DEFINING SUSTAINABILITY FOR BUILT ENVIRONMENT SYSTEMS: AN OPERATIONAL FRAMEWORK

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Abstract

One of the ongoing challenges in the quest to make our built environment more sustainable is defining what sustainability means in terms understandable to and measurable by built environment decision makers. This paper illustrates one approach to developing a comprehensive and exhaustive definition of sustainability for the built environment: deriving domain-specific variables from fundamental principles and constraints that govern how Earth systems work. The paper uses the concept of systems to define characteristics and critical constraints of both the Earth as a whole and built facilities in particular. These constraints provide a basis for identifying conditions which must be met in order for a built facility system to be sustainable. The contribution of the paper is a decision space based on required sustainability conditions that can be used to evaluate facility alternatives in terms of their relative sustainability.

Keywords

Sustainability, built environment, definition, operationalization, measurement, systems, framework, prioritization, variables

Biographical Notes

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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 increasingly difficult to deny. 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 [1].

Within this 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. Inherent in these many approaches is a broad variety of perspectives on what variables are important to define and measure the sustainability of built facilities [2]. One of the most significant challenges for applying sustainability to built environment systems is defining exactly what conditions must be met in order for a facility to be sustainable. These conditions then provide a basis for comparing alternative states of a facility to support sustainable decision making, allocation of resources, and planning.

Objective and Approach

The objective of this work is to illustrate a systematic approach to developing a comprehensive and exhaustive framework of sustainability for the built environment: deriving domain-specific variables from fundamental principles and constraints that govern how Earth systems function. This paper examines the parameters that can be used to define sustainability, identifies key thresholds that represent the boundary between sustainability and unsustainability for a system, and describes a decision space using the parameters as dimensions that can be used to represent the relative sustainability of facility systems. The research defines variables of built environment sustainability based on a sequence of the following actions:

1) Identify Earth-scale conditions that must be met in order for the Earth system to be considered sustainable
2) Scale these global conditions to smaller technological systems (since the behavior of technological systems contributes to the net behavior of the global Earth system as a whole)
3) Define continuua and thresholds for each condition that represent the spectrum of possible system states for that condition
4) Construct a decision space for comparison of alternatives by combining the continuaa that describe system conditions for sustainability

The outcome of this approach is a decision space that can be used to compare the performance of different facility system states in terms of the key parameters that define its sustainability. By modeling facility system states and placing them within the decision space, facility decision makers have a basis for comparing alternatives in terms of the degree to which they improve the sustainability of the facility as a whole.

In the context of this paper, 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” [3]. 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 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).

Developing Parameters to Define Sustainability

In order to develop a set of parameters to comprise a unified framework of the concept of sustainability for systems, the first step is to differentiate among the possible scales on which operationalization can occur. This section examines two scales for which sustainability is a relevant concept: the global systems scale and the technological systems scale (of which built facility systems are one type). 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 the behavior of smaller systems as well.

The Issue of Scale in Defining Sustainability

In the context of this paper, the term "technological systems" refers to systems smaller in scale than the entire global system. 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 largest level of analysis generally considered in the sustainability literature is the global scale of analysis. Analysts who take this perspective [4] 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.

Coupled with naturally existing entities such as plants and animals, manmade technologies comprise the technological 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. 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 that result from system creation, operation, and decommissioning.

Sustainability at a Global System Scale

In developing a unified framework of sustainability, basic laws of thermodynamics govern the global system and the natural and manmade systems that comprise it. After the laws of thermodynamics, human-related objectives add to the richness of the concept, resulting in three fundamental objectives of sustainability. The following sections describe the significance of these objectives and constraints.

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 [5]. 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 [6]. For the Earth system, however, the amount of energy received by Earth from the sun exceeds the amount of energy lost as thermal radiation (the difference is commonly called the solar energy budget [7]), and is 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 Earth system consumes less energy than is supplied by the solar energy budget. To remain within this budget, two global objectives of sustainability can be identified:

1) <u>Ecosystem Degradation</u> – Minimize degradation of natural ecosystems (since they are the mechanism for capturing the solar energy budget via photosynthesis)
2) <u>Resource Consumption</u> – Minimize the gain in entropy as a result of consumption-related processes.

