systems	Coevolution with ecological systems	
Quality of human life	Improvement	Sustainable development
	> "mere biological survival"	
Poverty	Alleviation	"[O]verriding priority given"
	Alleviation	Sustainable economic growth
	Reduced	Providing lasting and secure livelihoods
Living standards (future)	Not impaired by current decisions	
Culture	Minimize disruption	Develop
Local Culture	Respect	Human actions
Diversity	Value	
Society	Minimize instability	
Structure of Society	Respect	Human actions
Values of the people	Respect	Human actions
Persons and Communities	Indefinitely prolonged	
	Nourished	
	Self-actualizing	
Productivity	No reduction in the long run	
Human activities	Effects remain bounded so as not to destroy ecosystems	
Problem Solutions	Sustainable and Ecoregion-specific	Incorporating cultural data

Table B.3: Propositional Units for Resource-Related Variables

Variables	Objectives	Mechanisms
Energy		Env'l protection
Consumption standards	"[W]ithin the bounds of the ecological possible"	Promotion of values
	"[T]o which all can reasonably aspire"	
Living resources and source ecosystems	Meet human needs	Sustainable utilization
Environmental assets	Hold constant	
Resources	Use within availability	
	Minimize depletion	
	< managed or natural regeneration rates	Harvest
	Generation	Ecosystems
	Optimize	Sustainable use rates
	Live off dividend	
	Population well-being	Change in resource management practice
	Does not reduce future real income	Use
Natural resources	Avoid degradation	
	Meet human needs (implied)	Sustainable use over time
	Allocation	Conservation
Asset base	Maintain and improve	Can change over time
Stock Resources	Reallocate toward future	Use
	No decline	
Renewable natural resources	Non-degrading use	
Renewable resource base	Preservation	Resource use
Non-renewable mineral resources	Minimize entropy gain	Use
		Recycle
		Any use is unsustainable....
Self-exhaustible resources		Substitute with renewables
Non-renewable energy resources	Orderly societal transit'n to renewable sources	"Use at slow enough rate"
Energy	Within solar budget	All use
Natural resource base	Undeteriorating	Sustainable dev't
Natural capital stock	Constancy	Hold constant

Table B.4: Propositional Units for Ecosystem-Related Variables

Variables	Objectives	Mechanisms
Agriculture	Sustained	Environmental protection
Local Conditions	Value	
Ecological systems	Human system coevolution	
Ecological means	Consumption within limits	
Ecological processes/systems	Sustained regen. capacities	
Plant and animal species	Avoid extinction or loss	Conservation
	Maintain presence	
	Self-renewal	Sustainable utilization
Biota	Diversity	Slow loss
	Maintenance	Protection
Self-organizing ecosystems	Health and integrity	Do not destroy
Genetic diversity	Preserve	
Nature	Rights respected	
Environment	Minimize degradation	Protection
	"Humans take only within self-perpetuating limits"	
	Purging of toxins	
	Improvement	Economic growth
	Health	
Land, water, soil, fuel		Demand less
Living rscs/source ecosystems	Meet human needs	Sustainable utilization
Essential ecological processes and life support systems	Maintain	
Environmental "services"		Use over indefinite time
Environmental assets	Hold constant	
Environmental quality	No degradation	
Soil and soil quality	Non-negative changes/no decline	
Ground /surface water quality	Non-negative changes	
Land biomass	Non-negative changes	
Water biomass	Non-negative changes	
Waste assimilation capacity of receiving environments	Non-negative changes	
Trees	No decline	
Air systems	Maintenance	Protection
Water systems	Maintenance	Protection
	No decline	
Land systems	Maintenance	Protection
Living matter	Survival	
Biosphere	Protection	Sustainable modification
Biosphere components	Persistence of all	
Food	Maintain presence	
Life on Earth	Sustainability	Nourished and perpetuated
Global environment	Avoid destruction	
	Meet human needs (implied)	Sustainable use over time
Problem Solutions	Ecoregion-specific	Incorporating ecological data
Waste	< natural or managed assimilation rates	Environment as "sink"
Global climate	Curb changes	

Table B.5: Propositional Units for Economics-Related Variables

Variables	Objectives	Mechanisms
Economy	Sustainable growth	Environmental protection
	Development	Environmental protection
	Trade	Environmental protection
	Economic planning	Environmental protection
	Subject to constancy of natural capital stock	Change
	Fluctuate with social goals	
	Resilience to external shocks	
	Health	
	Supportable by physical and social environments	Growth
	Grow within limits of planet	
Economic growth	Environmentally sustainable	
Economic well-being	Reasonable, equitably distr.	Sustainable development
Economic systems	Live off dividends of resources	Management
Development	Sustainable	Political reform
		Access to knowledge/resources
		Just & equitable distribut'n of wealth in/between nations
		Social/structural transform.
		Resource harvest
		Waste to ecosystems
		Resource gen./waste sinks
		Worldwide political will
		Government institutions
		Economic change
		Intragenerational equity
		Help to keep poor people from destroying environment
	Greater real income	
	Better health/nutrition	
	Education	
	Resource access	
	Fairer distribution of income	
	Increases in basic freedoms	
	Grow monotonically over time	
	Self-reliant	
	Within natural rsc. limits	
	Cost-effective	Use fair economic criteria
	Maintain env'l quality	
	Long run productivity	
	Holistic	
Real income	Raise	Environmental inputs/quality
	Growth without depleting capital or env'l asset stock	Policy
	Not reduced in future	
Present value	Maximized	

Each set of propositional units contains variables with varying degrees of overlap and specificity. The four categories were determined by inspection after a review of the complete list of propositional units. A hierarchy of the four categories of sustainability variables is shown in Figure B.1.

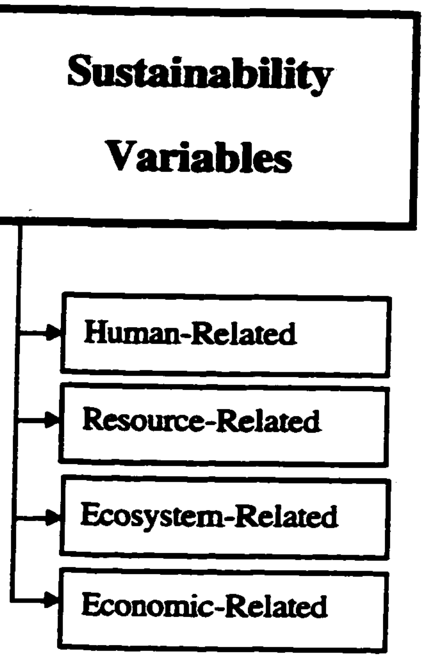


Figure B.1: Four Classes of Sustainability Variables

The four classes of sustainability variables are presented in hierarchical form in Chapter 4, along with a discussion of the variability and gaps within existing definitions of sustainability.

LISTING OF THE DEFINITIONS AND SOURCES USED FOR THE CONTENT ANALYSIS

Definition	Source
"We came to see that a new development path was required, one that sustained human progress not just in a few places for a few years, but for the entire planet into the distant future. Thus 'sustainable development' becomes a goal not just for the 'developing' nations but for industrial ones as well." (4)	WCED - World Commission on Environment and Development. (1987). *Our Common Future*. Oxford University Press, Great Britain. [Pezzey 1989].
"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs." (43)	WCED - World Commission on Environment and Development. (1987). *Our Common Future*. Oxford University Press, Great Britain. [Pezzey 1989].
"Living standards that go beyond the basic minimum are sustainable only if consumption standards everywhere have regard for long-term sustainability. Yet many of us live beyond the world's ecological means, for instance in our patterns of energy use. Perceived needs are socially and culturally determined, and sustainable development requires the promotion of values that encourage consumption standards that are within the bounds of the ecological possible and to which all can reasonably aspire." (44)	WCED - World Commission on Environment and Development. (1987). *Our Common Future*. Oxford University Press, Great Britain. [Pezzey 1989].
"Economic growth and development obviously involve changes in the physical ecosystem. Every ecosystem everywhere cannot be preserved intact." (45)	WCED - World Commission on Environment and Development. (1987). *Our Common Future*. Oxford University Press, Great Britain. [Pezzey 1989].
"The loss [i.e., extinction] of plant and animal species can greatly limit the options of future generations, so sustainable development requires the conservation of plant and animal species." (46)	WCED - World Commission on Environment and Development. (1987). *Our Common Future*. Oxford University Press, Great Britain. [Pezzey 1989].
"...satisfy the multiple criteria of sustainable growth, poverty alleviation, and sound environmental management." (10)	World Bank. (1987). *Environment, growth and development*. Development Committee Pamphlet 14, World Bank, Washington, DC. [Pezzey 1989].
"To a large degree, environmental management should be seen as a means of attaining the wider objectives of sustained economic growth and poverty alleviation."	World Bank. (1987). *Environment, growth and development*. Development Committee Pamphlet 14, World Bank, Washington, DC., p. 18. [Pezzey 1989].

Definition	Source
"...elevating concern about environmental matters...and developing the capacity to implement sound practices for environmental management...are [both] needed to reconcile, and, where appropriate, make tradeoffs among the objectives of growth, poverty alleviation, and sound environmental management." (28)	World Bank. (1987). *Environment, growth and development*. Development Committee Pamphlet 14, World Bank, Washington, DC. [Pezzey 1989].
"Sustainable utilization is a simple idea: we should utilize species and ecosystems at levels and in ways that allow them to go on renewing themselves for all practical purposes indefinitely." (18)	Allen, R. (1980). *How to Save the World*. Barnes & Noble Books, Totwa, NJ. [Based on IUCN 1980]. [Pezzey 1989].
"The importance of ensuring that utilization of an ecosystem or species is sustainable varies with a society's dependence on the resource in question. For a subsistence society, sustainable utilization of most, if not all its living resources is essential. ... The greater the diversity and flexibility of the economy, the less the need to utilize certain resources sustainably but by the same token the less the excuse not to." (18)	Allen, R. (1980). *How to Save the World*. Barnes & Noble Books, Totwa, NJ. [Based on IUCN 1980]. [Pezzey 1989].
"...it is essential...to ensure that...people protect those parts of the biosphere that need protecting and modify the rest only in ways that it can sustain." (20)	Allen, R. (1980). *How to Save the World*. Barnes & Noble Books, Totwa, NJ. [Based on IUCN 1980]. [Pezzey 1989].
"sustainable development - development that is likely to achieve lasting satisfaction of human needs and improvement of the quality of human life." (23)	Allen, R. (1980). *How to Save the World*. Barnes & Noble Books, Totwa, NJ. [Based on IUCN 1980]. [Pezzey 1989].
"The Commission defined sustainable development as meeting the needs and aspirations of present generations without compromising the ability of future generations to meet their needs. It requires political reform, access to knowledge and resources, and a more just and equitable distribution of wealth within and between nations...."	Brundtland, G.H. (1989). "Protecting the Global Commons," *Earth Ethics*, Fall, 12.
"Ecologically sustainable development can then be thought of as changes in economic structure, organization and activity of an economic ecological system that are directed towards maximum welfare and which can be sustained by available resources." (271)	Braat, L.C., and Steetskamp, I. (1991). "Ecological-Economic Analysis for Regional Sustainable Development," in *Ecological Economics*, R. Costanza, ed. Columbia University Press, New York, pp. 269-288.
"Sustainable development describes a process in which the natural resource base is not allowed to deteriorate. It emphasizes the hitherto unappreciated role of environmental quality and environmental inputs in the process of raising real income and the quality of life." (8)	Pearce, D.W., Warford, J.J. (1993). *World Without End*. Oxford University Press, Washington, DC.

Definition	Source
"In order to break its association with a limited, instrumental view of conservation and development, and in order to suggest some of the positive moral dimensions of the new social paradigm, most of our authors grope for a richer symbolic language with which to speak about the concept of sustainable development -- 'authentic integral development'..., 'ecological/holistic world view'..., 'reverential development' ..., 'ecosophical development' (Naess), 'noosphere'..., 'just, participatory ecodevelopment'..., 'communalism'..., 'desirable society'..." (10)	Engel, J.R. (1990). "Introduction: The Ethics of Sustainable Development," in *The Ethics of Environment and Development*, J. Engel and J.G. Engel, eds. University of Arizona Press, Tucson. 1-23.
Ignacy Sachs gave this definition in 1974: "A style of development that, in each ecoregion, calls for specific solutions to the particular problems of the region in light of cultural as well as ecological data and long-term as well as immediate needs." (186)	Hettne, B. (1990). *Development Theory and the Three Worlds*. John Wiley & Sons, New York.
"Sustainable economic development....In general terms, the primary objective is reducing the absolute poverty of the world's poor through providing lasting and secure livelihoods that minimize resource depletion, environmental degradation, cultural disruption, and social instability." (103)	Barbier, E.B. (1987). "The Concept of Sustainable Economic Development," *Environ. Conserv.*, 14(2), 101-110.
"Sustainable development is here defined as a pattern of social and structural economic transformations (i.e., 'development') which optimizes the economic and societal benefits available in the present, without jeopardizing the likely potential for similar benefits in the future. A primary goal of sustainable development is to achieve a reasonable (however defined) and equitably distributed level of economic well-being that can be perpetuated continually for many human generations." (36)	Goodland, R., and Ledec, G. (1987). "Neoclassical Economics and Principles of Sustainable Development," *Ecological Modeling*, 38, 19-46.
"...sustainable development implies using renewable natural resources in a manner which does not eliminate or degrade them, or otherwise diminish their usefulness for future generations......Sustainable development further implies using non-renewable (exhaustible) mineral resources in a manner which does not unnecessarily preclude easy access to them by future generations...... Sustainable development also implies depleting non-renewable energy resources at a slow enough rate so as to ensure the high probability of an orderly societal transition to renewable energy sources." (37)	Goodland, R., and Ledec, G. (1987). "Neoclassical Economics and Principles of Sustainable Development," *Ecological Modeling*, 38, 19-46.

