AUTHOR: **Dr Annie R. Pearce** (Ph.D., LEED AP)

Presenter: **Annie Pearce**

Title of Paper: **Measuring the Sustainability of Infrastructure Systems: Information Requirements and Desiderata**

Assistant Professor
Myers-Lawson School of Construction
Virginia Tech (0156)
330A Bishop-Favrao Hall
Blacksburg, VA 24061
Phone: US 540-818-7732
Fax: US 734-293-8538
Email: apearce@vt.edu

Civil infrastructure systems (CIS) 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. In response to these impacts, interest in evaluating the sustainability of CIS is increasing among the owners responsible for their design, delivery, and operation to facilitate better decision making with regard to the limited resources available to deliver the services these systems provide.

This paper presents an overview of three distinct approaches to evaluating the sustainability of CIS – prescriptive, performance-based, and systems-based. Based on experiences with and lessons learned from these three measurement approaches in vertical construction, the paper compares and contrasts the information requirements of each approach and the types of outcomes and guidance each approach would yield for the organizations that are responsible for CIS. The underlying theoretical framework for the paper is based on diffusion of innovation theory in organizational contexts, which provides a basis for evaluating which of the three approaches is most likely to succeed in the context of public sector decision making. The paper concludes with recommendations for the development of metrics of sustainability for CIS that take into account the organizational context of use to achieve both system sustainability and sustainability of implementation within the organization.

Introduction and Background

Civil infrastructure systems provide the basis for all contemporary human activity on Earth. From providing clean water, to treatment and disposal of solid and liquid waste, to generating and transmitting power and providing the means for mobility and communication, civil infrastructure is the "body" of civilized society. Without it, we could not survive and prosper. However, despite the ubiquity of civil infrastructure systems and the criticality of the services they provide, these systems have not always performed to desired levels of service (e.g., ASCE 2005; Heller 2001). Moreover, the penalties these systems exact on the underlying infrastructure of the natural environment are severe, and cannot be sustained at current levels without ongoing degradation of ecosystem services or depletion of resource bases (Doyle et al. 2008; Lemer 1996; Hendrickson & Horvath 1997).

In recognition of these challenges, there has been a growing interest in infrastructure sustainability as an area of research, education, and practice (Jeon & Amekudzi 2005). Multiple public agencies in the United States have adopted sustainability policies for all facilities, both vertical and horizontal, under their control (see inventories and analyses by USGBC 2002; Dubose et al. 2007; Pearce et al. 2007; Jeon & Amekudzi 2005; and Amekudzi & Khisty 2008 for examples).

Specific challenges associated with measuring built environment sustainability abound. At the foundation of the problem is the lack of a widely accepted operational definition of the construct of sustainability, although substantial work has been done to date to address this problem[1]. Efforts to date have focused on defining categories of frameworks to represent sustainability of infrastructure systems (e.g., Jeon & Amekudzi 2005) and identifying relevant indicators and appropriate amalgamation methods (e.g., Ugwu et al. 2005a, b). While acknowledging the importance of these efforts, this paper focuses instead on the more practical issues associated with measurement system implementation that should be considered during the development of such a system to ensure that it does what it is designed to do. The next section presents a taxonomy of these considerations and describes the options available in more detail.

Measurement Approaches for Civil Infrastructure Sustainability

There are a variety of purposes for measuring or assessing the sustainability of engineered systems (Pearce et al. 2000). These include:

<u>Baselining</u> – establishing an initial system state against which to calibrate future performance

<u>Benchmarking</u> – providing a basis for comparison with competitors and identifying what is the state of the art in a given practice

<u>Prioritization, decision support, or selection</u> – establishing a basis by which to allocate finite resources for implementation of one or more solutions with the objective of maximizing benefits

<u>Documentation</u> – capturing evidence to support conformance with standards, compliance with regulations, or progress being made toward improvement.