These basic physical constraints represent objectives that correspond to constraints within which actions on Earth must remain in order to be sustainable.

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 [8], as well as the self-interest of those whose task is to achieve sustainability. Three basic objectives can be identified:

1) <u>Motivation for Initiators</u> – Maintain standards of living at least as high as the ones that currently exist
2) <u>Intergenerational Equity</u> – Leave the Earth in at least as good a condition as it presently exists
3) <u>Intragenerational Equity</u> – 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 [9]. 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 [10]. Therefore, in order to foster acceptance of any proposal for sustainability, assurances must be included that those who 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 [11], to using nonrenewable resources as necessary provided that adequate substitutes are created [12]. Adopting the more conservative view, 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 paper stipulates the following interpretation with respect to setting a threshold of acceptability [13]: survival of the human species "with a quality of life beyond mere biological survival". 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 [14]. 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 [15]. 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 [16].

Sustainability at a Technological Systems Scale

Three fundamental objectives of sustainability for technological systems follow from the thermodynamic and anthropocentric objectives of sustainability developed in the previous section. 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 detail.

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 [17]. By subjecting materials and energy to consumption processes, we decrease their potential utility to current and future generations. Therefore, consuming as little matter and energy as possible is a fundamental objective of sustainability at a technological level.

Satisfying Human Needs and Aspirations: 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 actively accept the measures necessary to change the state of the world unless their needs are (or remain) 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.

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 [18]. 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 ecological destruction resulting from the creation and deployment of technologies, and to preserve the health of ecosystems that are impacted by those technologies.

A Unified Framework 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 with respect 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.

The Global Earth System

From the objectives of sustainability developed in the first part of this paper for the Earth system as a whole, three primary parameters can be used to define sustainability:

- 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 Human Species Parameter: The first variable, the Human Species, is based on the anthropocentric objectives of sustainability. Values for the Human Species variable can be represented along a continuum (Figure 1), where the threshold of sustainability is biological survival for the human species [19].

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.

The Resources Parameter: The second parameter, Resources, is based on the thermodynamic objectives of sustainability described in the first part of the paper. Values for the Resources parameter can be represented along a continuum (Figure 2), where the threshold of sustainability is consumption of resources equal to the regeneration rate of the resource base [20]. Regeneration rate is 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.

In terms of non-renewable resources, the concept of regeneration rate has led to many disputes. By definition, non-renewables 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-renewables are never to be used, then there is no reason to arbitrarily preserve them [21]. A substitute definition of regeneration rate for non-renewables is the amount of non-renewable resources which, when consumed, are replaced by an equivalent investment in natural or technological substitutes [22].

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 earlier, 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 3), 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 [23].

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: Figure 4 shows a triaxial representation of the parameters of global sustainability. 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 provides a convenient means of visually comparing sustainability states.

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

Technological Systems

In parallel to the global objectives of sustainability, three parameters of Humans, Resources, and Ecosystems emerge as being important in determining 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 where the technological system goes from being unsustainable to sustainable in terms of that parameter.

The Stakeholder Satisfaction Parameter: The first variable in technological sustainability, Stakeholder Satisfaction Impacts, is based on the anthropocentric objectives of sustainability described earlier, and ties into the question of who is being sustained at a technological systems level – System Stakeholders. Values for the Stakeholder Satisfaction parameter can be represented along a continuum (Figure 5), 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.

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 minimizing negative impacts to resource bases. Values for the Resource Base Impacts variable can be represented along a continuum (Figure 6), where the threshold of sustainability is zero net resource base impact caused by 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 being used by the system.

The entropy gain as a result of the resource flows through the system is also of interest. In the case of a built facility 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, i.e., the solar energy budget.