Definition	Source
"Environmental protection is integral to issues such as trade, development, energy, transport, agriculture and economic planning. Therefore, environmental considerations must be taken into account in economic decision-making. ... In order to achieve sustainable development, we shall ensure the compatibility of economic growth and development with the protection of the environment. Environmental protection and related investment should contribute to economic growth..." (paragraph 37 of Paris Summit Communiqué)	Group of Seven. (1989). Communiqué from the 15th Annual Economic Summit in Paris. *New York Times*, 17 July 1989, p. A5. [Pezzey 1989].
"...activities should be considered that would be aimed at maintaining over time a constant effective natural resource base. This concept was proposed by Page (1977) and implies not an unchanging resource base but a set of resource reserves, technologies, and policy controls that maintain or expand the production possibilities of future generations." (337)	Howe, C.W. (1979). *Natural Resource Economics - Issues, Analysis and Policy*. John Wiley & Sons, New York, NY. [Pezzey 1989].
"In simple terms [sustainable development] argues for (a) development subject to a set of constraints which set resource harvest rates at levels no higher than managed or natural regeneration rates; and (b) use of the environment as a 'waste sink' on the basis that waste disposal rates should not exceed rates of (natural or managed) assimilation by the counterpart ecosystem." (58)	Pearce, D. (1988). "Optimal Prices for Sustainable Development," in *Economics, Growth, and Sustainable Environments*, D. Collard, D. Pearce, and D. Ulph, eds. St. Martin's Press, New York. [Pezzey 1989].
"A major challenge in the coming decades is to learn how long-term, large-scale interactions between environment and development can be better managed to increase the prospects for ecologically sustainable improvements in human well-being." (5)	Clark, W.C. and Munn, R.E. (1986). *Sustainable Development of the Biosphere*. Cambridge University Press, Cambridge, UK. [Pezzey 1989].
"[The] sustainable society is one that lives within the self-perpetuating limits of its environment. That society...is not a 'no-growth' society. ... It is, rather, a society that recognizes the limits of growth...[and] looks for alternative ways of growing." (1)	Coomer, J.C. (1979). "The nature of the quest for a sustainable society." In Coomer, J.C., ed. *Quest for a Sustainable Society*. Pergamon Press, New York. [Pezzey 1989].
"Socially sensitive interpretations of sustainable development emphasize the opportunity for a return to community values, local control over resources, community-based development and other forms of decentralized government..." (22)	Rees, W.E. (1990). "The Ecology of Sustainable Development," *The Ecologist*, 20(1), 18-23.
"...in order for a course of action to be sustainable it should be compatible with the local culture by respecting the structure of the society and values of the people..." (114) - p.7 in DuBose 1994	Dower, N. (1992). "Sustainability and the Right to Development," in *International Justice and the Third World*, Attfield, R., and Wilkins, B., eds. Routledge Publishing, New York. [DuBose 1994]

Definition	Source
"But there are also some basic requirements to reach ... a situation [of sustainable development]. First of all, there should be a worldwide political will to attain a sustainable development. One cannot expect this will to exist in a world of poverty, so that sustainable development requires an equity oriented policy." (88)	Nijkamp, P. and Soeteman, F. (1988). "Ecologically sustainable economic development: key issues for strategic environmental management." *International Journal of Social Economics*, 15(3/4), 88-102. [Pezzey 1989].
"If sustainable development is to be achieved, we will have to devise institutions, at all levels of government, to reallocate the use of stock resources towards the future, curb the pace and disruption of global climatic changes, reverse the accumulation of toxins in the environment and slow the loss of biological diversity. These are the key resource and environmental issues that must be addressed." (608)	Norgaard, R.B. (1988). "Sustainable development: a coevolutionary view." *Futures*, 20(6), December, 606-620. [Pezzey 1989].
"Until the use of hydrocarbons, development was a process of social system and ecosystem coevolution that favoured human welfare. ...Obviously this coevolutionary process did not result in sustainable development for all societies. Many suffered, some were overtaken by others and the welfare of the survivors did not steadily increase. But at least those societies which historically met their demise did not take the global environment with them." (617)	Norgaard, R.B. (1988). "Sustainable development: a coevolutionary view." *Futures*, 20(6), December, 606-620. [Pezzey 1989].
"In simple terms [sustainable development] argues for (a) development subject to a set of constraints which set resource harvest rates at levels no higher than managed or natural regeneration rates; and (b) use of the environment as a 'waste sink' on the basis that waste disposal rates should not exceed rates of (natural or managed) assimilation by the counterpart ecosystems. ... ... There are self-exhaustible resources, so that 'sustainabilitists' tend to think in terms of a resource set encompassing substitution between renewables and exhaustibles. Equally self-evident is the implicit assumption that sustainability is a 'good thing' - that is optimizing within sustainable use rates is a desirable objective. On these terms, sustainability could imply use of environmental services over very long time periods and, in theory, indefinitely." (58)	Pearce, D.W. (1988). "Optimal prices for sustainable development." in Collard, D., Pearce, D., and Ulph, D., eds. *Economics, Growth and Sustainable Environments*. St. Martin's Press, New York. [Pezzey 1989].

Definition	Source
"Sustainable development is categorized by economic change subject to 'constancy of the natural capital stock' - the stock of environmental assets is held constant while the economy is allowed whatever social goals are deemed appropriate. Such a rule, which has its own difficulties, accommodates the main concerns of the advocates of sustainability - equity between generations, equity within a generation, economic resilience to external shocks, and uncertainty about the functions and values of natural environments in social systems. It may also accommodate some of the concerns of the 'deep ecology' movement by respecting rights in nature." (598)	Pearce, D.W. (1988). "Economics, equity and sustainable development." *Futures*, 20(6), December, 598-605. [Pezzey 1989].
"We take development to be a vector of desirable social objectives, and elements might include: - increases in real income per capita - improvements in health and nutritional status - educational achievement - access to resources - a 'fairer' distribution of income - increases in basic freedoms. ...Sustainable development is then a situation in which the development vector increases monotonically over time." (4)	Pearce, D.W., Barbier, E., and Markandya, A. (1988). *Sustainable development and cost benefit analysis*. LEEC Paper 88-03, IIED/UCL London Environmental Economics Centre, 3 Endsleigh St., London WC1. [Pezzey 1989].
"We summarize the necessary conditions [for sustainable development] as 'constancy of the natural capital stock'. More strictly, the requirement is for non-negative changes in the stock of natural resources such as soil and soil quality, ground and surface water and their quality, land biomass, water biomass and the waste assimilation capacity of receiving environments." (6)	Pearce, D.W., Barbier, E., and Markandya, A. (1988). *Sustainable development and cost benefit analysis*. LEEC Paper 88-03, IIED/UCL London Environmental Economics Centre, 3 Endsleigh St., London WC1. [Pezzey 1989].
"Over the last decade or so international attention has increasingly become focused on the problem of ensuring that modern development on this planet takes place at a pace which the earth's environment can sustain. ... Economic growth is a necessary precondition for environmental improvement but it is possible and necessary to plan for economic growth which is environmentally sustainable."	Ridley, N. (1989). *Policies against Pollution: The Conservative Record - and Principles*. Centre for Policy Studies, London. [Pezzey 1989].
"...the health of the economy and the health of our environment are totally dependent upon each other. The [British] Government espouses the concept of sustainable economic development. Stable prosperity can be achieved throughout the world provided the environment is nurtured and safeguarded."	Thatcher, M. (1988). Speech at 1988 Royal Society Dinner (September). [Pezzey 1989].

Definition	Source
"In broad terms the concept of sustainable development encompasses: (1) help for the very poor because they are left with no option other than to destroy their environment; (2) the idea of self-reliant development, within natural resource constraints; (3) the idea of cost-effective development using different economic criteria to the traditional approach; that is to say development should not degrade environmental quality, nor should it reduce productivity in the long run; (4) the great issues of health control, appropriate technologies, food, self-reliance, clean water, and shelter for all; (5) the notion that people-centred initiatives are needed; human beings, in other words, are the resources in the concept." (98)	Tolba, M.K. (1987). *Sustainable Development: Constraints & Opportunities*. Butterworth-Heinemann, London, UK. [Pezzey 1989].
"The current state of scientific knowledge ... leads inexorably to the conclusion that anyone driven by either long-term self-interest, or concern for poverty, or concern for intergenerational equity should be willing to support the operational objectives of sustainable development." (p. 17, paraphrasing Repetto 1986)	Lele, S.M. (1990). "Sustainable Development: A Critical Review," *World Development*, forthcoming. [Pezzey 1989].
"The precise meaning of terms such as 'sustainable resource usage', sustainable growth' and 'sustainable development' has so far proved elusive." (5)	Turner, R.K. (1988). "Sustainability, resource conservation and pollution control: an overview." In Turner, R.K., ed. *Sustainable Environmental Management: Principles and Practice*. Belhaven Press, London. [Pezzey 1989].
"The World Conservation Strategy...gave considerable prominence to the sustainability concept, although its precise meaning and practical applications were not presented in a detailed and operational form." (576)	Turner, R.K. (1988). "Sustainable global futures - common interest, interdependency, complexity and global possibilities." *Futures* 19(5), 574-582. [Pezzey 1989].
"Two principles of 500-year planning: Principle 1: Future generations should not inherit, from present generations, unacceptable risks of death owing to environmental or other preventable catastrophes. Principle 2: Future, as well as present, generations may inherit constraints on their primary freedoms as sacrifices for enjoying the conditions of Principle 1."	Tonn, B.E. (1989). Cited in [Pezzey 1989].
"The sustainability criterion suggests that, at a minimum, future generations should be left no worse off than current generations." (33)	Tietenberg, T.H. (1984). *Environmental and Natural Resource Economics*. Scott, Foresman & Co., Glenview, IL. [Pezzey 1989].

Definition	Source
"Conservation has three basic objectives: (1) To maintain essential ecological processes and life support systems. (2) To preserve genetic diversity. (3) To ensure that the utilization of living resources and the ecosystems in which they are found, is sustainable." (4)	Talbot, L.M. (1984). "The World Conservation Strategy." In Thibodeau, F.R. and Field, H.H., *Sustaining Tomorrow - A Strategy for World Conservation and Development*. University Press of New England. [Pezzey 1989].
"...a society that invests in reproducible capital the competitive rents on its current extraction of exhaustible resources, will enjoy a consumption stream constant in time. ...this result can be interpreted as saying that an appropriately defined stock of capital - including the initial endowment of resources - is being maintained intact, and that consumption can be interpreted as the interest on that patrimony." (141)	Solow, R.M. (1986). "On the intergenerational allocation of natural resources." *Scandinavian Journal of Economics*, 88(1), 141-149. [Pezzey 1989].
"...the main text [of WCED 1987] combines views that have often been regarded as hard to reconcile. Traditional objectives of economic growth are believed to be compatible with sustainability. In fact, the position taken by the Commission is that a high level of GNP growth will facilitate the transition towards sustainability." (20)	Soderbaum, P. (1988). "Sustainable development - a challenge to our world views and ideas of economics." In Stockhold Group for Studies on Natural Resource Management, *Perspectives of Sustainable Development: Some Critical Issues Related to the Brundtland Report*. SGN, Stockholm. [Pezzey 1989].
"[Sustainable growth] means economic growth that can be supported by physical and social environments in the foreseeable future. An ideal sustainable society would be one in which all energy would be derived from current solar income and all non-renewable resources would be recycled." (10f)	Pirages, D.C. (1977). "A social design for sustainable growth." in Pirages, D.C., ed. *The Sustainable Society - Implications for Limited Growth*. Praeger, New York. [Pezzey 1989].
"The core of the idea of sustainability, then, is the concept that current decisions should not impair the prospects for maintaining or improving future living standards. ... This implies that our economic systems should be managed so that we live off the dividend of our resources, maintaining and improving the asset base. This principle also has much in common with the ideal concept of income that accountants seek to determine: the greatest amount that can be consumed in the current period without reducing prospects for consumption in the future." (10)	Repetto, R. (1985). *The Global Possible - Resources, Development and the New Century*. Yale University Press, New Haven. [Pezzey 1989].
"All economic growth in the future must be sustainable: that is to say, it must operate within and not beyond the finite limits of the planet." (120)	Porritt, J. (1984). *Seeing Green - The Politics of Ecology Explained*. Basil Blackwell, Oxford. [Pezzey 1989].
"The sustainability criterion requires that the conditions necessary for equal access to the resource base be met for each generation." (13)	Pearce, D.W. (1987). "Foundations of an ecological economics." *Ecological Modeling* 38, 9-18. [Pezzey 1989].

Definition	Source
"The key concept [regarding natural resource degradation in developing countries] is 'sustainability'. Changes in resource management practice toward sustainable resource use could at least contribute to the preservation of the renewable resource base and hence to the direct well-being of the population and to the future of the macroeconomy." (102)	Pearce, D.W. (1988). "The sustainable use of natural resources in developing countries." in Turner, R.K., ed., *Sustainable Environmental Management: Principles and Practice*. Belhaven Press, London. [Pezzey 1989].
"We developed our own simple, anthropocentric working definition by which we mean sustainability to be the indefinite survival of the human species (with a quality of life beyond mere biological survival) through the maintenance of basic life support systems (air, water, land, biota) and the existence of infrastructure and institutions which distribute and protect the components of these systems." (133)	Liverman, D.M., Hanson, M.E., Brown, B.J., and Merideth, R.W., Jr. (1988). "Global Sustainability: Toward Measurement." *Environmental Management*, 12(2), 133-143.
"It may only be a matter of time before the metaphor of sustainability becomes so abused as to be meaningless, certainly as a device to straddle the ideological conflicts that pervade contemporary environmentalism." (29)	O'Riordan, T. (1988). "The politics of sustainability." In Turner, R.K., ed. *Sustainable Environmental Management: Principles and Practice*. Belhaven Press, London. [Pezzey 1989].
"Sustainability is a much broader phenomenon [than sustainable development], embracing ethical norms pertaining to the survival of living matter, to the rights of future generations and to institutions responsible for ensuring that such rights are fully taken into account in policies and actions." (30)	O'Riordan, T. (1988). "The politics of sustainability." In Turner, R.K., ed. *Sustainable Environmental Management: Principles and Practice*. Belhaven Press, London. [Pezzey 1989].
"...much of the desertification literature also suggests that desertification is nonoptimal from both the producer's and society's perspective. Sustainable use is generally put forward as the optimal strategy. [Morey then shows how sustainable land use may or may not be optimal.]" (551)	Morey, E.R. (1985)."Desertification from an economic perspective." *Ricerche Economiche*, 39(4), 550-560. [Pezzey 1989].
"The basic idea [of sustainability] is simple in the context of natural resources (excluding exhaustibles) and environments: the use made of these inputs to the development process should be sustainable through time. ....If we now apply the idea to resources, sustainability ought to mean that a given stock of resources - trees, soil quality, water and so on - should not decline." (9-10)	Markandya, A. and Pearce, D.W. (1988). "Natural environments and the social rate of discount." *Project Appraisal*, 3(1), 2-12. [Pezzey 1989].

Definition	Source
"In the narrowest sense, global sustainability means the indefinite survival of the human species across all the regions of the world. A broader sense of the meaning specifies that virtually all humans, once born, live to adulthood and that their lives have quality beyond mere biological survival. Finally the broadest sense of global sustainability includes the persistence of all components of the biosphere, even those with no apparent benefit to humanity." (717)	Brown, B.J., et al. (1987). "Global sustainability: toward definition." *Environmental Management*, 11(6), 713-719. [Pezzey 1989].
"...in a pedagogical sense sustainability requires that all processes operate only at their steady state, renewable level, which might then suggest a return to a regulated caveman culture." (323)	Burness, H.S. and Cummings, R.G. (1986). "Thermodynamic and economic concepts as related to resource-use policies: reply." *Land Economics*, 62(3), 323-324. [Pezzey 1989].
"'Sustainable', by definition, means not only indefinitely prolonged, but nourishing for the self-actualizing of persons and communities. The word 'development' need not be restricted to economic activity, much less to the kind of economic activity that now dominates the world, but can mean the evolution, unfolding, growth, and fulfillment of any and all aspects of life. Thus 'sustainable development', in the broadest sense, may be defined as the kind of human activity that nourishes and perpetuates the historical fulfillment of the whole community of life on earth." (10)	Engel, J.R. (1990). "Introduction: The Ethics of Sustainable Development," in *The Ethics of Environment and Development*, J. Engel and J.G. Engel, eds. University of Arizona Press, Tucson. 1-23.
"This chapter will address these two opposing meanings of 'sustainability' and their respective development paradigms. It will differentiate between sustainability as a narrow economic ideal and sustainability as an ethical ideal, between sustainability of privileges and sustainability of life on Earth." (28)	Kothari, R. (1990). "Environment, Technology, and Ethics," in *The Ethics of Environment and Development*, J. Engel and J.G. Engel, eds. University of Arizona Press, Tucson. 27-35.
"[I]t is an obligation to conduct ourselves so that we leave to the future the option or the capacity to be as well off as we are. It is not clear to me that one can be more precise than that. Sustainability is an injunction not to satisfy ourselves by impoverishing our successors...There is no specific object that the goal of sustainability, the obligation of sustainability, requires that we leave untouched." (181)	Solow, R.M. (1993). "Sustainability: An Economist's Perspective," in *Economics of the Environment: Selected Readings*. R. Dorfman and N.S. Dorfman, eds. W.W. Norton & Company, New York, 179-187.