The ultimate use to which sustainability assessment is to be put, within the organizational context of application, helps to guide the selection of an appropriate approach. Existing approaches to measure the sustainability of built facilities can be divided into three classes: prescriptive approaches, performance-based approaches, and systems-based approaches. The following subsections describe each of these classes in more detail, along with the context in which each can be effectively applied and examples from vertical construction measurement systems used in the United States. The section concludes with a summary of the issues to consider when applying each approach to the various purposes of measurement described above.

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[1] See (Pearce 1999) and (Pearce & Vanegas 2001) for an overview of work in this area and a proposed operational definition of sustainability for engineered systems.

Prescriptive Approaches to Measurement

Prescriptive tools consist of sets of recommended or best practices toward achieving the goal state of sustainability, and as measurement tools they are primarily point-based. A facility system could be evaluated using such a tool by allocating one or more points for each best practice that is implemented in the facility at the time of measurement. For example, early versions of the Leadership in Energy & Environmental Design (LEED) Green Building Rating tool (e.g., USGBC 1998) assigned a point for using specific technologies such as porous pavement. Porous pavement is an effective technology in many circumstances for addressing the problem of urban stormwater runoff, and as such is a recommended best practice for certain paved areas of facility systems. Later versions of the system (e.g., USGBC 2004) still rely for some of their credits on best practices with respect to specific technologies (e.g., Low VOC paints and carpets), although other credits are more performance-based (such as water and energy efficiency credits). Low VOC paints and carpets are actually somewhat of a hybrid between prescriptive and performance-based, since they allow multiple kinds of paints and/or carpets within the envelope of the low VOC criteria (a performance-based approach), but they still limit the points to instances where floors are covered with carpet (not other types of floor coverings) and walls are covered with paint (not other types of wall coverings).

Based on these examples, we can see that prescriptive measurement approaches suffer from several weaknesses. First, they are dependent upon present technologies and best practices, which necessarily change over time due to improvements in state of the art. Second, generalizability to multiple types of facilities in multiple contexts is difficult to achieve with these tools; to be useful in decision making, they must contain recommendations that are specific enough to apply to real facilities in real contexts, which usually means that they are limited in scope to the types of facilities and contexts for which they were developed.

For example, the LEED New Construction tool is applicable primarily to new commercial or institutional construction in urban or suburban areas. In this type of context and for these facility types, using porous pavement and low VOC paints and carpets makes sense as a best practice. But what about adaptive reuse of existing facilities in urban areas, where pavement already exists that would not usually be replaced? In this situation, removing existing pavement and replacing it with porous pavement to obtain a point would involve significant additional impacts outside the typical scope of work (and perhaps is one of the reasons that porous pavement was removed as a potential point in later versions of the LEED system). What about facilities that contain no paved areas, such as certain residential facilities? From a runoff standpoint, having no paved areas is superior to having porous pavement, which is superior to using impervious pavement. Yet the prescriptive standard would penalize the facility with no paved areas, since it does not meet the criterion as stated. What if the LEED system is being applied to a warehouse, where carpet is not typically used at all? Should project teams include a token amount of low VOC carpet for the sake of the point, even though they would not otherwise do so in a good warehouse design?

Optimizing the facility from this standpoint would likely result in negative impacts from a whole systems standpoint that would overwhelm the benefits realized from undertaking the best practice. What is most sustainable for one type of construction is not necessarily sustainable for other kinds of construction. Yet prescriptive standards for measuring facility sustainability offer an easily understood and easily measured way to encourage industry to adopt sustainability best practices (Bray & McCurray 2006). The ethics and talent of the design team are the primary control to ensure that these systems do not encourage suboptimization in the project for the sake of points. Prescriptive methods work well in situations where they are contextually adapted and applied, such as the proliferation of residential green building rating systems that are being developed locally in over 30 cities or regions around the United States (see NAHBRC 2002 for one list of these programs).