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 from the system without depleting resources within the system, which serves as input to other systems. An example of this type of system is a sustainably managed forest in which timber is extracted from the system at a rate less than or equal to its renewal rate. 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. Values for the Ecosystem Impacts variable can be represented along a continuum (Figure 7), where the threshold of sustainability is neutral or no impact on ecosystems as a result of the operation of the technological system.

Values to the right of the sustainability threshold represent a state of sustainability beyond the minimum requirements, and include situations where the system 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: Figure 8 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.

The positive region for each axis 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

Sustainability for Built Environment Systems

The next step in translating sustainability into an operational model for built facilities is to identify variables for each parameter that are meaningful in the context of built facility systems. The following sections describe a model of facility systems that can be used to accomplish this task.

Scale and Boundary

To classify the possible impacts a facility system could have on the three parameters of sustainability, we must first define a representation of a facility system with a meaningful boundary to distinguish it from its context. The boundary of the facility system can be conveniently defined as the legal boundary of the site, and the scale of analysis is 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 was selected because:

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

According to systems theory, emergent properties are those attributes that exist for a system as a whole, but not for its individual parts [24]. 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 relevant 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 9 provides a graphical representation of the entities and flows between the entities for typical facilities at this scale.

Key Facility and Context System Variables for Stakeholder Satisfaction

The first sustainability parameter to be considered is Stakeholder Satisfaction. As described earlier, the sustainability of technological systems 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.

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. One can not only measure levels of stakeholder satisfaction based on expectations for built environment performance, but also the relative importance of these expectations across the spectrum of possible needs that built facility systems could meet [26]. The hybrid combination of these perspectives provides a foundation for measuring stakeholder satisfaction as afforded by built environment systems. Accordingly, the following variables determine the Stakeholder Satisfaction parameter of sustainability:

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

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 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 [27].

Extra-System Impacts of Facility Systems on Ecosystems and Resource Bases: According to the built environment system model (Figure 9), 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 illustrated in Figure 10, 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 [28].

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 in the system's context. 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.

Three key facility and context system variables are part of the mapping of extra-system impacts to the resource base and ecosystem parameters of sustainability:

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

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 (and qualities) of resources or ecosystems. 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 the case of throughput facilities, the main causes 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 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 [29]. 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. Instead, 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.

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 [30]. 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.

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:

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

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 1).

Implications for Built Facility Systems

Given the classification of variables that can be used to estimate relative or absolute values for the three sustainability parameters of built facility systems, we can begin to see how the three-dimensional decision space developed in the first part of the paper could be used to compare the relative sustainability of different states of a facility system. Figure 11 shows an example of how alternatives can be visually compared within "sustainability space" to determine which of several alternatives provides the greatest increase in sustainability for a facility system. Figure 11a illustrates how a baseline state of sustainability can be established for a facility system – the status quo state of the facility system is represented in terms of how well stakeholder satisfaction is achieved and the facility's present level of impacts on resource bases and ecosystems. This baseline state provides a point of reference in Figure 11b for representing sustainability states corresponding to facility performance in terms of the three parameters after implementation of four different alternatives. The final phase of analysis, shown in Figure 11c, involves mapping the predicted facility sustainability states onto a comparison vector to determine which one provides the greatest increase in sustainability, assuming that the desire of the decision maker is to uniformly maximize increase in all three dimensions at once. In implementation, the scales of the axes could be stretched or compressed to reflect weightings of the three parameters appropriate to the decision making environment.

The benefit of using this approach is that it provides a way of comparing and prioritizing alternatives based on their relative impacts to the sustainability of a facility system in a *context-sensitive* fashion. On the other hand, precise calculation of values for the variables listed in Table 1 poses a challenge for even the most well-documented facility operation. While research is ongoing to develop better calculational methods and data sources for using this model, significant additional work must be done before the model can be used on a widespread basis.

Until such data exists, however, the three-dimensional decision space of sustainability parameters provides a visual point of reference for comparing alternatives in terms of the fundamental system stability constraints derived in this paper. As such, it affords both decision makers and researchers an operational point of departure for interpreting the meaning of sustainability with respect to built facility systems.