Definition	Source
"While other attributes such as color or temperature can be ascribed to isolated objects, this is not the case with sustainability. It is somewhat of a misnomer to say that a technology in and of itself is sustainable. This is not to say that therefore nothing is sustainable or that sustainability can not occur – it is simply that our way of speaking of sustainability is imprecise and misleading. Sustainability does not describe a quality that resides within the confines of an individual technology or practice but refers instead to the nature of the relationship between the technology and its context." (14)	DuBose, J.R. (1994). *Sustainability as an Inherently Contextual Concept: Some Lessons from Agricultural Development.* Unpublished M.S. Thesis, School of Public Policy, Georgia Institute of Technology, Atlanta, GA.
"Even the narrow notion of physical sustainability implies a concern for social equity between generations, a concern that must logically be extended to equity within each generation." (43)	WCED - World Commission on Environment and Development. (1987). *Our Common Future.* Oxford University Press, Great Britain. [Pezzey 1989].
"The core of the idea of sustainability, then, is the concept that current decisions should not impair the prospects for maintaining or improving future living standards....This implies that our economic systems should be managed so that we live off the dividend of our resources, maintaining and improving the asset base....This does not mean that sustainable development demands the preservation of the current stock of natural resources or any particular mix of human, physical, and natural assets." (10)	Repetto, R. (1985). *The Global Possible - Resources, Development, and the New Century.* Yale University Press, New Haven, CT. [Pezzey 1989].
"The sustainable community, as the architect planner Sim Van der Ryn suggests, 'exacts less of its inhabitants in time, wealth, and maintenance, and demands less of its environment in land, water, soil, and fuel.' I would add that it also demands more of its inhabitants in terms of participation, cooperation, and civicness, and provides more opportunities for these as well." (2)	Veiderman, S. (1993). "The Economics and Economy of Sustainability; Five Capitals and Three Pillars." presented at the Delaware Estuary Program Conference on "Preserving Our Future", November 30, 1993, Philadelphia, PA.
"Sustainability is a relationship between dynamic human economic systems and larger, dynamic, but normally slower-changing ecological systems, such that human life can continue indefinitely, human individuals can flourish, and human cultures can develop--but also a relationship in which the effects of human activities remain within bounds so as not to destroy the health and integrity of self-organizing systems that provide the environmental context for these activities." (25)	Norton, B.G. (1992). "A New Paradigm for Environmental Management," in *Ecosystem Health: New Goals for Environmental Management,* R. Costanza, B.G. Norton, and B.D. Haskell, eds. Island Press, Washington, DC, 23-41.
"Sustainability within the economic paradigm is sustainability of human welfare through the sustenance of the productive capacities of the economy; sustainability in the ecological paradigm makes essential reference to crucial productive capacities of ecological processes and systems."	Norton, B.G. (1996). "Evaluating Ecosystem States: Two Competing Paradigms," *Ecological Economics.*

Definition	Source
"The market does not distinguish an ecologically sustainable scale of matter-energy throughput from an unsustainable scale, just as it does not distinguish between ethically just and unjust distributions of income. Sustainability, like justice, is a value not achievable by purely individualistic market processes." (320)	Daly, H.E. (1986). "Thermodynamic and economic concepts as related to resource-use policies: comment." *Land Economics*, 62(3). 319-322. [Pezzey 1989].
"By 'growth' I mean quantitative increase in the scale of the physical dimensions of the economy; ... By 'development' I mean the qualitative improvement in the structure, design and composition of physical stocks and flows, that result from greater knowledge, both of technique and of purpose." (323)	Daly, H.E. (1987). "The economic growth debate: what some economists have learned but many have not." *Journal of Environment and Economics Management*, 14(4), 323-336. [Pezzey 1989].
"... 'growth' is if you get just an increasing number of the same type of mail coaches. And if you pass from traveling in mail coaches to traveling by railway, that is 'development'." (294)	Georgescu-Roegen, N. (1988). "About economic growth - a variation on a theme by David Hilbert." *Economics and Development of Cultural Change*. 36(3) Supplement, S291-S307. [Pezzey 1989].
"[S]ustainability is by default taken to mean 'the existence of the ecological conditions necessary to support human life at a specified level of well-being through future generations, what I call 'ecological sustainability'."	Lele, S.M. (1990). "Sustainable Development: A Critical Review," *World Development*. [Pezzey 1989].
"In principle, such an optimal [sustainable growth] policy would seek to maintain an 'acceptable' rate of growth in per-capita real incomes without depleting the national capital asset stock or the natural environmental asset stock." (12)	Turner, R.K. (1988). "Sustainability, resource conservation and pollution control: an overview." In Turner, R.K., ed. *Sustainable Environmental Management: Principles and Practice*. Belhaven Press, London. [Pezzey 1989].
"It makes no sense to talk about the sustainable use of a non-renewable resource (even with substantial recycling effort and reuse rates). Any positive rate of exploitation will eventually lead to exhaustion of the finite stock." (13)	Turner, R.K. (1988). "Sustainability, resource conservation and pollution control: an overview." In Turner, R.K., ed. *Sustainable Environmental Management: Principles and Practice*. Belhaven Press, London. [Pezzey 1989].
"...in this [sustainable development] mode...conservation becomes the sole basis for defining a criterion with which to judge the desirability of alternative allocations of natural resources." (21)	Turner, R.K. (1988). "Sustainability, resource conservation and pollution control: an overview." In Turner, R.K., ed. *Sustainable Environmental Management: Principles and Practice*. Belhaven Press, London. [Pezzey 1989].
"Rather than eliminating the [positive] discount rate, the present-value criterion should be complemented by other criteria, such as sustainability. ....For example, we might choose to maximise present value subject to the constraint that future generations are not made worse off." (432)	Tietenberg, T.H. (1984). *Environmental and Natural Resource Economics*. Scott, Foresman & Co., Glenview, IL. [Pezzey 1989].
"This does not mean that sustainable development demands the preservation of the current stock of natural resources or any particular mix of human, physical and natural assets. As development proceeds, the composition of the underlying asset base changes." (10)	Repetto, R. (1985). *The Global Possible - Resources, Development and the New Century*. Yale University Press, New Haven. [Pezzey 1989].

Definition	Source
"There is broad agreement that pursuing policies that imperil the welfare of future generations, who are unrepresented in any political or economic forum, is unfair." (11)	Repetto, R. (1985). *The Global Possible - Resources, Development and the New Century*. Yale University Press, New Haven. [Pezzey 1989].
"...sustainability might be redefined in terms of a requirement that the use of resources today should not reduce real incomes in the future..." (11)	Markandya, A. and Pearce, D.W. (1988). "Natural environments and the social rate of discount." *Project Appraisal*, 3(1), 2-12. [Pezzey 1989].
"One can identify four primary criteria for sustainable development when it is conceived as an ethical ideal: a holistic view of development; equity based on the autonomy and self-reliance of diverse entities instead of on a structure of dependence founded on aid and transfer of technology with a view to 'catching up'; an emphasis on participation; and an accent on the importance of local conditions and the value of diversity." (34)	Kothari, R. (1990). "Environment, Technology, and Ethics," in The *Ethics of Environment and Development*, J. Engel and J.G. Engel, eds. University of Arizona Press, Tucson. 27-35.
"[Sustainability] can be accomplished by leaving adequate resources, be they natural or manmade....[G]oods and services can be substituted for one another...what we are obligated to leave behind is a generalized capacity to create well-being, not any particular thing or any particular natural resource."	Solow, R.M. (1993). "Sustainability: An Economist's Perspective," in *Economics of the Environment: Selected Readings*. R. Dorfman and N.S. Dorfman, eds. W.W. Norton & Company, New York, 179-187.
"...you are almost forced logically to think about equity not between periods of time but equity right now..." (185)	Solow, R.M. (1993). "Sustainability: An Economist's Perspective," in *Economics of the Environment: Selected Readings*. R. Dorfman and N.S. Dorfman, eds. W.W. Norton & Company, New York, 179-187.
"[S]ustainability is a vague concept. It is intrinsically inexact. It is not something that can be measured out in coffee spoons. It is not something that you could be numerically accurate about." (187)	Solow, R.M. (1993). "Sustainability: An Economist's Perspective," in *Economics of the Environment: Selected Readings*. R. Dorfman and N.S. Dorfman, eds. W.W. Norton & Company, New York, 179-187.
"No one element can by itself indicate sustainability; it is the nexus of relations between elements working in harmony that indicates sustainability -- like an equation for which an answer cannot be derived from one variable alone but requires the interaction of the variables for solution." (15)	DuBose, J.R. (1994). *Sustainability as an Inherently Contextual Concept: Some Lessons from Agricultural Development*. Unpublished M.S. Thesis, School of Public Policy, Georgia Institute of Technology, Atlanta, GA.

Definition	Source
"Like an equation in which the terms are multiplied by one another, many different values can be assigned to the variables while still yielding the same answer. Sustainability does not require a specific configuration of these variables (culture, environment and society) -- there are numerous and perhaps limitless possible ways in which they could interact sustainably. This is not to deny that there are perhaps some non-negotiable elements that would have to be present in any imaginable sustainability scenario such as air, water, food, and maybe even specific animal species. Even while recognizing that there are some essential elements in the equation the possible permutations are many."	DuBose, J.R. (1994). *Sustainability as an Inherently Contextual Concept: Some Lessons from Agricultural Development*. Unpublished M.S. Thesis, School of Public Policy, Georgia Institute of Technology, Atlanta, GA.
"Sustainability, I argue, is a community's control and prudent use of capital -- all forms of capital: natural capital, human capital, human-created capital, social capital, and cultural capital -- to ensure, to the degree possible, that present and future generations can attain a high degree of economic security and achieve democracy while maintaining the integrity of the ecological systems upon which all life and all production depends."	Veiderman, S. (1993). "The Economics and Economy of Sustainability; Five Capitals and Three Pillars." presented at the Delaware Estuary Program Conference on "Preserving Our Future", November 30, 1993, Philadelphia, PA.

APPENDIX C

MODEL DEFAULTS AND CALCULATIONS

The metric developed in this investigation requires knowledge or estimation of a significant amount of data to be applied. The purpose of this appendix is to show the default values used to populate the model in order to demonstrate its application in Chapter 6, along with the calculations used to transform the variables into a composite value of facility sustainability.

C.1. Stakeholder Satisfaction Variables and Calculations

Relevant subvariables for calculating stakeholder satisfaction are the degree to which each stakeholder expectation is met by the facility and the weight or relative importance assigned by the stakeholder to each expectation. The equation to calculate a value for this parameter was shown in Chapter 5, equation (6) as follows:

$$SS = \sum_{E_E} E_i w_i - \sum_{E_{NM}} E_j w_j$$

where

	i	=	Expectation that is exceeded
	w_i	=	Normalized weight of exceeded Expectation i
	j	=	Expectation that is not met
	w_j	=	Normalized weight of unmet Expectation j

Each of the variables for this parameter is queried directly from system stakeholders or some representative set thereof, and therefore no default values were needed for this parameter. The set of expectations used as a satisfaction scale to evaluate this parameter are shown in Table 5.3.

C.2. Resource Base Impact Variables and Calculations

As described in Chapters 5 and 6, the calculations to determine Resource Base Impact are based on default values describing the properties of the system itself, and the source and sink systems with which it is affiliated. Intra-System Resource Base Impact, while assumed to be zero for residential facilities, is dependent on the changes in quantities of resources on site times the significance of those resources in terms of the remaining capacity for each resource base affected. Likewise, Extra-System Resource Base Impact is based on the proportional quantity of all resource depletion or accumulation for a given source or sink system attributable to the facility system, times a significance factor for each resource considered. In the operationalization of sustainability developed in the dissertation, Extra-System Resource Base Impact is calculated as described in Chapter 6:

$$(RBI_E)_I = (Q * RBI_S/Q_T)_i$$

$$RBI_S \equiv I_{ST} * (\omega_{\Delta RB})_{ST}$$

where

$(RBI_E)_i$ = Extra-system Resource Base Impact for Flow *I*
RBI_S = Net Resource Base Impact for Source or Sink
I_{ST} = Unit load imposed by Source or Sink Technology
$(\omega_{\Delta RB})_{ST}$ = Significance of Imposed Unit Load

To evaluate a value for the Resource Base Impact parameter, Intra-system Resource Base Impact is assumed to be zero in the baseline state calculations, and was negligible or zero for all six improvement options considered in the case study. Thus, RBI is equal to the Extra-System Resource Base Impact as described by the preceding equation, and requires a knowledge of the variables Q, Q_T, I_{ST}, and $(\omega_{\Delta RB})_{ST}$. for each resource flow crossing the boundary of the system. Q, the quantity of a particular resource flow, can be either monitored directly or estimated as described in Appendix D. Likewise, Q_T is determined either by estimation or by direct inquiry of the source or sink system. This leaves I_{ST}, the Unit load imposed by the source or sink system, and $(\omega_{\Delta RB})_{ST}$, the significance of that imposed unit load. As described in Chapter 5, the set of all resource bases can be classified into five subsets of resource base types: Energy, Water, Nonrenewable Materials, Plants, and Animals. Table C.1 shows values for the unit loads in terms of these five components used for the purpose of the case study in Chapter 6. These values were estimated using the decision criteria shown in Chapter 5, Table 5.5, based on review of engineering handbooks providing lists and descriptions of typical impacts by industry sector (Metcalf & Eddy 1991; Tchobanoblous et al. 1993; Jain et al. 1993; Seinfeld 1986; Rosaler 1995; Merritt et al. 1996; Kalpakjian 1991).

The significance factor was calculated for each resource flow using the step function shown in Chapter 5, Figure 5.11, using Remaining Capacity values differentiated by United States bioregion as described in Chapter 5. Table C.2 shows these remaining capacities in terms of Resource Base classes.

The preceding values provide all necessary default values to determine Resource Base Impacts for the case study facility as described in Chapter 6 and Appendix D.