Performance-Based Approaches to Measurement

Performance-based approaches to measurement address some of the weaknesses of prescriptive standards. Rather than specify a specific best practice or technology that might not be appropriate for all situations, performance-based tools denote compliance based on whether or not the solution meets or exceeds a threshold on some continuum representing the problem that a best practice is meant to address. For instance, a performance-based measurement system might allocate a point if the pavement used in the parking lot produces less than a certain amount of runoff for a storm event of a certain magnitude, or if the net runoff from the site is less than or equal to predevelopment conditions. Newer versions of the LEED rating system have moved toward this type of standard for many credits, although there are still some prescriptive credits (most notably the Alternative Transportation credit and the several credits in Sustainable Sites dealing with site selection). Performance-based measures specify an objective to be met by the pavement, not *which pavement* should be used to meet this objective. The designer or decision maker is free to choose a pavement type that is most appropriate in the context of the specific facility. As long as the pavement results in a condition that meets the objective, the point is obtained.

While performance-based measurement tools represent a significant improvement over prescriptive tools, they still encourage reductionist optimization of specific aspects of a built facility. As such, they fail to recognize that what is optimal from the perspective of a single problem (e.g., stormwater runoff) might reduce the optimality of the system from a holistic standpoint (e.g., total resource consumption). How the problem is framed can also have a serious impact on the overall performance of the whole system. For example, if the measurement tool requires calculation of stormwater runoff from the pavement system, the decision maker might never even consider the question of whether pavement is needed at all. Considering tradeoffs among objectives and designing for an optimal balance of points is left to the decision maker, and can be a serious challenge in all but the simplest of contexts.

Systems-Based Approaches to Measurement

Systems-based measurement tools represent the most comprehensive approach to measuring facility sustainability. Systems-based measurement is equivalent to performance-based measurement, but on the scale of whole facilities, not individual building features. As such, systems-based measurement accounts for synergies among subsystems that comprise the facility system as a whole. An example of a system-level standard is to allocate credit if the whole facility system generates less than or equal to a certain quantity of stormwater runoff for a storm event. For instance, current LEED v.2.x stormwater credits take this approach. Notice that the idea of threshold-based credits remains the same, but the scale of measurement is based on the response of the facility as a whole – runoff from the pavement system as well as other impermeable surfaces such as roofs could be captured by swales surrounding the parking area, or diverted into a settling basin for later use in groundwater recharge or irrigation, or any of a number of other strategies, as long as the combined effect meets the system-level requirement. What matters is the total impact of the whole facility system, which in the stormwater example can be different than the mere sum of the impacts of the subsystems due to potential interactions among them.

The challenges associated with systems-based approaches to measurement are primarily associated with modeling the synergistic effects of multiple subsystems acting in concert with one another and in obtaining commensurate and reliable data to conduct the analysis. Very few attributes of the built environment have been effectively modeled on this scale in ways that have been widely adopted by designers as a decision aid. Energy performance is one example – multiple models of whole building energy performance exist, and a growing number of designers either integrate this capability in-house or rely upon out-sourced expertise to incorporate it into design decisions. Yet the ability to concurrently optimize multiple facility attributes and easily compare implications and tradeoffs with respect to different design alternatives remains elusive. Approaches to concurrently optimizing multiple systems remain in their infancy and often rely on non-traditional modeling techniques such as genetic algorithms (e.g., Wang et al. 2005a, b; Gustafsson 2000). Similar approaches have been applied as well in the horizontal facility domain using tools ranging from case-based reasoning to neural networks and Markov chains (e.g., Morcous 2005; Morcous & Lounis 2005a, b).