Despite the a variety of attempts in the literature [32], there is still no consensus on how to comprehensively and uniformly define the concept of sustainability as it pertains to the built environment, nor is there consensus on what aspects of the built environment should be considered in evaluating the sustainability of a built facility. The framework developed in this paper is one possible solution to this problem. By deriving domain-specific variables from fundamental principles and constraints of the Earth system as a whole, the approach described in this paper focuses on articulating sustainability parameters on a generalizable scale and *then* identifying what attributes of built facility systems affect those parameters. As such, the approach provides a starting point to develop a quantitative model of built facility sustainability that, by incorporating increasing levels of detail, identifies measurable variables to exhaustively define sustainability for built facilities.

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Tables

Table 1: Classification of Key Variables Defining Facility Sustainability

	Intra-System Impacts	**Extra-System Impacts**
Stakeholder Satisfaction	• Stakeholder expectations met • Relative importance of stakeholder expectations	Covered by attending to Extra-System Resource Base and Ecosystem Impacts
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

Figure Captions

Figure 1: Continuum of Values for the Global Human Species Parameter
Figure 2: Continuum of Values for the Global Resources Parameter

Figures

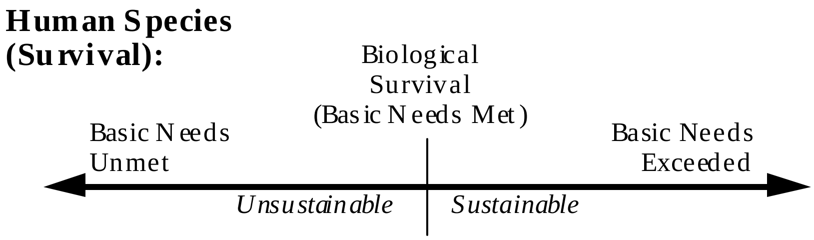


Figure 1: Continuum of Values for the Global Human Species Parameter

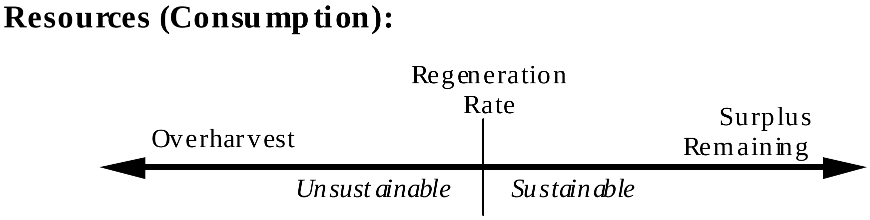