Table C.1: Default Resource Base Unit Loads for Source and Sink Technologies

		Resource Base Unit Loads for Technology				
Electricity	Ex-situ fossil	0.5	0	-1	0	0
Fresh Water	Ex-situ surface water	0	-0.5	0	-0.5	-0.5
Wood	Tree farm	-0.5	0	0	-0.5	-0.5
Steel	Mill - virgin	-1	-0.5	-1	0	0
Concrete	Concrete plant	-1	-0.5	-1	0	0
HVAC filters	Secondary mfg. Plant	-0.5	-0.5	-0.5	0	0
Incandescent light bulbs	Primary mfg. Plant	-0.5	-0.5	-1	0	0
Hot water heater jacket	Secondary mfg. Plant	-0.5	-0.5	-0.5	0	0
Fiberglass Insulation	Primary mfg. Plant	-0.5	-0.5	-1	0	0
Plants/Landscaping Materials	Nursery	0	-0.5	0	0.5	0
Gasoline (for lawn mower)	Refinery	-0.5	-0.5	-1	0	-0.5
Natural Gas	Refinery	-0.5	-0.5	-1	0	-0.5
Energy Saving Products	Recycler/Retrofitter	-0.5	-0.5	-0.5	0	0
Sealer/Stain	Chemical Factory	-0.5	-1	-1	0	-0.5
Pool Cover	Plastic manufacturer	-0.5	-0.5	-1	0	0
Pesticide	Chemical Factory	-0.5	-1	-1	0	-0.5
Chlorine	Chlorine Factory	-0.5	-1	-1	0	-0.5
Waste Water	POTW - Secondary	-0.5	0	-0.5	0.5	0
Mixed MSW	Sanitary Landfill	-0.5	0	0.5	-0.5	-0.5
Bagged Compostable Waste	Central Composting Facility	-0.5	-0.5	0	-0.5	-0.5

Table C.2: Remaining Capacity Default values for Resource Base Classes by Bioregion (drawn from Sierra Club 1997)

	Resource Base Load Bearing Capacity				
Bioregion					
Pacific Northwest	1	1	0	0	0
Pacific Coast	1	- 1	0	1	0
Sierra Nevada	1	1	0	1	1
Boreal Forest	0	1	1	1	1
Alaska Rainforest	0	1	1	1	1
Great Basin High Desert	0	- 1	1	- 1	- 1
Rocky Mountains	0	0	1	- 1	0
Colorado Plateau	1	0	0	0	0
Southwest Deserts	1	- 1	1	0	0
Great North American Prairie	0	- 1	1	1	1
Interior Highlands	0	0	0	1	0
American Southeast	0	1	1	1	1
Mississippi Basin	1	1	0	1	0
Great Lakes	0	1	0	0	0
South Appalachian Highlands	1	1	0	1	0
Central Appalachia	0	0	- 1	0	0
Northern Forest	0	0	0	- 1	0
Atlantic Coast	0	0	- 1	0	0

C.3. Ecosystem Impact Variables and Calculations

As described in Chapters 5 and 6, the calculations to determine Ecosystem Impact are based on default values describing the properties of the system itself, and the source and sink systems with which it is affiliated. Intra-System Ecosystem Impact is dependent on the changes in land use times the significance of those resources in terms of the remaining capacity for the location of the site, as described in Chapter 5. Likewise, Extra-System Ecosystem Impact is based on the proportional quantity of all changes to ecosystems for a given source or sink system attributable to the facility system, times a significance factor for each ecosystem affected.

In the operationalization of sustainability developed in the dissertation, Extra-System Ecosystem Impact is calculated as described in Chapter 6:

$$(EI_E)_I = (Q * EI_S/Q_T)_i$$

$$EI_S \cong I_{ST} * (\omega_{\Delta E})_{ST}$$

where

$(EI_E)_i$	=	Extra-system Ecosystem Impact for Flow *I*
EI_S	=	Net Ecosystem Impact for Source or Sink
I_{ST}	=	Unit load imposed by Source or Sink Technology
$(\omega_{\Delta E})_{ST}$	=	Significance of Imposed Unit Load

To evaluate a value for the Ecosystem Impact parameter, Intra-system Ecosystem Impact is calculated using the Land Use Calculator shown in Chapter 5, Section 5.3.4. Thus, EI is equal to the value for Intra-System Ecosystem Impact calculated by the proportions of land use on site plus Extra-System Ecosystem Impact as described by the preceding equation. Calculating Extra-System Impact requires a knowledge of the variables Q, Q_T, I_{ST}, and $(\omega_{\Delta E})_{ST}$ for each resource flow crossing the boundary of the system. Q, the quantity of a particular resource flow, can be either monitored directly or estimated as described in Appendix D. Likewise, Q_T is determined either by estimation or by direct inquiry of the source or sink system. This leaves I_{ST}, the Unit load imposed by the source or sink system, and $(\omega_{\Delta E})_{ST}$, the significance of that imposed unit load. As described in Chapter 5, the set of all ecosystems can be classified into five subsets of ecosystem indicators: Air Quality, Water Quality, Soil Quality, Flora Quality, and Faunal Quality. Table C.3 shows values for the unit loads in terms of these five components used for the purpose of the case study in Chapter 6. These values were estimated using the decision criteria shown in Chapter 5, Table 5.5, based on review of engineering handbooks providing lists and descriptions of typical impacts by industry sector (Metcalf & Eddy 1991; Tchobanoblous et al. 1993; Jain et al. 1993; Seinfeld 1986; Rosaler 1995; Merritt et al. 1996; Kalpakjian 1991).

The significance factor was calculated for each ecosystem impact using the step function shown in Chapter 5, Figure 5.11, using Remaining Capacity values differentiated by United States bioregion as shown in Chapter 5, Table 5.7. The preceding values provide all necessary default values to determine Ecosystem Impacts for the case study facility as described in Chapter 6 and Appendix D.

Table C.3: Default Ecosystem Unit Loads for Source and Sink Technologies

		Ecosystem Unit Loads for Technology				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Electricity	Ex-situ fossil	-1	-0.5	-0.5	-0.5	-0.5
Fresh Water	Ex-situ surface water	0	-0.5	-0.5	0	0
Wood	Tree farm	0.5	-0.5	-0.5	0	0
Steel	Mill - virgin	-0.5	-0.5	-0.5	-0.5	-0.5
Concrete	Concrete plant	-0.5	-0.5	0	-0.5	-0.5
HVAC filters	Secondary mfg. Plant	0	-0.5	0	0	0
Incandescent light bulbs	Primary mfg. Plant	-0.5	-0.5	-0.5	0	0
Hot water heater jacket	Secondary mfg. Plant	0	-0.5	0	0	0
Fiberglass Insulation	Primary mfg. Plant	-0.5	-0.5	-0.5	0	0
Plants/Landscaping Materials	Nursery	0.5	-0.5	0	0.5	0
Gasoline (for lawn mower)	Refinery	-1	-1	-0.5	-0.5	-0.5
Natural Gas	Refinery	-1	-1	-0.5	-0.5	-0.5
Energy Saving Products	Recycler/Retrofitter	0	0	0	0	0
Sealer/Stain	Chemical Factory	-1	-1	-1	-0.5	-0.5
Pool Cover	Plastic manufacturer	-1	-0.5	-0.5	-0.5	0
Pesticide	Chemical Factory	-1	-1	-1	-0.5	-0.5
Chlorine	Chlorine Factory	-1	-1	-1	-0.5	-0.5
Waste Water	POTW - Secondary	-0.5	1	-0.5	-0.5	-0.5
Mixed MSW	Sanitary Landfill	-0.5	-0.5	-1	-0.5	-0.5
Bagged Compostable Waste	Central Composting Facility	-0.5	-0.5	0.5	0	0

APPENDIX D

CASE STUDY DATA

The metric developed in this investigation was demonstrated in Chapter 6 using a case study of a real facility. The purpose of this appendix is to provide additional information about the case and show supporting calculations for the metric demonstration in Chapter 6. It describes the features of the case study facility, followed by a description of the assumptions and calculations to support inputs to the model for the demonstration.

D.1 Features of the Case Study Facility

The facility used to demonstrate the metric in this investigation was a single-family detached residence in suburban Atlanta, GA. The case study selected for this investigation is a single-family detached residence in Atlanta, GA. Permission to analyze the facility was obtained through a third party to reduce the potential for selection bias on the part of the investigator. Due to the potentially sensitive nature of some of the data needed to complete the survey (e.g., utility bills, store receipts, etc.), completely random sampling was not part of the research design. Based on preliminary discussion and qualitative assessment, the homeowner participating in the case study was only cursorily aware of the concept of sustainability with respect to built facilities.

The residence itself is a 1950's style structure, 4 bedroom, 2.5 bath house with in-ground pool and whirlpool in the back yard. The facility is approximately 10 years older than the median age of single-family detached residences in the United States (U.S. Department of Commerce 1993), and is comparable in terms of square footage, fixtures and finishes, landscaping, and other amenities to houses in the same neighborhood (as noted in the appraisal documents for the house). It places slightly higher than the average U.S. house in these terms (ibid.). Figure D.1 shows a photo of the front of the residence, and Figure D.2 shows the floor plans of the house. The house is situated in a subdivision in Decatur, GA, to the northeast of downtown Atlanta. It contains a sun porch and small deck area on the rear face (Figure D.3), and a hot tub and swimming pool in the back yard (Figure D.4). A secondary structure containing the pool pump and heater, along with an enclosed finished storage area, is also in the back yard (Figure D.5). A site visit was conducted in April 1998, including an informal interview and stakeholder satisfaction survey of the homeowner, flow data collection from historical records, survey of land uses on site, and assessment of on-site resource bases. The following subsections detail the information collected in each of these categories.

D.1.1 Stakeholder Interview and Satisfaction Survey

An informal interview was conducted with the owner of the house, who felt she was representative of the set of residents living in the home. The current number of residents in the house is seven, including three adults and four children. The homeowner completed the Stakeholder Satisfaction survey, the results of which are shown in Table D.1. She rated each item on a scale of 0 to 5 to indicate relative importance, with 0 indicating no importance and 5 indicating extremely important.