An interesting point to note is that while it is difficult to accurately *predict* future performance of a facility using a systems-based approach due to the difficulty of modeling complex systems interaction, it is considerably easier to *monitor* performance at a systems level using such an approach through the use of procurement information. By establishing a boundary around the facility system and tracking the flows of matter and energy across that boundary over time, a mass balance-type model can be constructed to model the *actual* performance of the system, thereby permitting inferences about the synergistic effects of the various sub-systems contained within the larger system. Pearce and Fischer (2001; see also Pearce 2008a, b) have developed and applied a protocol for systems-based sustainability analysis in the context of sustainable rehabilitation of historically significant structures that describes in detail the steps and assumptions involved in such an analysis.

Utility of Measurement Approaches

Which approach is most useful for a given purpose depends on a number of factors, including the degree of resolution required, the information available during measurement, and the purpose to which the results will be put. Table 1 provides a summary of the three approaches in terms of potential utility for the four purposes identified at the beginning of this section. While each of the three approaches can be used for any of the four purposes, the shaded areas indicate a higher likelihood of usefulness given the requirements of use.

Table 1: Measurement Approaches vs. Purposes of Measurement

Approach	**Prescriptive**	**Performance-based**	**Systems-based**
Baselining			
Benchmarking			
Prioritization			
Documentation			
Summary	Useful where coarse resolution is sufficient or best practices are well-established and do not frequently change	Useful where good performance simulation models exist and system behavior is predictable	Useful when facilities are considered within a larger mission context and ongoing changes to the system are possible to optimize overall system performance

Lessons from Vertical Construction

Sustainability assessment of built facilities has been an active undertaking in multiple countries for the past fifteen years or more, with growing popularity especially in the United States (e.g., Ahn & Pearce 2007). In considering how to evaluate the sustainability of civil infrastructure systems, lessons learned from experiences with vertical construction can provide valuable guidance. The following sections describe some of the many challenges that have been faced in the vertical sector as a point of departure for determining how to proceed in measuring the sustainability of infrastructure systems.

Scale of measurement – where to draw the boundaries of analysis for a built system is a major challenge in establishing a measurement approach. Table 2 shows five different scales at which sustainability assessment has been attempted with respect to vertical construction. At each scale, there are both threshold systems that seek to provide a single result or value, and profile systems, which provide values for an array of variables relevant for consideration. Similar consideration must be given for CIS evaluation. What level of analysis is most meaningful in terms of the desired changes in behavior sought as a result of the rating system? For vertical construction, smaller scale ratings are often rolled up as part of larger scale ratings, e.g., materials achieving a GreenSeal certification are part of a building receiving a LEED-Homes certification which is part of a development receiving a LEED-Neighborhood Development certification which was constructed by a company that is rated using a triple bottom line metric.

Table 2: Examples of Sustainability Assessment at Various Scales

Scale	Threshold Systems	Profile Systems
Raw Material	Forest Stewardship Council Certification (http://www.fsc.org)	BEES (http://www.bfrl.nist.gov/oae/software/bees/)
Product or Assembly	GreenSeal (http://www.greenseal.org), GreenLabel Plus (http://www.carpet-rug.org)	Athena (http://www.athenasmi.ca)
Building	LEED (http://www.usgbc.org), GreenGlobes (http://www.greenglobes.com)	GBTool (http://www.iisbe.org/gbc2k/gbtool/gbtool-main.htm)
Development, City, or Region	LEED-ND (http://www.usgbc.org), Ecological Footprint (http://www.gdrc.org/uem/footprints/index.html), Carbon Footprint (various)	ICLEI Profile (http://www.iclei.org)
Enterprise	Ranking in Dow Jones Sustainability Index (http://www.sustainability-indexes.com), Carbon Footprint (various)	Global Reporting Initiative's Triple Bottom Line (http://www.globalreporting.org), SAM Corporate Sustainability Assessment (http://www.sam-group.com)

Amalgamation and scale validity – particularly with point-based systems, the temptation exists to use ratings as a basis for comparing buildings, but this is not appropriate from a mathematical validity standpoint. Are all points of equal "worth" in measuring sustainability? Are the two points one can earn in LEED for achieving 60% energy reduction over minimum requirements worth the same as the two points one earns for achieving 20%? Can mathematical operations be validly performed when combining or amalgamating values for individual indicators into a single rating value (e.g., Elliott 1981)? Does the combination of points have any true meaning when comparing sustainability states of alternatives? These questions must be addressed and limitations clearly defined when determining how a metric should be used in application.