Figure 2: Continuum of Values for the Global Resources Parameter

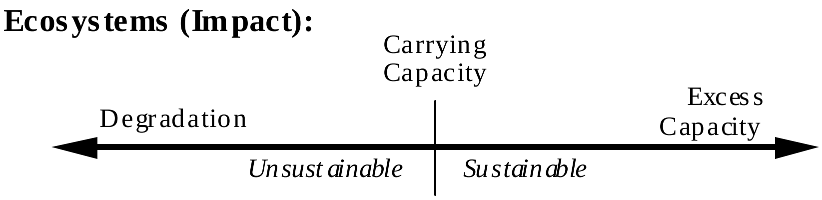


Figure 3: Continuum of Values for the Global Ecosystems Parameter

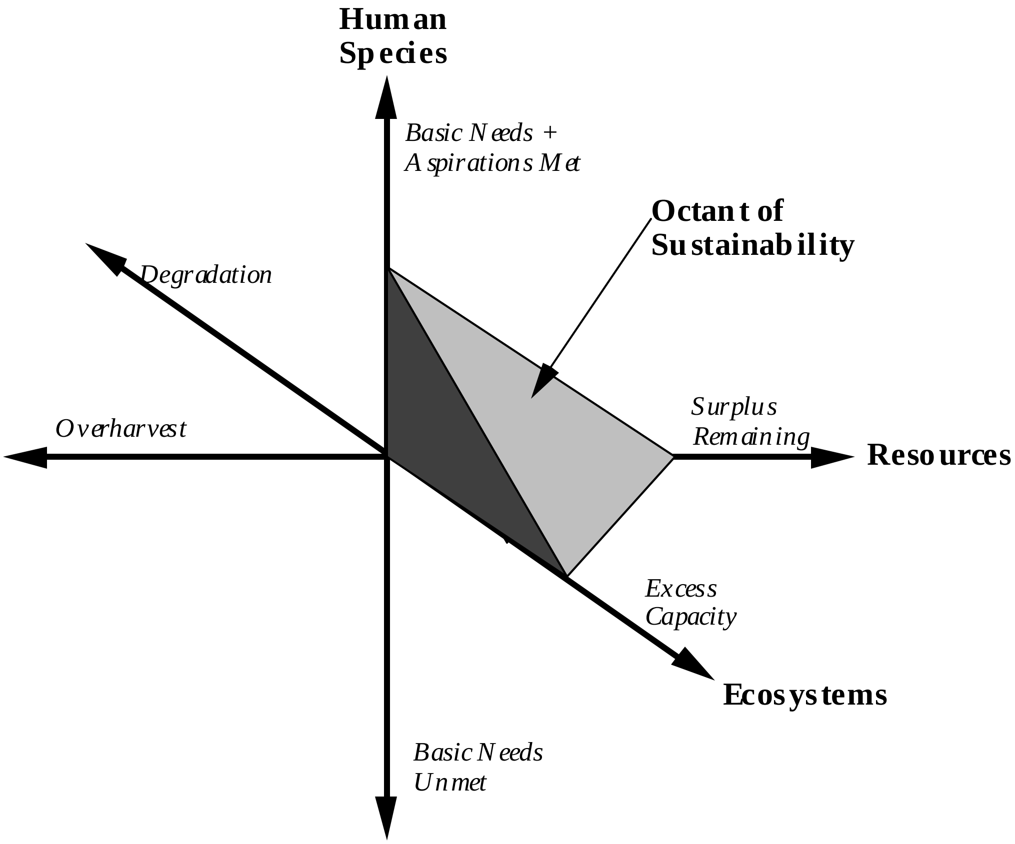


Figure 4: Triaxial Representation of Global Sustainability

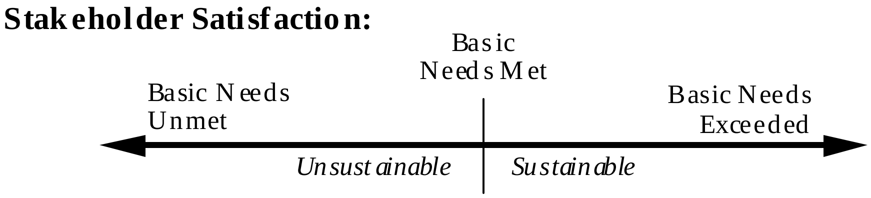


Figure 5: Continuum of Values for the Stakeholder Satisfaction Parameter

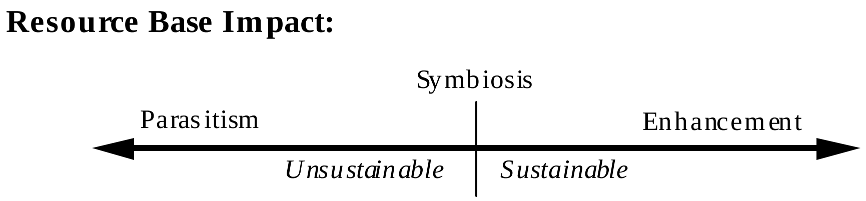


Figure 6: Continuum of Values for the Resource Base Impact Parameter

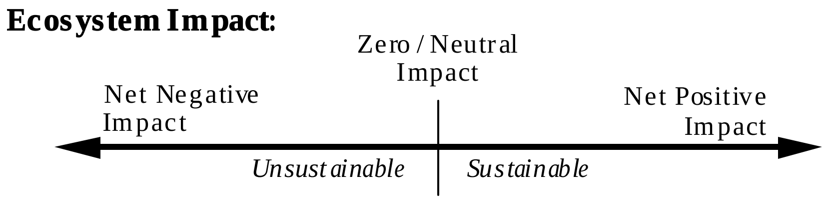


Figure 7: Continuum of Values for the Ecosystem Impacts Parameter

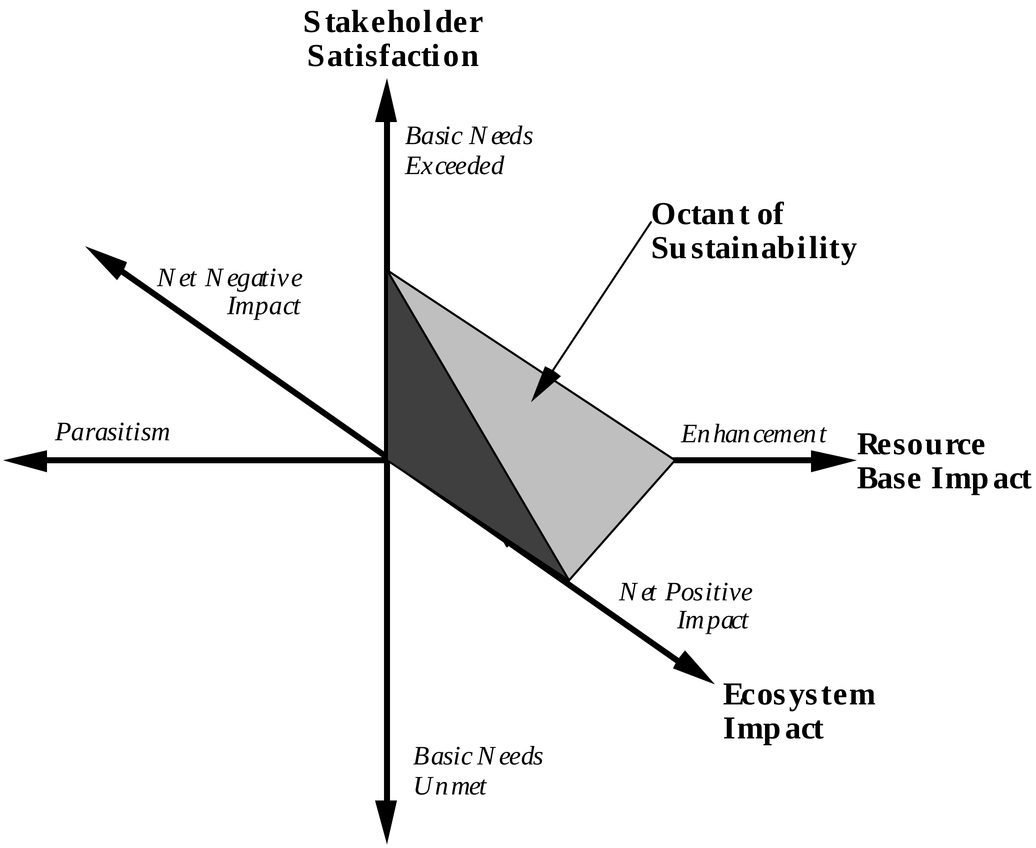


Figure 8: Triaxial Representation of Technological Sustainability

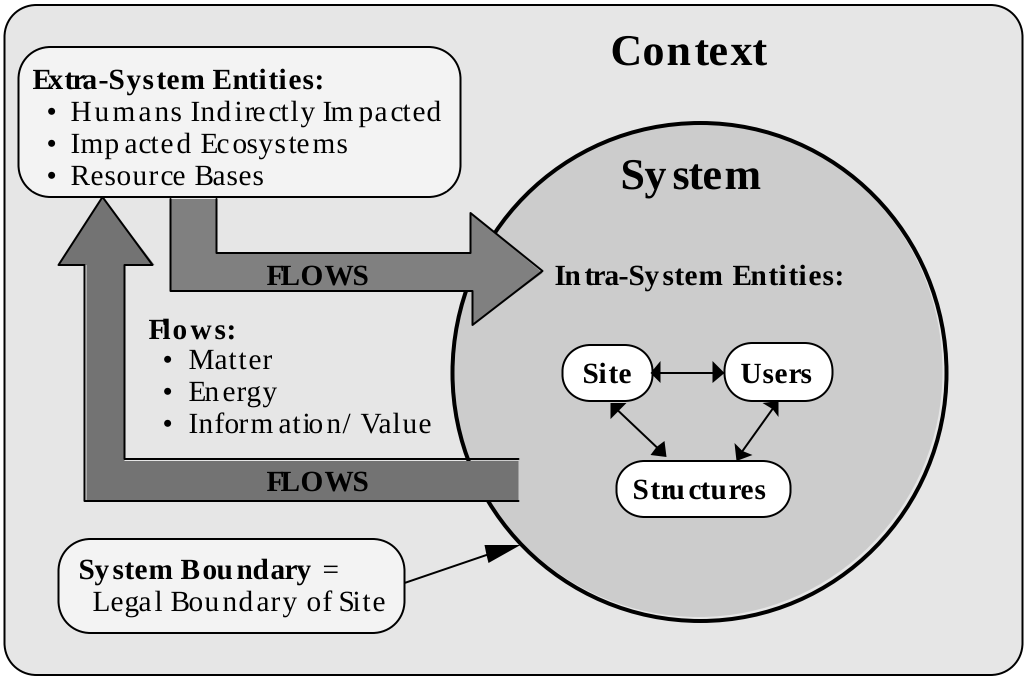


Figure 9: Entities and Flows of a Built Facility System [25]