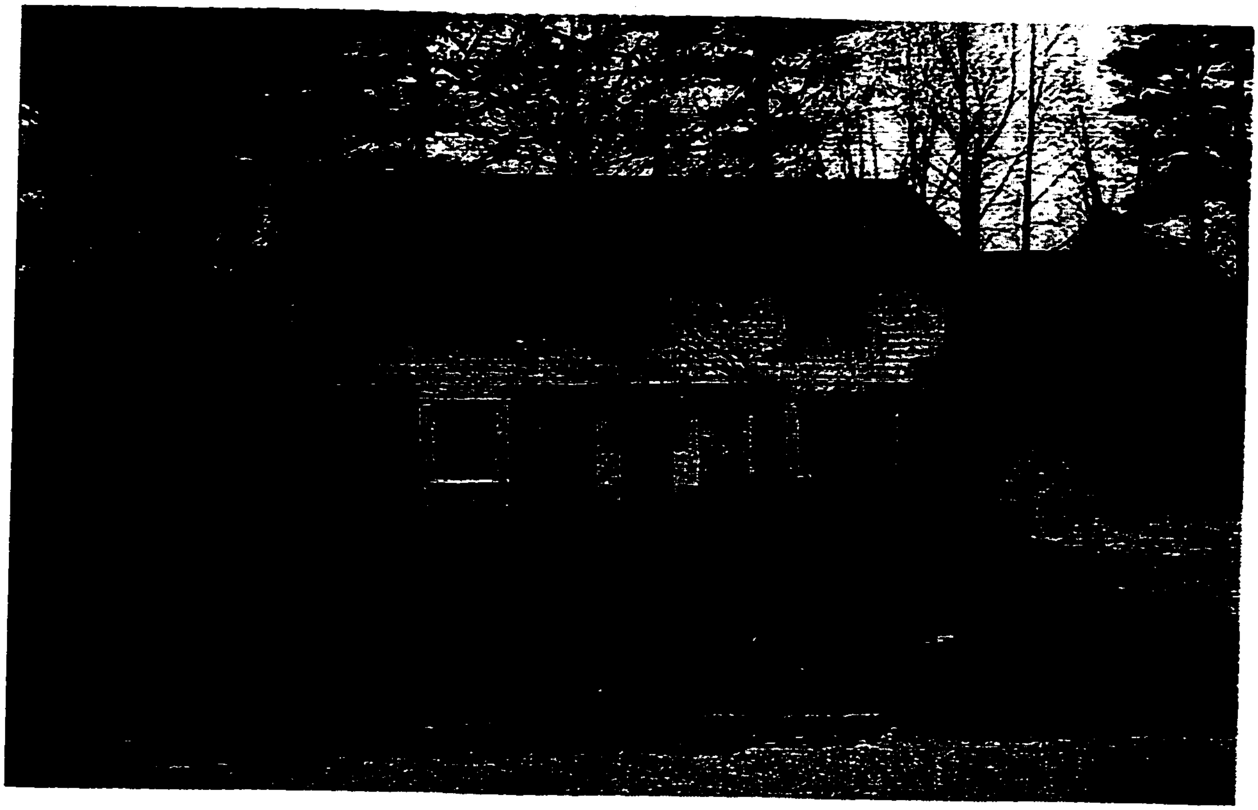


Figure D.1: Photo of the Front of the Case Study House

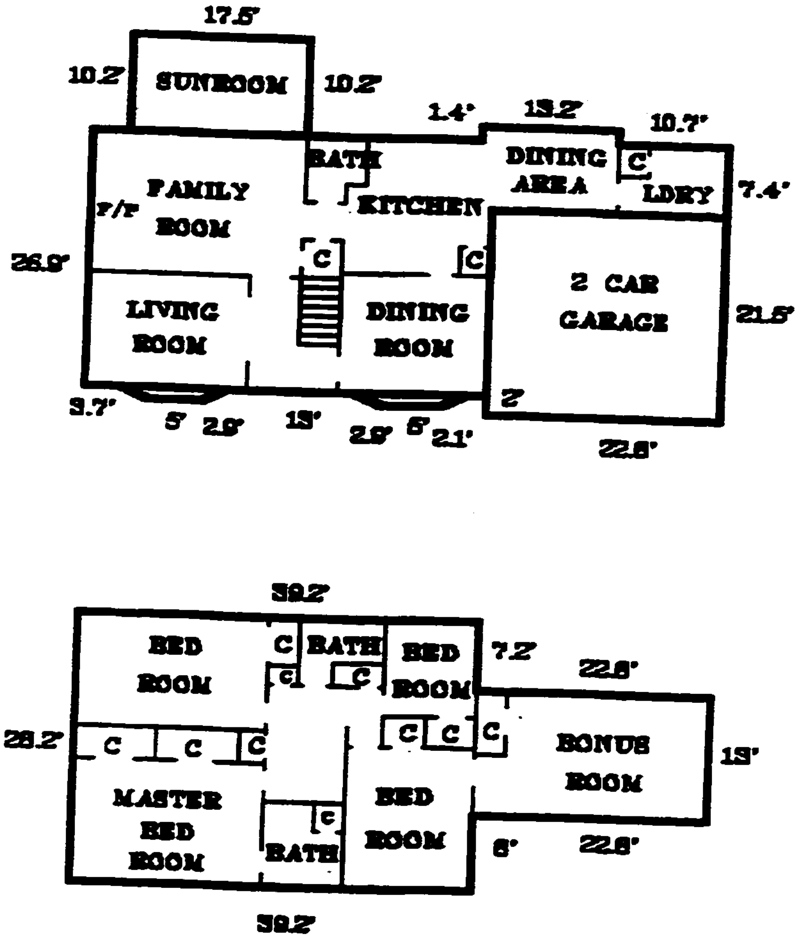


Figure D.2: Floor Plans of the Case Study House

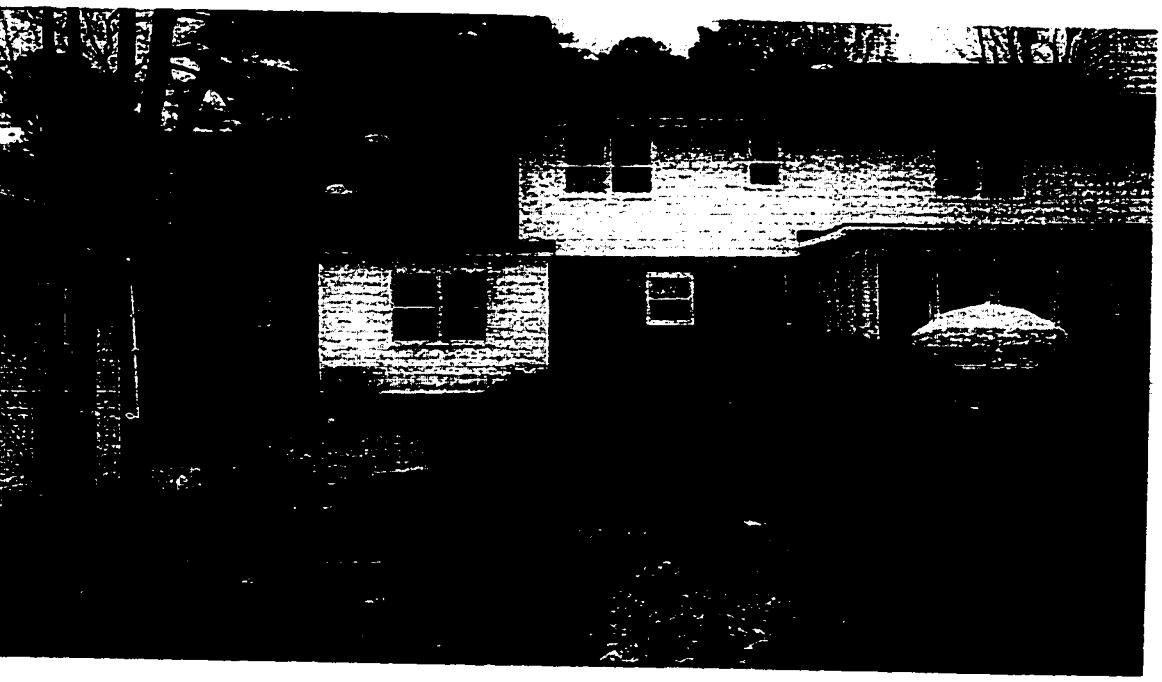


Figure D.3: Case Study House: Deck and Sun Porch

Figure D.4: Case Study House: Pool and Hot Tub

Figure D.5: Case Study House: Pool Shed

Table D.1: Stakeholder Satisfaction Survey – Baseline State

Baseline Stakeholder Satisfaction

Importance	Item	Expectations: Not Met	Met	Exceeded
5	Clean Air Supply		1	
5	Fresh Water Supply		1	
4	Solid Waste Removal		1	
4	Wastewater Removal		1	
4	Comfortable Air Temperature			1
3	Comfortable Surface Temperature	1		
4	Comfortable Humidity		1	
4	Comfortable Air Flow		1	
5	Protection from Weather			1
4	Adequate Lighting		1	
5	Visual Privacy			1
5	Adequate Noise Conditions			1
5	Acoustical Privacy			1
5	Adequate Security/Safety		1	
5	Adequate Protection from Vectors	1		
3	Adequate Power		1	
3	Adequate Communication Capacity - Phones			1
4	Adequate Functional Surfaces - Floor Areas			1
4	Adequate Functional Surfaces - Work Surfaces			1
3	Adequate Functional Surfaces - Storage		1	
4	Adequate Structural Stability		1	
4	Adequate Protection of Building from Water Damage		1	
2	Adequate Structural Integrity/Flexibility		1	
5	Adequate Fire Safety		1	
4	Adequate Operational Cost	1		
3	Adequate Ease of Operation/Maintenance	1		
5	*Adequate Indoor Aesthetics			1
4	*Adequate Outdoor Aesthetics			1
4	*Adequate Access to Transportation			1
3	*Adequate Access to Shopping			1
4	*Adequate Access to Parking			1
5	*Adequate Access to Dining/Entertainment			1
5	*Adequate Circulation Capacity			1
5	*Adequate User Amenities			1
5	*Adequate Hygeine/Sanitation/Cleanliness			1
146				

During the informal interview, several problems with the facility were identified that led to the responses shown in the satisfaction survey. First, the homeowner noted that the floor surface on the first floor of the house (Figure D.6) tended to be uncomfortably cold at times, especially during the winter. This discomfort resulted in a "Not Met" rating for the Comfortable Surface Temperature scale item. The second "Not Met" item, Adequate Protection from Vectors, was unsatisfactory due to the propensity for lady bugs to enter the house through the supposedly sealed windows on the second floor of the house. The third and fourth "Not Met" items, Adequate Operational Cost and Adequate Ease of

Operation/Maintenance, were deemed unsatisfactory due to the perceived high utility bills (see D.1.2) and large amount of time required to maintain the pool and hot tub. Difficult access to the filters for the HVAC system also contributed to a low rating for Adequate Ease of Operation/Maintenance.

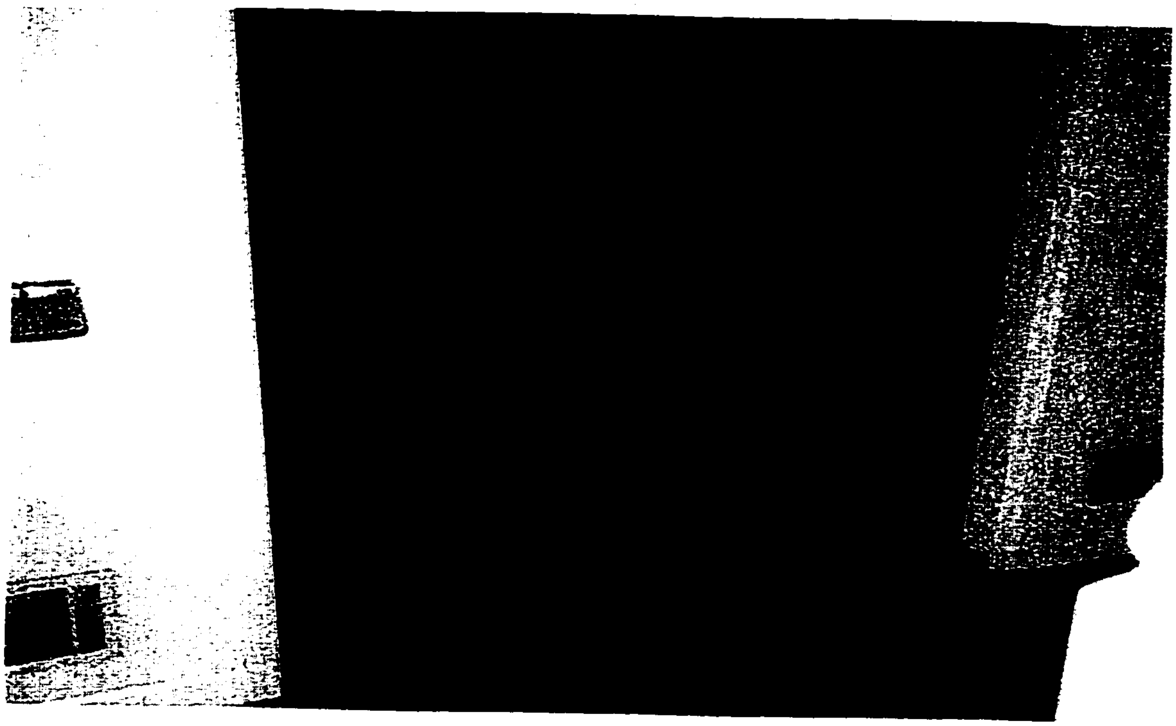


Figure D.6: Case Study House: Tile Floor

D.1.2 Flow Data for the Case Study Facility

Flow data for the home was derived from the informal interview with the homeowner as well as a survey of utility bills and receipts maintained by the residents. Table D.2 and Figure D.7 show the electrical power consumption of the facility as tabulated from Georgia Power utility bills. Figure D.8 shows water consumption and assumed wastewater generation for the house based on Dekalb County utility bills, and Figure D.9 shows natural gas consumption based on utility bills from Atlanta Gas Light Company.

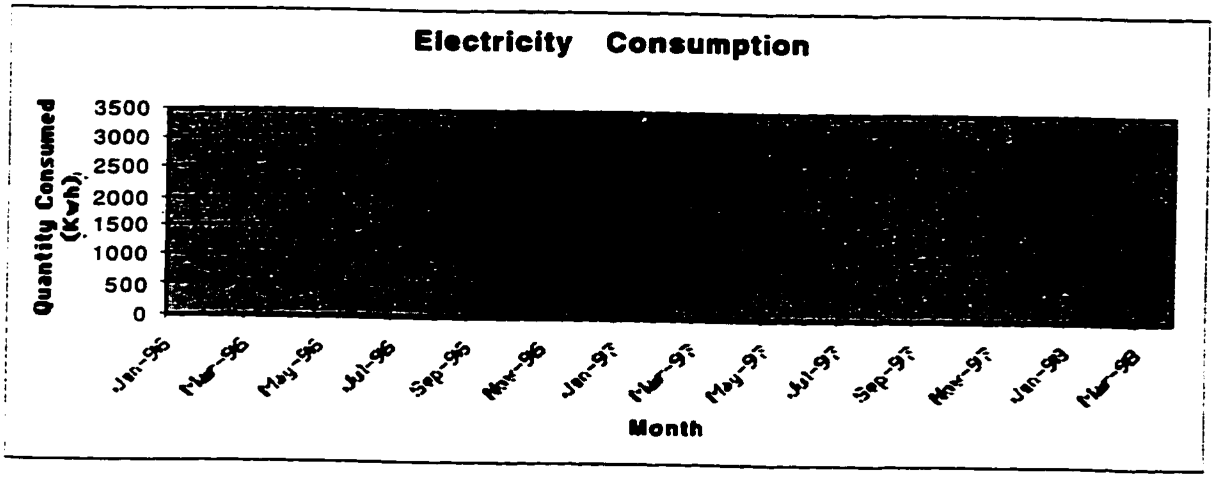


Figure D.7: Case Study Facility: Electrical Power Consumption

Table D.2: Case Study Facility: Electrical Power Consumption

Electrical Power Consumption - Georgia Power			
Month	**Quantity**	**Units**	**Notes**
Jan-96	693	Kwh	2 adults, one kid
Feb-96	584	Kwh	2 adults, one kid
Mar-96	518	Kwh	2 adults, one kid
Apr-96	489	Kwh	2 adults, one kid
May-96	2298	Kwh	2 adults, one kid
Jun-96	2267	Kwh	2 adults, one kid
Jul-96	2706	Kwh	2 adults, one kid
Aug-96	2497	Kwh	2 adults, one kid
Sep-96	2104.75	Kwh	2 adults, one kid
Oct-96	1712.5	Kwh	2 adults, one kid
Nov-96	1320.25	Kwh	2 adults, one kid
Dec-96	928	Kwh	2 adults, one kid
Jan-97	857	Kwh	2 adults, one kid
Feb-97	768	Kwh	2 adults, one kid
Mar-97	932	Kwh	2 adults, one kid
Apr-97	1422	Kwh	2 adults, one kid
May-97	2070	Kwh	2 adults, one kid
Jun-97	2546	Kwh	2 adults, one kid
Jul-97	3205	Kwh	2 adults, one kid
Aug-97	3213	Kwh	4 more people moved in
Sep-97	2974	Kwh	3 adults, four kids
Oct-97	2735	Kwh	3 adults, four kids
Nov-97	2496	Kwh	3 adults, four kids
Dec-97	2257	Kwh	3 adults, four kids
Jan-98	2018	Kwh	3 adults, four kids
Feb-98	1901	Kwh	3 adults, four kids
Mar-98	1890	Kwh	3 adults, four kids
1997 Sum =	25475	Kwh	
	(shaded) = linear interpolation		

Water Consumption & Wastewater Generation - Dekalb County			
Time	**Quantity**	**Unit**	**Notes:**
10/96-12/96	14.2	kgal	2 adults, one kid
12/96-2/97	17.2	kgal	2 adults, one kid
2/97-4/97	26.6	kgal	2 adults, one kid
4/97-6/97	28.7	kgal	Pool filling, occasional outdoor plant watering
6/97-8/97	25.3	kgal	2 adults, one kid
8/97-10/97	22.65	kgal	3 adults, four kids
10/97-12/97	20	kgal	3 adults, four kids
12/97-2/98	17.95	kgal	3 adults, four kids
2/98-4/98	14.7	kgal	Opened the pool later this year than last
1997 Sum =	**140.45**	**kgal**	
	[shaded] = linear interpolation		

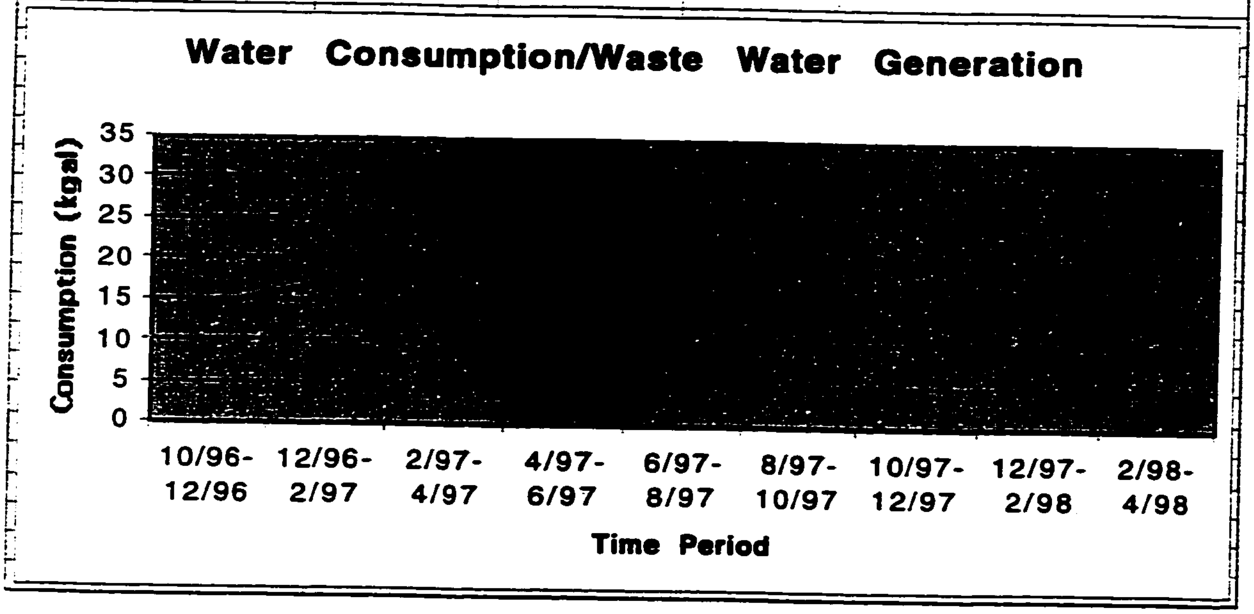


Figure D.8: Case Study Facility: Water Consumption and Wastewater Generation

Natural Gas Consumption - Atlanta Gas Light Co.				
Quarter	**CCF**	**BTU**	**Therms**	**Notes:**
Jan-97	279	1.024	285.7	2 adults, one kid
Feb-97	278	1.024	284.666667	2 adults, one kid
Mar-97	277	1.024	283.633333	2 adults, one kid
Apr-97	276	1.024	282.6	2 adults, one kid
May-97	267	1.033	275.8	2 adults, one kid
Jun-97	265.333333	1.03[illegible]	273.3	2 adults, one kid
Jul-97	263.666667	1.027	270.8	2 adults, one kid
Aug-97	262	1.024	268.3	4 more people moved in
Sep-97	182	1.0255	186.55	3 adults, four kids
Oct-97	102	1.027	104.8	3 adults, four kids
Nov-97	161	1.026	165.1	3 adults, four kids
Dec-97	220	1.025	225.4	3 adults, four kids
		1997 Sum =	2906.65	Therms