Context specificity – to a large degree, the sustainability of a given solution will vary dramatically based on its context of use. For instance, incinerating toilets may be a tremendously unsustainable solution where energy is scarce or difficult to produce, but an excellent solution where energy is abundant and water is scarce. How can a measurement system incorporate context of use in weighting the relative importance of attributes or variables, without also incorporating rater biases? The newest version of the LEED rating system, currently under development, is proposing to do this via a system of region-specific credit requirements applied to buildings based on location, but undertaking such an effort in a point system makes valid comparison of ratings across buildings even more difficult. Table 3 shows the evolution of approach to this issue over the multiple versions of the LEED rating system.

Table 3: Context Specificity and the LEED Rating System[2]

Version	Launch	Approach to Context Specificity
LEED v1	1998	Somewhat prescriptive; limited building types – application guides proposed as mechanism for customization
LEED v 2.0, 2.1, and 2.2	2001ff	More performance-based; most credits converted; additional application guides developed; additional core rating systems developed for Homes, Neighborhood Development, Existing Buildings, Core & Shell, and Commercial Interiors
LEED 2009	2009	Regional credits and bookshelf approach introduced (USGBC 2008)

Mutual exclusivity and collective exhaustiveness – how can we be sure we have considered all the relevant variables for sustainability without double-counting? For instance, why is Legionella important enough to warrant its own category in some British rating systems, but not other potentially threatening building-related illnesses (BREEAM 1993)? Having a broadly accepted operational definition for sustainability can lay the groundwork to ensure that variables considered as part of a measurement system are mutually exclusive and collectively exhaustive (Pearce 1999; Pearce & Vanegas 2002).

Utility to one or more target audiences – the construction of a measurement system affects its utility to potential target audiences, and can provide either a bridge or a barrier to effective communication and motivation among project stakeholders. The form of the assessment, e.g., technical detail, accuracy, etc. should be influenced by who will receive and interpret the results, and the measurement system to be used must effectively match its context and purpose of application (Gray & Baird 1996). O'Hare (1980) recommends packaging information by *user*, not by subject as has typically been done in the past. Information presented in a way that is sensitive to the needs of the recipient increases the likelihood that the recipient will use the data in line with the goals of the assessment.

Balance between meaningful results and level of effort – Meaningful results are the minimum level of precision at which true distinctions can still be made among options being considered. From an analytical standpoint, more precision is generally desirable, but analysts often forget that data is only as precise as its lowest common denominator, collecting good data is expensive, and distinctions among options can often be made with quite coarse data. From a decision standpoint, it may be better to have comprehensive data at a very coarse resolution than to have incomplete data with high precision, even though the former may be perceived to have less analytical rigor

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[2] See http://www.usgbc.org for the history/details of previous, current, and future versions of LEED rating systems

than the latter (see Pearce & Fischer 2001; Pearce 2008a). This tradeoff between perceived rigor and level of effort must be managed to ensure that measurement systems are useful for their intended purpose without imposing undue costs on their implementers.

Real degree of distinction among potential alternatives – In many cases, facility alternatives may be, for all intents and purposes, virtually equivalent in terms of certain sustainability indicators, in which case those indicators are irrelevant for decision making and only complicate the analysis. Stochastic approaches to modeling key variables may in some cases be the only approach to accounting for potential differences, particularly in cases where representative distribution of data is known. For instance, it is nearly impossible to specify the recycled content of a particular sheet of gypsum board, given that feedstock to manufacturing processes varies on a daily basis due to market variations in amount of recycled feedstock available. What matters more in this case is not the specific recycled content of the specific sheet of drywall, but rather the statistically likely recycled content. Incorporation of stochastic methods into environmental performance modeling has the potential to substantially reduce the complexity of product documentation as well as increase the comfort level of manufacturers in disclosing specific information. Third party verification can help to ensure that the basis for evaluation is consistently and validly applied.