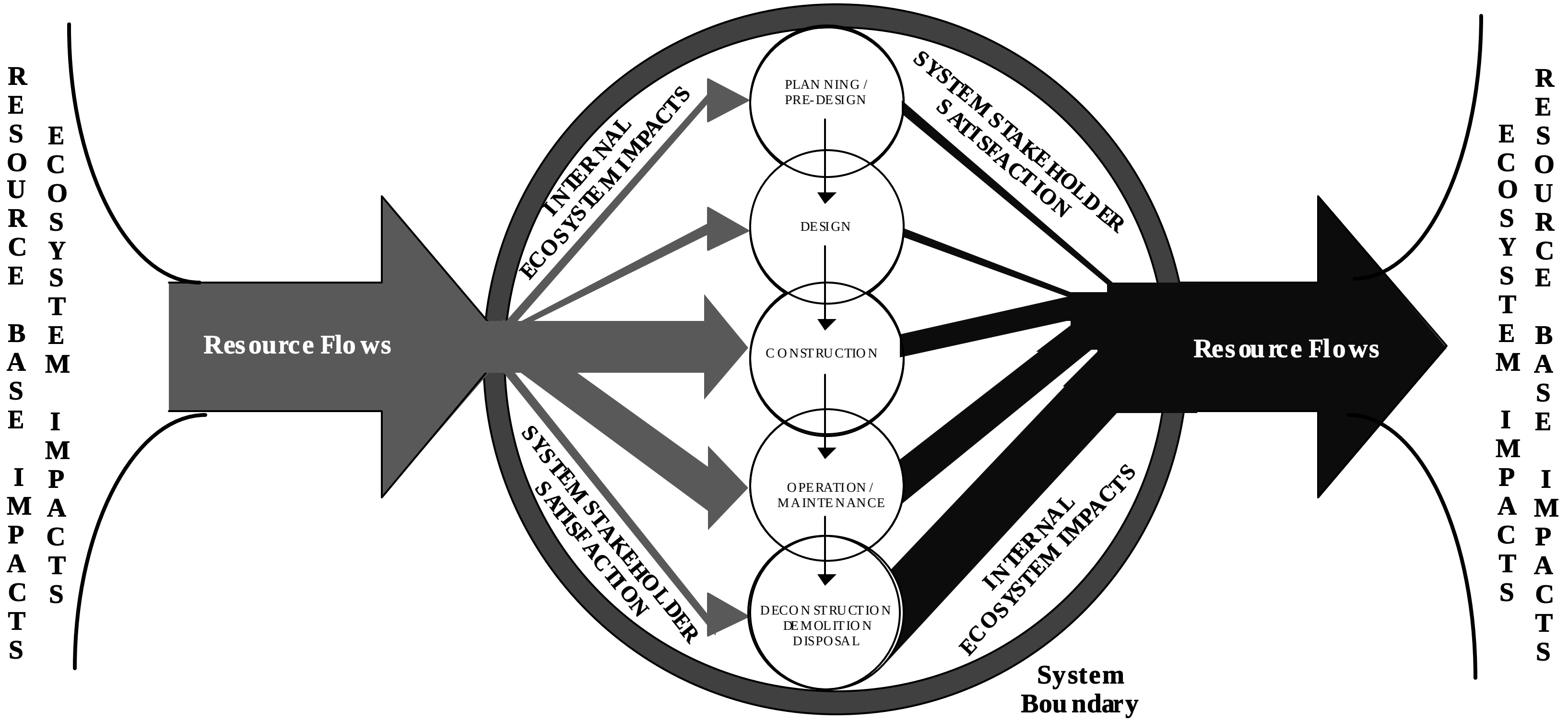
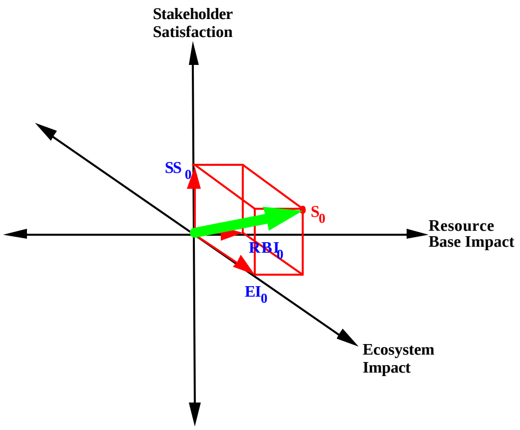
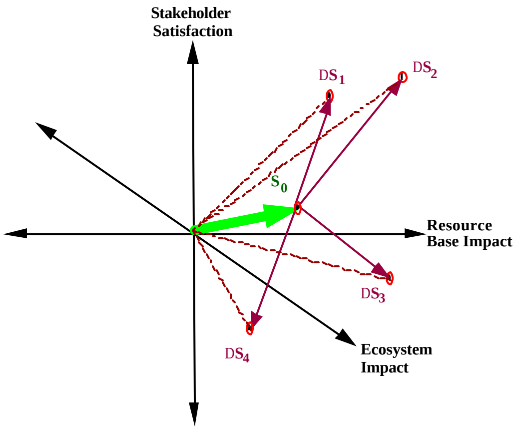


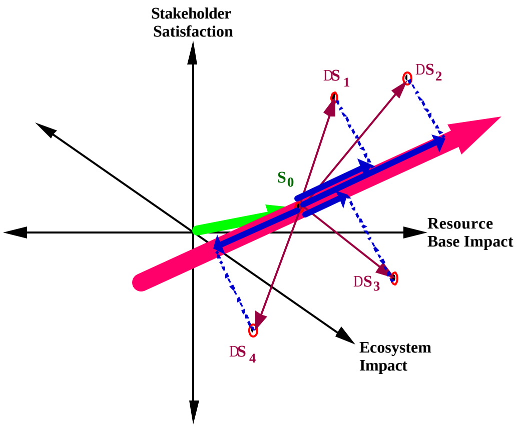
Figure 10: Resource Flows and their Impacts over the Life Cycle of a Typical Throughput Facility



a) establish baseline sustainability state



b) calculate sustainability change for candidate actions



c) compare projects via projection onto most positive unit vector

Figure 11: Prioritizing Candidate Projects according to Sustainability Increase [31]