(shaded) = linear interpolation

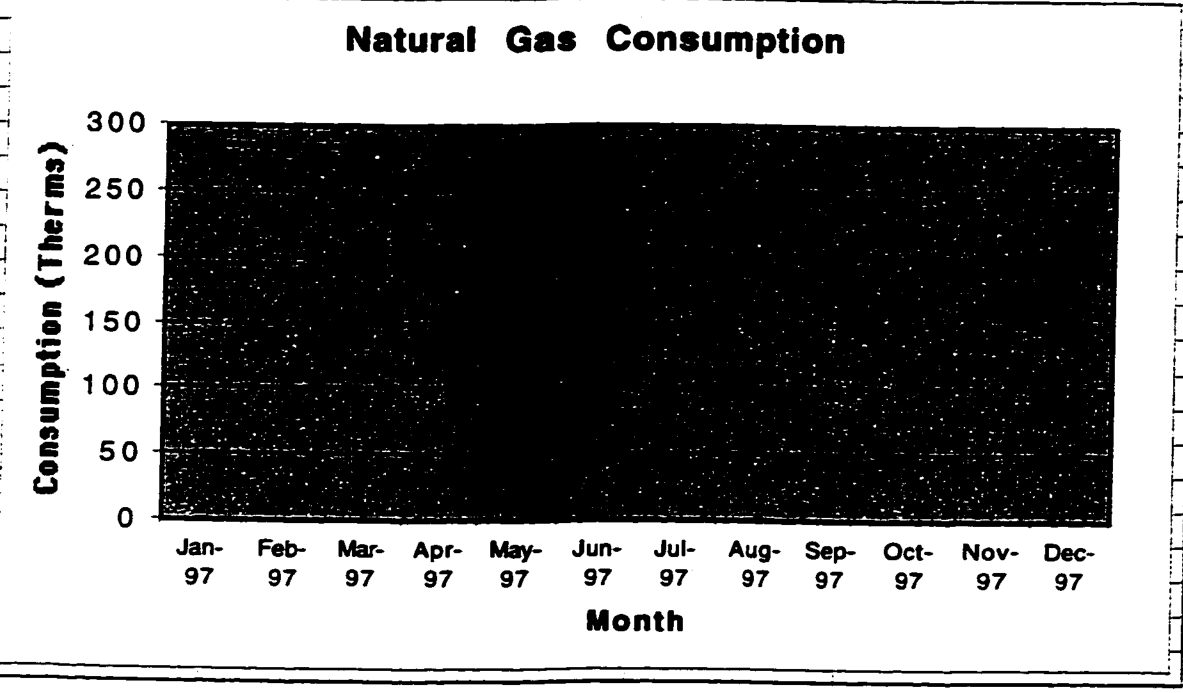


Figure D.9: Case Study Facility: Natural Gas Consumption

Additional flows were identified by the homeowner as being typical for operation of the house over a one year period. These flows included:

- Three HVAC filters changed per year
- One package or four incandescent bulbs per year
- Approximately one gallon of pesticide used for once-a-year pest control
- One bucket or five gallons of chlorine used per year for pool maintenance
- Approximately five flats of annual flowers planted per year (see Figure D.10)
- Estimated 15 gallons of gasoline used by lawn maintenance service per year
- Estimated 20 cubic yards of yard waste collected and composted by lawn maintenance service per year
- Estimated 52 cubic yards of mixed municipal solid waste collected by the Dekalb County per year, based on one cubic yard disposed per week

Table D.3 shows these baseline facility flows as estimated by the homeowner, along with identified or estimated source and/or sink facilities associated with each flow.

D.1.3 Survey of Land Uses on Site

The second part of the site visit was to assess the land uses on site to calculate Intra-System Ecosystem Impacts. The homeowner provided a site map which was used to estimate relative proportions of land uses on the site as shown in Figure D.11. The site itself is approximately 22,000 square feet.

Figure D.10: Case Study Facility: Annual Flowerbeds

Table D.3: Case Study Facility: Baseline Cross-Boundary Flows

Baseline Facility Flows					
Flow Type	Qty	Unit	Information Source	Resource Source/Sink	Location
Fresh water consumed	140450	gal	Water utility bills	POWW	Atlanta, GA
Waste water disposed	140450	gal	Water utility bills	POTW	Atlanta, GA
Electricity consumed	25475	kWh	Power utility bills	Coal-fired Power Plant	Cartersville, GA
Natural gas consumed	2906.7	Therms	Gas utility bills	Natural Gas Plant	Houstin, TX
HVAC filters	3	each	Homeowner estimate	Precisionaire Inc.	Dunwoody, GA
Incandescent light bulbs	4	each	Homeowner estimate	Halco Corp.	Norcross, GA
Pesticide	1	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Chlorine	5	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Flowers - potted, annual	5	flats	Homeowner estimate	Farmer's Market	Atlanta, GA
Gasoline (for lawn mower)	15	gal	Homeowner estimate	Oil Refinery	Houstin, TX
Mixed MSW disposed	52	cy	Estimate - trash can capacity * # of annual pickups	Southern States Env. Landfill	Marietta, GA
Bagged compostable waste disposed	20	cy	Homeowner estimate	GreenCycle Composting Facility	Smyrna, GA

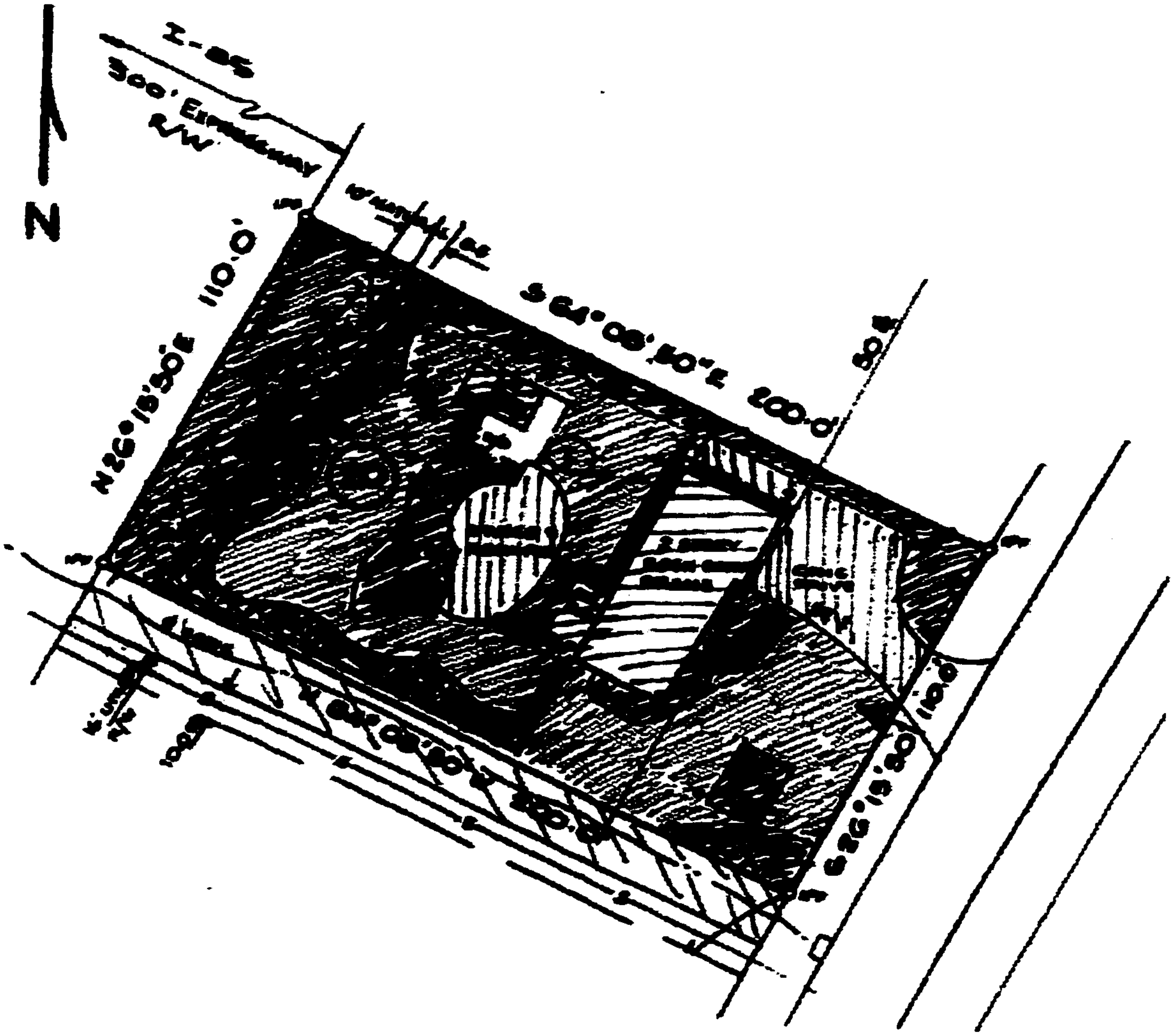


Figure D.11: Site Map showing Land Uses

Several different kinds of land uses were identified on the site. Figure D.10 shows an example of the lawn, hardscape, building footprint, and ornamental garden classes of land use. Figure D.12 shows an example of an area classified as sporadically cleared, and Figure D.13 shows an example of an area classified as fallow. Table D.4 shows the Baseline State of Site Ecosystems as determined by the site survey.

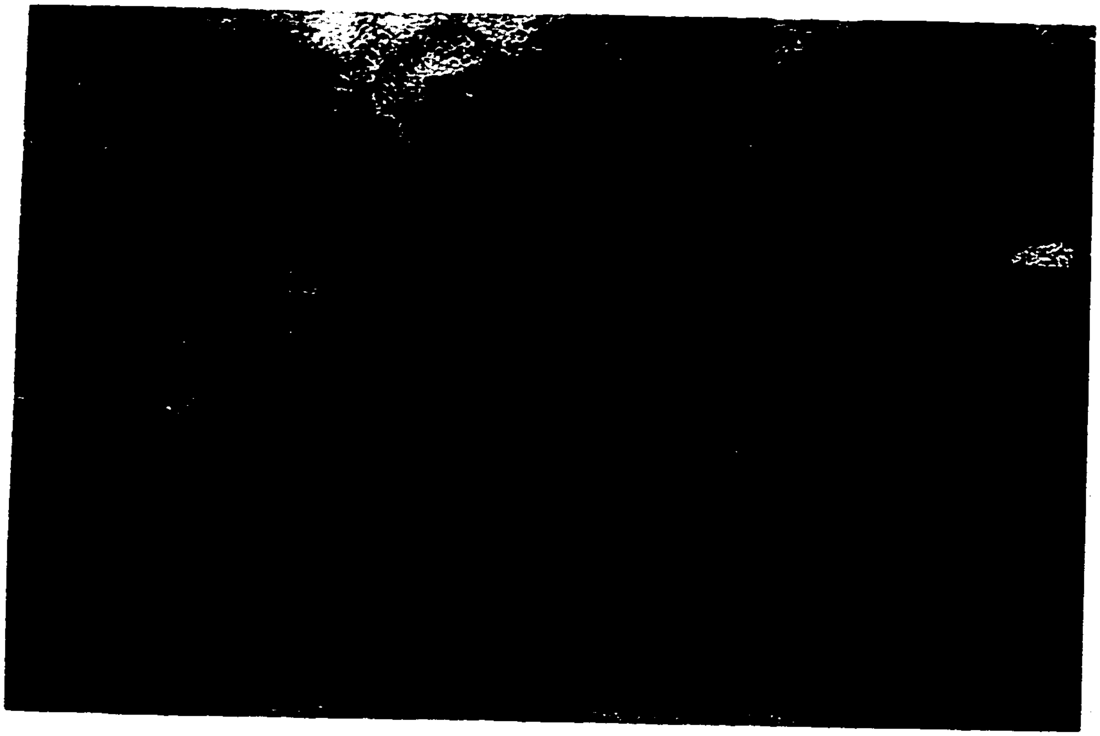


Figure D.12: Land Use Class – Sporadically Cleared

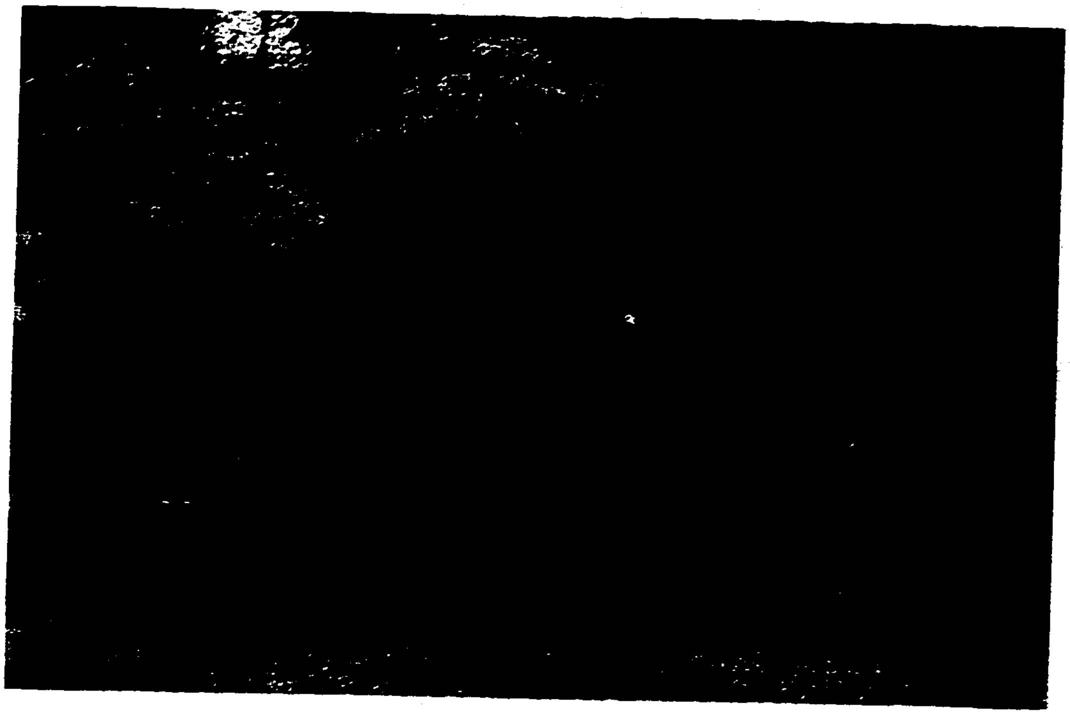


Figure D.13: Land Use Class – Fallow

Table D.4: Case Study Facility: Baseline State of Site Ecosystems

Intra-system Ecosystem Impacts - Baseline State

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Virgin/Undisturbed Areas	None	0	0.7	0
Managed Natural Ecosystems	Fallow	16.81%	0.583333333	0.09805303
	Sporadically Cleared	8.96%	0.466666667	0.041798485
	Regularly Cleared	0	0.333333333	0
	Used as Sink/Storage for Non-Toxics	0	0.066666667	0
	Used as Sink/Storage for Toxics	0	-0.35	0
Artificial Ecosystems	Lawn	59.30%	-0.033333333	-0.019766515
	Ornamental Garden	0.68%	0.166666667	0.001136364
	Agricultural	0	-0.2	0
	Bare Soil	0	-0.4	0
Built Areas	Hardscape with Container Plants	0.80%	-0.25	-0.002
	Hardscape/Paved Area	7.32%	-0.683333333	-0.050038636
	Building Footprint	6.13%	-0.75	-0.045975
		100%	On-Site EI =	[illegible]

D.1.4 Survey of On-Site Resource Bases

The final part of the site visit was to determine if any significant on-site resource bases existed and were impacted over the evaluation period. No significant resources in any of the five categories (power, water, non-renewable materials, plants, and animals) were identified on site, and no significant changes to any on-site resource bases were identified. Thus, Intra-System Resource Base Impact was assumed to be zero for the baseline sustainability state as well as for each of the considered improvement options.