Projected vs. actual performance – A sustainable facility on the drawing board is not necessarily a sustainable facility in actual practice. Key to the performance of a facility is the context of its application and the interaction between the building and the stakeholders who occupy and otherwise interact with it. Metrics like LEED-NC compare building alternatives on the basis of projected performance of the design, but they have no way of taking into account what will actually happen with the facility after it is in operation[3], and at least one study has found considerable discrepancies between forecast and actual performance in LEED buildings (Turner 2006). This is one reason that there has been some industry resistance to establishing green building product ratings in the United States – there is a widespread recognition that products are only as green as the use to which they are put. An environmentally friendly product applied incorrectly or inappropriately quickly becomes a waste of resources and disposal problem when it must be replaced by an alternative.

Obtaining uniform data – with many building products being essentially commodities and others being proprietary, obtaining consistent and uniform data on relevant sustainability indicators for building products is exceedingly difficult. Data requirements should respect the proprietary interests of manufacturers while still providing enough accurate information to permit meaningful analysis. New methods are needed to establish consistent evaluation methods across multiple material classes to allow valid amalgamation and cross-indicator comparison of products.

Comparison of Approaches as Innovations

Innovation diffusion and adoption provides a relevant knowledge base on which to evaluate potential measurement approaches. For the purposes of this analysis, the innovation adoption decision being considered is which sustainability measurement approach to take. The adopter in question is the public sector owner or agency responsible for the infrastructure system being evaluated, since this owner has the authority to impose measurement and performance requirements on

[3] The US Green Building Council has begun to address this challenge with the deployment of LEED for Existing Buildings, which can be periodically applied to a building over time to ensure excellent performance.

all other stakeholders of the system. Given this perspective, both the concept itself and the tools and techniques used to achieve it represent innovations in that they are either new or perceived to be new and are previously unused by their potential adopters (Rogers 2003). This theory then becomes helpful for enhancing the design of measurement systems to encourage their successful adoption.

Other key characteristics defining the context of adoption considered here include resource constraints in terms of time and money; rigid organizational requirements such as procurement rules that must be met to achieve a successful solution; significant risk aversion of public sector clients due to public accountability requirements; competing objectives; and low levels of organizational and individual slack among involved stakeholders (OFEE 2003; Pearce & Fischer 2001; Pearce 2001; Pearce 2003; Keysar & Pearce 2007). Many of these characteristics serve as inhibitors to innovation adoption (Rogers 2003).

The rate and success of diffusion of innovations across a population of potential adopters is influenced by characteristics of the innovations themselves along with characteristics of adopters. The characteristics of innovations that have been most widely studied are relative advantage, compatibility, complexity, trialability, and observability (Rogers 2003). Diffusion of innovation and innovation implementation theory suggests that, all else being equal, the likelihood of adopting an innovation increases with the extent to which perceived benefits exceed costs (e.g., Panzano et al. 2004; Rogers 2003). Key to this notion is the relative importance of perception over hard evidence; in fact, one author states that "…scientific evidence in support of the effectiveness of an innovation may be helpful but it is neither necessary nor sufficient for the adoption of innovative practices by organizations" (Panzano et al., 2004, paraphrasing Abrahamson 1991; Denis et al., 2002). Rogers' five attributes of innovations (2003) that affect their successful adoption provide a useful framework for evaluating and comparing candidate approaches and predicting their likelihood of success/adoptability. Table 4 provides a definition for each of these constructs along with an interpretation of that construct in the context of civil infrastructure systems.