D.2 Facility Change Calculations and Assumptions

Six change options were identified for consideration in the analysis, based on the informal interview with the homeowner as described in Chapter 6. The following subsections present calculations, assumptions, and associated deviations from the baseline sustainability state for each option.

D.2.1 Option 1: Low Flow Showerheads & Toilet Dams

The first option involved installing low flow showerheads on three shower fixtures in the house, plus toilet dams on four toilets. The total cost of installing these items was estimated to be **$120**, based on costs per fixture as determined from a vendor catalog. This option affects consumption of fresh water, generation of waste water, and consumption of natural gas used to heat water for showers.

Water Savings: Based on typical savings from retrofits identified in Metcalf & Eddy (1991), installing retrofits on showers saves approximately four gallons per capita per day, and toilet dams save approximately three gallons per capita per day. Retrofitting all fixtures would thus save approximately seven gallons per capita per day. Multiplying this savings times seven people living in the house times 365 days per year results in an estimated water savings of **17,885 gallons per year**. This savings was assumed to apply to both fresh water consumption and generation of waste water.

Natural Gas Savings: Based on the amount of water saved per shower (Metcalf & Eddy 1991), the low-flow shower heads result in a savings of

4 gallons/shower saved ÷ 16 gallons/shower typical

= 25% of heat used for showers saved

The next step is to determine what proportion of total hot water is allocated to showers. Ratios of typical hot water consumption for fixtures and appliances found in the case study house are shown in Table D.5 (from Harris 1996). The total of all ratios is 8.5. Dividing the load attributable to showers (1.5) by the total of all ratios (8.5), the estimated total hot water load attributable to showers is 35%. Assume that hot water heating is responsible for 484 therms/year, based on a hot water heater half as efficient as the leading hot water heater available today (Wilson & Morrill 1994). The total natural gas savings can then be calculated by multiplying the savings due to flow restriction (25%) times the heating load due to showers (35%) times the total natural gas consumed for hot water heating (484 therms/year), resulting in a savings of **43 therms per year**.

Table D.5: Ratios of Hot Water Loads by Appliance (Harris 1996)

Use/Appliance	Load Ratio
Laundry Machine	1.5
Dishwasher	1
Kitchen Sink	1.5
Shower	3
Lavatory	1.5

Table D.6 shows the estimated cross-boundary flows for Option 1. Stakeholder satisfaction changes are shown in Table D.7. As described earlier, Intra-System Resource Base Impacts are assumed to be zero. Since option one retrofits occur exclusively within the house, no changes are reflected to Intra-System Ecosystem Impacts, which remains the same as in the Baseline case.

Table D.6: Option 1 Cross-Boundary Flows

Option 1 Flows - Low Flow Showerheads & Toilet Dams					
Flow Type	Qty	Unit	Information Source	Resource Source/Sink	Location
Fresh water consumed	122565	gal	Water utility bills	POWW	Atlanta, GA
Waste water disposed	122565	gal	Water utility bills	POTW	Atlanta, GA
Electricity consumed	25475	kWh	Power utility bills	Coal-fired Power Plant	Cartersville, GA
Natural gas consumed	2863.7	Therms	Gas utility bills	Natural Gas Plant	Houston, TX
HVAC filters	3	each	Homeowner estimate	Precisionaire Inc.	Dunwoody, GA
Incandescent light bulbs	4	each	Homeowner estimate	Halco Corp.	Norcross, GA
Pesticide	1	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Chlorine	5	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Flowers - potted, annual	5	flats	Homeowner estimate	Farmer's Market	Atlanta, GA
Gasoline (for lawn mower)	15	gal	Homeowner estimate	Oil Refinery	Houstin, TX
Mixed MSW disposed	52	cy	Estimate - trash can capacity * # of annual pickups	Southern States Env. Landfill	Marietta, GA
Low-flow showerheads (one time)	3	each		Resources Conservation	Greenwich, CT
Toilet dams (one time)	4	each		Resources Conservation	Greenwich, CT
Bagged compostable waste disposed	20	cy	Homeowner estimate	GreenCycle Composting Facility	Smyrna, GA

D.2.2 Option 2: Pool Cover

The second option involved buying a solar cover for the swimming pool, made of industrial grade bubble wrap. The total cost of the pool cover was estimated to be **$500**, based on a vendor estimate. This option affects consumption of fresh water, generation of waste water, consumption of natural gas used to heat the pool water, and consumption of chlorine to maintain the pool water.

Table D.7: Option 1 Stakeholder Satisfaction

Option 1 - Low Flow Showerheads & Toilet Dams

Importance	Item	Expectations: Not Met	Met	Exceeded
5	Clean Air Supply		1	
5	Fresh Water Supply		1	
4	Solid Waste Removal		1	
4	Wastewater Removal		1	
4	Comfortable Air Temperature			1
3	Comfortable Surface Temperature	1		
4	Comfortable Humidity		1	
4	Comfortable Air Flow		1	
5	Protection from Weather			1
4	Adequate Lighting		1	
5	Visual Privacy			1
5	Adequate Noise Conditions			1
5	Acoustical Privacy			1
5	Adequate Security/Safety		1	
5	Adequate Protection from Vectors	1		
3	Adequate Power		1	
3	Adequate Communication Capacity - Phones			1
4	Adequate Functional Surfaces - Floor Areas			1
4	Adequate Functional Surfaces - Work Surfaces			1
3	Adequate Functional Surfaces - Storage		1	
4	Adequate Structural Stability		1	
4	Adequate Protection of Building from Water Damage		1	
2	Adequate Structural Integrity/Flexibility		1	
5	Adequate Fire Safety		1	
4	Adequate Operational Cost	1		
3	Adequate Ease of Operation/Maintenance		1	
5	*Adequate Indoor Aesthetics			1
4	*Adequate Outdoor Aesthetics			1
4	*Adequate Access to Transportation			1
3	*Adequate Access to Shopping			1
4	*Adequate Access to Parking			1
5	*Adequate Access to Dining/Entertainment			1
5	*Adequate Circulation Capacity			1
5	*Adequate User Amenities			1
5	*Adequate Hygeine/Sanitation/Cleanliness			1
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Water Savings: The savings in water consumption is due to reduced evaporation of water from the pool surface area. Assume that approximately 12" of water is lost from the pool each year that would normally be replaced by refilling. The area of the pool is approximately 18 feet by 20 feet, resulting in a net loss of 1' * 18' * 20' or approximately 360 gallons of water lost from the pool each year due to evaporation. Assume that the pool cover prevents approximately 75% of this evaporation. The total water savings is thus 75% of 360 gallons lost, or **270 gallons per year**.

Natural Gas Savings: The amount of gas consumed to heat pool water is sporadic, according to the homeowner. The pool heater is operated as needed, and thus precise estimation of savings is impossible. To calculate approximated natural gas savings, assume that the pool cover saves approximately 25% as much natural gas as the shower head retrofit, or 25% times 43 terms/year, for a total savings of **10.75 therms per year.**

Chlorine Savings: By preventing both evaporation and collection of debris in the pool, the pool cover is estimated to reduce chlorine needs by approximately 50%, or **2.5 gallons per year**.

Table D.8 shows the estimated cross-boundary flows for Option 2. Stakeholder satisfaction changes are shown in Table D.9. As described earlier, Intra-System Resource Base Impacts are assumed to be zero. Since the pool cover does not affect any existing land uses, no changes are reflected to Intra-System Ecosystem Impacts, which remains the same as in the Baseline case.

Table D.8: Option 2 Cross-Boundary Flows

Option 2 Flows - Pool Cover					
Flow Type	**Qty**	**Unit**	**Information Source**	**Resource Source/Sink**	**Location**
Fresh water consumed	140180	gal	Water utility bills	POWW	Atlanta, GA
Waste water disposed	140180	gal	Water utility bills	POTW	Atlanta, GA
Electricity consumed	25475	kWh	Power utility bills	Coal-fired Power Plant	Cartersville, GA
Natural gas consumed	2895.9	Therms	Gas utility bills	Natural Gas Plant	Houston, TX
HVAC filters	3	each	Homeowner estimate	Precisionaire Inc.	Dunwoody, GA
Incandescent light bulbs	4	each	Homeowner estimate	Halco Corp.	Norcross, GA
Pesticide	1	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Chlorine	2.5	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Flowers - potted, annual	5	flats	Homeowner estimate	Farmer's Market	Atlanta, GA
Gasoline (for lawn mower)	15	gal	Homeowner estimate	Oil Refinery	Houston, TX
Mixed MSW disposed	52	cy	Estimate - trash can capacity * # of annual pickups	Southern States Env. Landfill	Marietta, GA
Pool cover (one time)	1	each		Plastic Mfr.	Trenton, NJ
Bagged compostable waste disposed	20	cy	Homeowner estimate	GreenCycle Composting Facility	Smyrna, GA

Table D.9: Option 2 Stakeholder Satisfaction

Option 2 - Pool Cover

Importance	Item	Expectations: Not Met	Expectations: Met	Expectations: Exceeded
5	Clean Air Supply		1	
5	Fresh Water Supply		1	
4	Solid Waste Removal		1	
4	Wastewater Removal		1	
4	Comfortable Air Temperature			1
3	Comfortable Surface Temperature	1		
4	Comfortable Humidity		1	
4	Comfortable Air Flow		1	
5	Protection from Weather			1
4	Adequate Lighting		1	
5	Visual Privacy			1
5	Adequate Noise Conditions			1
5	Acoustical Privacy			1
5	Adequate Security/Safety		1	
5	Adequate Protection from Vectors	1		
3	Adequate Power		1	
3	Adequate Communication Capacity - Phones			1
4	Adequate Functional Surfaces - Floor Areas			1
4	Adequate Functional Surfaces - Work Surfaces			1
3	Adequate Functional Surfaces - Storage		1	
4	Adequate Structural Stability		1	
4	Adequate Protection of Building from Water Damage		1	
2	Adequate Structural Integrity/Flexibility		1	
5	Adequate Fire Safety		1	
4	Adequate Operational Cost		0	1
3	Adequate Ease of Operation/Maintenance		0	1
5	*Adequate Indoor Aesthetics			1
4	*Adequate Outdoor Aesthetics			1
4	*Adequate Access to Transportation			1
3	*Adequate Access to Shopping			1
4	*Adequate Access to Parking			1
5	*Adequate Access to Dining/Entertainment			1
5	*Adequate Circulation Capacity			1
5	*Adequate User Amenities			1
5	*Adequate Hygeine/Sanitation/Cleanliness			1
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D.2.3 Option 3: Crawl Space Insulation

The third option involved insulating the crawl space beneath the first floor of the house. The total cost of the insulation installation was estimated to be **$360**, based on insulating approximately 1,320 square feet of space with fiberglass insulation costing 17 cents per square foot, plus two laborers for one eight-hour day at $8/hour each. This option affects consumption of natural gas used to heat the house in the winter and consumption of electricity to cool the house in the summer.

Natural Gas Savings: Based on changes in consumption of natural gas during the heating season (see Figure D.9), the amount of natural gas consumed was approximately 250 therms per month during four heating months per year. Assume that approximately 80% of this gas is used for heating, and that 10% of this is heat loss through the crawl space. The total savings in natural gas is thus 250 therms/month * 4 heating months * 80% used for space heating * 10% savings in heat loss due to insulation = **80 therms per year** saved.

Electricity Savings: Similar to the calculations for natural gas savings, the amount of electricity consumed during the peak six cooling months was determined to be an average of 2,750 kW/month from Figure D.7. Assume that 80% of this electricity is used for cooling during these months, and 10% of this energy is wasted due to heat gain through the crawl space. The total savings in electricity is thus 2,750 kW/month * 6 cooling months * 80% used for cooling * 10% savings in heat gain due to insulation = **1,320 kW per year** saved.

Table D.10 shows the estimated cross-boundary flows for Option 3. Stakeholder satisfaction changes are shown in Table D.11. As described earlier, Intra-System Resource Base Impacts are assumed to be zero. Since insulating the crawl space does not affect any existing land uses, no changes are reflected to Intra-System Ecosystem Impacts, which remains the same as in the Baseline case.

Table D.10: Option 3 Cross-Boundary Flows

Option 3 Flows - Insulate Crawl Space					
Flow Type	Qty	Unit	Information Source	Resource Source/Sink	Location
Fresh water consumed	140450	gal	Water utility bills	POWW	Atlanta, GA
Waste water disposed	140450	gal	Water utility bills	POTW	Atlanta, GA
Electricity consumed	24155	kWh	Power utility bills	Coal-fired Power Plant	Cartersville, GA
Natural gas consumed	2826.7	Therms	Gas utility bills	Natural Gas Plant	Houstin, TX
HVAC filters	3	each	Homeowner estimate	Precisionaire Inc.	Dunwoody, GA
Incandescent light bulbs	4	each	Homeowner estimate	Halco Corp.	Norcross, GA
Pesticide	1	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Chlorine	5	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Flowers - potted, annual	5	flats	Homeowner estimate	Farmer's Market	Atlanta, GA
Gasoline (for lawn mower)	15	gal	Homeowner estimate	Oil Refinery	Houstin, TX
Mixed MSW disposed	53	cy	Estimate - trash can capacity * # of annual pickups	Southern States Env. Landfill	Marietta, GA
Fiberglass Insulation (one time)	12	rolls	Square foot estimate	Owens-Corning Plant	Toledo, OH
Bagged compostable waste disposed	20	cy	Homeowner estimate	GreenCycle Composting Facility	Smyrna, GA

Table D.11: Option 3 Stakeholder Satisfaction

Option 3 - Insulate Crawl Space

		Expectations		
Importance	Item	Not Met	Met	Exceeded
5	Clean Air Supply		1	
5	Fresh Water Supply		1	
4	Solid Waste Removal		1	
4	Wastewater Removal		1	
4	Comfortable Air Temperature			1
3	Comfortable Surface Temperature		1	
4	Comfortable Humidity		1	
4	Comfortable Air Flow		1	
5	Protection from Weather			1
4	Adequate Lighting		1	
5	Visual Privacy			1
5	Adequate Noise Conditions			1
5	Acoustical Privacy			1
5	Adequate Security/Safety		1	
5	Adequate Protection from Vectors	1		
3	Adequate Power		1	
3	Adequate Communication Capacity - Phones			1
4	Adequate Functional Surfaces - Floor Areas			1
4	Adequate Functional Surfaces - Work Surfaces			1
3	Adequate Functional Surfaces - Storage		1	
4	Adequate Structural Stability		1	
4	Adequate Protection of Building from Water Damage		1	
2	Adequate Structural Integrity/Flexibility		1	
5	Adequate Fire Safety		1	
4	Adequate Operational Cost		1	
3	Adequate Ease of Operation/Maintenance	1		
5	*Adequate Indoor Aesthetics			1
4	*Adequate Outdoor Aesthetics			1
4	*Adequate Access to Transportation			1
3	*Adequate Access to Shopping			1
4	*Adequate Access to Parking			1
5	*Adequate Access to Dining/Entertainment			1
5	*Adequate Circulation Capacity			1
5	*Adequate User Amenities			1
5	*Adequate Hygeine/Sanitation/Cleanliness			1
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D.2.4 Option 4: Hot Water Heater Jacket

The fourth option involved installing an insulating jacket on the hot water heater storage tank to prevent heat loss from stored water. The total cost of the hot water heater jacket was estimated to be **$15**, based on an average cost as specified by Wilson & Morrill (1994). This option affects consumption of natural gas used to heat hot water.