The characteristics of adopters also affect adoption decisions (Rogers 2003; Moore 1991; Panzano et al. 2004). In this paper, we assume that the adopter base of interest is public agencies responsible for civil infrastructure systems that have not previously attempted to measure sustainability of their projects, along with their design and contracting firms who would implement new systems and evaluate their performance. Depending on the ultimate purpose of measurement, there may also be other stakeholders who are relevant and exert influence on the public agencies who implement a measurement system. For instance, if the system being evaluated is a public project, then measuring its sustainability performance for benchmarking purposes may be relevant from a public relations standpoint, and therefore the general public may be a stakeholder interested in the findings. One example of an approach meant to appeal to the general public in the United States is the American Society of Civil Engineers' Infrastructure Report Card (ASCE 2005), which periodically rates CIS in the United States using a "letter grade" approach. Design of the front-end interface of such an information system may be as important as the content of the system itself, depending on the intended outcomes of the system and the audience it is intended to address (e.g., Bosch & Pearce 2003).

Table 4: Attributes of innovations that affect their adoption (after Rogers 2003)

Attribute	**Definition**	**Interpretation with respect to Civil Infrastructure Systems**
Relative Advantage	The extent to which an innovation is better than the product/tool it is replacing	Degree to which measurement system can provide results useful for decision making or system improvement (or whatever purpose is driving its adoption) vs. the amount of investment (time, funds, political capital) required for its implementation
Compatibility	The degree to which the innovation fits within the existing processes and culture of potential adopters	Degree to which system fits within the established project delivery process and existing data structures for the type of project being evaluated, e.g., no new steps added; no additional time required; no additional supporting innovations required to implement tool; no new stakeholder involvement required
Complexity	The degree of difficulty an adopter has in understanding and/or using an innovation	Level of training or prior knowledge required to effectively use the measurement system; degree to which system requires non-traditional information or knowledge to achieve results
Trialability	The degree to which a potential adopter can "test drive" an innovation prior to making an adoption commitment	Level of commitment required to use the measurement system, including fiscal and other resource commitments on the part of the owner as well as level of market commitment required to generate the necessary information to use the system
Observability	The degree to which the benefits resulting from innovation adoption are apparent as an outcome of adoption	Degree to which system provides outcomes or measurement results that correlate well with observed system performance and understanding of relevant performance constructs by key stakeholders.

Comparing Measurement Approaches in Terms of Requirements and Outcomes

The first step in comparing the three measurement approaches discussed in this paper is to identify the types of information required to populate each type of system, the approach required to validate measurements generated by the system, and the expected outcomes and utility of information provided by the system. Table 5 describes these factors for each of the three approaches to measurement.

In terms of required information, prescriptive measurement approaches are perhaps the easiest to implement, although coordination of timing is required to ensure that the features requiring observation are in fact observable when the inspector appears to evaluate them. Based on design to survive worst case scenarios, the prescribed design features are also more likely to be over-designed if the system is generalized to a variety of contexts. In contrast, while performance-based and systems-based approaches require much more information and effort to evaluate system performance, they support a better understanding and optimization of the relationship between the designed facility and its context. Given that CIS are typically unique, custom designed facilities to meet specific contextual requirements, the latter two measurement approaches would seem to be better suited for these types of systems.

Comparing Measurement Approaches in Terms of Innovation Attributes

The second basis for comparison is to evaluate the three measurement approaches in terms of Roberts' attributes of innovation. Table 6 provides a description of how each approach fares in

Table 5: Comparison of Measurement Approaches in Terms of Requirements and Outcomes