Natural Gas Savings: In Option 1, the amount of natural gas used for hot water heating was assumed to be 484 therms per year. Typical range of savings due to insulating a hot water storage tank is from 4-9% (Wilson & Morrill 1994). Taking an average, assume that 6.5% of hot water heating consumption can be saved. The total savings in natural gas consumption is thus 484 therms/year * 6.5% savings due to jacket = **31.5 therms per year** saved.

Table D.12 shows the estimated cross-boundary flows for Option 4. Stakeholder satisfaction changes are shown in Table D.13. As described earlier, Intra-System Resource Base Impacts are assumed to be zero. Since installing a hot water heater jacket does not affect any existing land uses, no changes are reflected to Intra-System Ecosystem Impacts, which remains the same as in the Baseline case.

Table D.12: Option 4 Cross-Boundary Flows

Option 4 Flows - Hot Water Heater Jacket					
Flow Type	**Qty**	**Unit**	**Information Source**	**Resource Source/Sink**	**Location**
Fresh water consumed	140450	gal	Water utility bills	POWW	Atlanta, GA
Waste water disposed	140450	gal	Water utility bills	POTW	Atlanta, GA
Electricity consumed	25475	kWh	Power utility bills	Coal-fired Power Plant	Cartersville, GA
Natural gas consumed	2875.2	Therms	Gas utility bills	Natural Gas Plant	Houstin, TX
HVAC filters	3	each	Homeowner estimate	Precisionaire Inc.	Dunwoody, GA
Incandescent light bulbs	4	each	Homeowner estimate	Halco Corp.	Norcross, GA
Pesticide	1	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Chlorine	5	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Flowers - potted, annual	5	flats	Homeowner estimate	Farmer's Market	Atlanta, GA
Gasoline (for lawn mower)	15	gal	Homeowner estimate	Oil Refinery	Houstin, TX
Mixed MSW disposed	52	cy	Estimate - trash can capacity * # of annual pickups	Southern States Env. Landfill	Marietta, GA
Hot Water Heater Jacket (one time	1	each	Estimate	Owens-Corning Plant	Toledo, OH
Bagged compostable waste disposed	20	cy	Homeowner estimate	GreenCycle Composting Facility	Smyrna, GA

Table D.13: Option 4 Stakeholder Satisfaction

Option 4 - Hot Water Heater Jacket

Importance	Item	Expectations: Not Met	Expectations: Met	Expectations: Exceeded
5	Clean Air Supply		1	
5	Fresh Water Supply		1	
4	Solid Waste Removal		1	
4	Wastewater Removal		1	
4	Comfortable Air Temperature			1
3	Comfortable Surface Temperature	1		
4	Comfortable Humidity		1	
4	Comfortable Air Flow		1	
5	Protection from Weather			1
4	Adequate Lighting		1	
5	Visual Privacy			1
5	Adequate Noise Conditions			1
5	Acoustical Privacy			1
5	Adequate Security/Safety		1	
5	Adequate Protection from Vectors	1		
3	Adequate Power		1	
3	Adequate Communication Capacity - Phones			1
4	Adequate Functional Surfaces - Floor Areas			1
4	Adequate Functional Surfaces - Work Surfaces			1
3	Adequate Functional Surfaces - Storage		1	
4	Adequate Structural Stability		1	
4	Adequate Protection of Building from Water Damage		1	
2	Adequate Structural Integrity/Flexibility		1	
5	Adequate Fire Safety		1	
4	Adequate Operational Cost		1	
3	Adequate Ease of Operation/Maintenance	1		
5	*Adequate Indoor Aesthetics			1
4	*Adequate Outdoor Aesthetics			1
4	*Adequate Access to Transportation			1
3	*Adequate Access to Shopping			1
4	*Adequate Access to Parking			1
5	*Adequate Access to Dining/Entertainment			1
5	*Adequate Circulation Capacity			1
5	*Adequate User Amenities			1
5	*Adequate Hygeine/Sanitation/Cleanliness			1
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D.2.5 Option 5: Compact Fluorescent Light Bulbs

The fifth option involved retrofitting eight incandescent light fixtures with compact fluorescent light bulbs. The total cost of the retrofit was estimated to be **$120**, based on an average cost per bulb of $15. This option affects consumption of electricity used to operate the lighting in the house.

Electricity Savings: According to Wilson & Morrill (1994), a savings of approximately 55 kW per year can be realized by switching from a typical 75 watt incandescent bulb to an equivalent 20 watt compact fluorescent bulb. Multiplying this savings (55 kW/year) times the number of bulbs replaced (8) results in an estimated savings of **440 kW per year**. While savings in cooling loads may also result from the bulb retrofit, these savings were assumed to be negligible in this analysis.

Table D.14 shows the estimated cross-boundary flows for Option 5. Stakeholder satisfaction changes are shown in Table D.15. As described earlier, Intra-System Resource Base Impacts are assumed to be zero. Since replacing light bulbs does not affect any existing land uses, no changes are reflected to Intra-System Ecosystem Impacts, which remains the same as in the Baseline case.

Table D.14: Option 5 Cross-Boundary Flows

Option 5 Flows - Compact Fluorescent Light Bulbs					
Flow Type	Qty	Unit	Information Source	Resource Source/Sink	Location
Fresh water consumed	140450	gal	Water utility bills	POWW	Atlanta, GA
Waste water disposed	140450	gal	Water utility bills	POTW	Atlanta, GA
Electricity consumed	25035	kWh	Power utility bills	Coal-fired Power Plant	Cartersville, GA
Natural gas consumed	2906.7	Therms	Gas utility bills	Natural Gas Plant	Houston, TX
HVAC filters	3	each	Homeowner estimate	Precisionaire Inc.	Dunwoody, GA
Incandescent light bulbs	0	each	Homeowner estimate	Halco Corp.	Norcross, GA
Pesticide	1	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Chlorine	5	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Flowers - potted, annual	5	flats	Homeowner estimate	Farmer's Market	Atlanta, GA
Gasoline (for lawn mower)	15	gal	Homeowner estimate	Oil Refinery	Houston, TX
Mixed MSW disposed	52	cy	Estimate - trash can capacity * # of annual pickups	Southern States Env. Landfill	Marietta, GA
Compact Fluorescent bulbs (1/10	8	each	One for select incandescent sockets	Phillips Mfg. Plant	Trenton, NJ
Bagged compostable waste disposed	20	cy	Homeowner estimate	GreenCycle Composting Facility	Smyrna, GA

Table D.15: Option 5 Stakeholder Satisfaction

Option 5 - Compact Fluorescent Light Bulbs

Importance	Item	Expectations: Not Met	Met	Exceeded
5	Clean Air Supply		1	
5	Fresh Water Supply		1	
4	Solid Waste Removal		1	
4	Wastewater Removal		1	
4	Comfortable Air Temperature			1
3	Comfortable Surface Temperature	1		
4	Comfortable Humidity		1	
4	Comfortable Air Flow		1	
5	Protection from Weather			1
4	Adequate Lighting		1	
5	Visual Privacy			1
5	Adequate Noise Conditions			1
5	Acoustical Privacy			1
5	Adequate Security/Safety		1	
5	Adequate Protection from Vectors	1		
3	Adequate Power		1	
3	Adequate Communication Capacity - Phones			1
4	Adequate Functional Surfaces - Floor Areas			1
4	Adequate Functional Surfaces - Work Surfaces			1
3	Adequate Functional Surfaces - Storage		1	
4	Adequate Structural Stability		1	
4	Adequate Protection of Building from Water Damage		1	
2	Adequate Structural Integrity/Flexibility		1	
5	Adequate Fire Safety		1	
4	Adequate Operational Cost		1	
3	Adequate Ease of Operation/Maintenance	1		
5	*Adequate Indoor Aesthetics			1
4	*Adequate Outdoor Aesthetics			1
4	*Adequate Access to Transportation			1
3	*Adequate Access to Shopping			1
4	*Adequate Access to Parking			1
5	*Adequate Access to Dining/Entertainment			1
5	*Adequate Circulation Capacity			1
5	*Adequate User Amenities			1
5	*Adequate Hygeine/Sanitation/Cleanliness			1
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D.2.6 Option 6: Gazebo

The last option involved installing a treated-wood gazebo in the backyard of the house. The total cost of the insulation installation was estimated to be **$1,350**, based on the cost items shown in Table D.16. This option affects Intra-system Ecosystem Impacts by converting approximately 25 square feet of the site from lawn to hardscape with container plants. It also affects resource flows by importing the raw materials for the gazebo as shown in Table D.17, and solid waste generation due to scraps from the construction process.

Table D.16: Gazebo Costs

Item	Quantity	Unit	Unit Price	Total
#2 Treated Yellow Pine	500	BF	$ 1.00	$ 500.00
Fasteners	10	lbs	$ 3.60	$ 36.00
Sack-crete	16	bags	$ 1.88	$ 30.00
Shingles	0.3	square	$ 166.67	$ 50.00
Plywood	8	sheets	$ 8.00	$ 64.00
Sealer/Stain	2	cans	$ 15.00	$ 30.00
Labor	80	hours	$ 8.00	$ 640.00
			Total =	$ 1,350.00

Table D.17: Gazebo Materials

Material	Description	Quantity	Unit
TYP Lumber		500	BF
Floor decking	2x6 TYP; 25 sq.ft.	*50*	*BF*
Posts	8@4x4x12' TYP	*128*	*BF*
Joists	2x10 TYP; 11@5'	*94*	*BF*
Benches	7@2x10x2' TYP; 6@2x8x5' TYP	*64*	*BF*
Balusters	80@2x2x3' TYP	*80*	*BF*
Rail	4@2x6x5' TYP	*20*	*BF*
Roof trusses	8@2x6x8' TYP	*64*	*BF*
Plywood	1/2" Marine grade; 8 sheets	256	sq. ft.
Shingles	15 year asphalt; 30 sq. ft.	0.3	square
Fasteners	Galvanized steel screws	10	lbs
Sack-Crete	Post foundations; apron	16	bags
Water sealer/stain	Initial coverage	2	gallons

Legend: TYP = Treated Yellow Pine; #2
BF = board feet

Table D.18 shows the estimated cross-boundary flows for Option 6. Stakeholder satisfaction changes are shown in Table D.19. As described earlier, Intra-System Resource Base Impacts are assumed to be zero. Table D.20 shows the revised distribution of land uses and subsequent Intra-System Ecosystem Impacts due to installation of the gazebo.

Table D.18: Option 6 Cross-Boundary Flows

Option 6 Flows - Gazebo

Flow Type	Qty	Unit	Information Source	Resource Source/Sink	Location
Fresh water consumed	140450	gal	Water utility bills	POWW	Atlanta, GA
Waste water disposed	140450	gal	Water utility bills	POTW	Atlanta, GA
Electricity consumed	25475	kWh	Power utility bills	Coal-fired Power Plant	Cartersville, GA
Natural gas consumed	2906.7	Therms	Gas utility bills	Natural Gas Plant	Houstin, TX
HVAC filters	3	each	Homeowner estimate	Precisionaire Inc.	Dunwoody, GA
Incandescent light bulbs	4	each	Homeowner estimate	Halco Corp.	Norcross, GA
Pesticide	1	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Chlorine	5	gal	Homeowner estimate	Chemical Plant	Tucker, GA
Flowers - potted, annual	5	flats	Homeowner estimate	Farmer's Market	Atlanta, GA
Gasoline (for lawn mower)	15	gal	Homeowner estimate	Oil Refinery	Houstin, TX
Mixed MSW disposed	60	cy	Estimate - trash can capacity * # of annual pickups	Landfill	Marietta, GA
#2 Treated Yellow Pine	500	bf	Estimate - contractor	Tree farm/sawmill	Valdosta, GA
Fasteners	10	lbs	Estimate - contractor	Steel mill	Birmingham, AL
Sack-crete	16	bags	Estimate - contractor	Concrete plant	Charlotte, NC
Shingles - 15 yr. Asphalt	0.3	square	Estimate - contractor	Shingle mfg. Plant	Columbus, OH
Plywood	256	sq ft	Estimate - contractor	Louisiana Pacific Plant	Savannah, GA
Water sealer/stain	2	gal	Estimate - contractor	Chemical Plant	Columbus, OH
Bagged compostable waste disposed	20	cy	Homeowner estimate	GreenCycle Composting Facility	Smyrna, GA

Table D.19: Option 6 Stakeholder Satisfaction

Option 6 - Gazebo

Importance	Item	Expectations: Not Met	Expectations: Met	Expectations: Exceeded
5	Clean Air Supply		1	
5	Fresh Water Supply		1	
4	Solid Waste Removal		1	
4	Wastewater Removal		1	
4	Comfortable Air Temperature			1
3	Comfortable Surface Temperature	1		
4	Comfortable Humidity		1	
4	Comfortable Air Flow		1	
5	Protection from Weather			1
4	Adequate Lighting		1	
5	Visual Privacy			1
5	Adequate Noise Conditions			1
5	Acoustical Privacy			1
5	Adequate Security/Safety		1	
5	Adequate Protection from Vectors	1		
3	Adequate Power		1	
3	Adequate Communication Capacity - Phones			1
4	Adequate Functional Surfaces - Floor Areas			1
4	Adequate Functional Surfaces - Work Surfaces			1
3	Adequate Functional Surfaces - Storage		1	
4	Adequate Structural Stability		1	
4	Adequate Protection of Building from Water Damage		1	
2	Adequate Structural Integrity/Flexibility		1	
5	Adequate Fire Safety		1	
4	Adequate Operational Cost	1		
3	Adequate Ease of Operation/Maintenance	1		
5	*Adequate Indoor Aesthetics			1
4	*Adequate Outdoor Aesthetics			1
4	*Adequate Access to Transportation			1
3	*Adequate Access to Shopping			1
4	*Adequate Access to Parking			1
5	*Adequate Access to Dining/Entertainment			1
5	*Adequate Circulation Capacity			1
5	*Adequate User Amenities			1
5	*Adequate Hygeine/Sanitation/Cleanliness			1
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Table D.20: Revised Intra-System Ecosystem Impact due to Installing Gazebo

[redacted]				
Virgin/Undisturbed Areas	None	0	0.7	0
Managed Natural Ecosystems	Fallow	16.81%	0.583333333	0.09805303
	Sporadically Cleared	8.96%	0.466666667	0.041798485
	Regularly Cleared	0	0.333333333	0
	Used as Sink/Storage for Non-Toxics	0	0.066666667	0
	Used as Sink/Storage for Toxics	0	-0.35	0
Artificial Ecosystems	Lawn	58.50%	-0.033333333	-0.019499848
	Ornamental Garden	0.68%	0.166666667	0.001136364
	Agricultural	0	-0.2	0
	Bare Soil	0	-0.4	0
Built Areas	Hardscape with Container Plants	1.60%	-0.25	-0.004
	Hardscape/Paved Area	7.32%	-0.683333333	-0.050038636
	Building Footprint	6.13%	-0.75	-0.045975
	Total =	100%	On-Site EI =	[redacted]

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