Approach	Information Required	Validation	Outcomes
Prescriptive	Information is needed about the presence or absence of specific observable design features.	A third party inspector typically visits the project to determine whether those features are included, OR the project team may document their inclusion via photographs, videos, or other means and provide this documentation for review by a third party.	If inspection occurs during construction before the system is "enclosed", discrepancies can be corrected before they are irreversible. Design features are typically generic from context to context and may represent significant over-design in order to succeed in the worst case scenario.
Performance-based	Information is needed about the ability of specific facility systems to meet or exceed specified performance thresholds under normal operating conditions.	Performance is typically either (a) observed post-construction through performance testing or during use; (b) predicted using simulation models; or (c) verified using design heuristics applicable to the particular system type and conditions being installed.	If validation is not undertaken until the whole system is completed and functioning, fixing performance failures may be costly and require taking the facility out of service. Validation occurring during design using simulation or heuristics may not correspond to actual facility performance when measured post hoc. Systems can be designed to better fit contextual requirements, thus reducing the penalties of over-design.
Systems-based	Information is needed about the inputs, outputs, sources, and sinks required to implement and operate the facility as a whole. This information may be derived from corresponding information at the subsystem scale.	Simulation or heuristic modeling is required to predict system flows based on design features. Verification of actual flows, sources, and sinks requires careful tracking during delivery and operation.	Problems with predicted performance may not be observable until it is too late to correct them without undoing previous efforts. Isolating and fixing the cause of discrepancies may be difficult. Balancing the impacts of many subsystems can result in whole system performance improvement.

terms of these five variables, based on the interpretation of variables listed in Table 4 and experiences with the three approaches for vertical construction.

The descriptions of each measurement approach in the table represent the owner's, i.e., public agency's, perspective on each innovation attribute. Although the table provides some useful insights into the merits and challenges associated with each approach, it is a comparatively simplistic evaluation of what is a complex question: how to measure the quality of sustainability in a way that most rapidly encourages movement toward a sustainable society. This question is perhaps best answered in the context of specific situations. Just as we would wish for a context-sensitive approach to evaluating the sustainability of our facility systems, so also would we wish for a context-sensitive approach to evaluating the organizational sustainability of our measurement systems.

Conclusions and Future Research

This paper has attempted to evaluate three potential approaches to measuring the sustainability of civil infrastructure systems: prescriptive, performance-based, and systems-based. Building on key

Table 6: Comparison of Measurement Approaches in Terms of Innovation Attributes

Approach	Prescriptive	Performance-based	Systems-based
Relative Advantage	Low utility for custom-designed systems; low investment in resources for implementation.	Higher utility for custom-designed systems; medium investment in resources for implementation.	Highest utility for custom-designed systems; variable investment in resources for implementation depending on type of decision support sought.
Compatibility	Good fit with typical existing delivery processes. Additional inspection or review may be required.	May require changes in existing delivery systems, including additional design documentation and review. May require modeling new performance characteristics of the system not previously considered.	May require changes in existing delivery systems, although can sometimes be inferred from existing data streams. Will require additional tracking and manipulation of data.
Complexity	Limited training required for third party inspectors/reviewers. Processes very similar to existing inspection processes.	Depending on what performance indicators are modeled, may require extensive modeling expertise or measurement equipment post hoc.	System derives new knowledge from existing data streams and requires additional training to interpret. May require obtaining new data streams from vendors and providers that are not traditionally requested (e.g., source of raw materials, transport distance, etc.).
Trialability	Low commitment on the part of the owner other than initial development of prescriptive requirements and training of inspectors.	Medium commitment on the part of the owner, but substantial commitment on the part of design and contracting firms required to estimate performance parameters. May result in higher design and construction fees to owner.	High commitment on the part of the owner, particularly with regard to tracking procurement information and obtaining additional information from vendors. Medium to high commitment on the part of design and construction firms to solicit data from vendors. Cooperation on the part of vendors and manufacturers to disclose new kinds of information.
Observability	By definition, use of prescribed design features is easy to observe during construction, but these may or may not correlate with observable increases in performance by the public.	Correlates well with relevant performance indicators observable by the public.	Does not necessarily correlate well with performance indicators observable by the public, but may correlate positively with accountability metrics pertaining to efficiency of resource use.

issues and lessons learned from application of these approaches in vertical construction, the paper identifies key considerations, precedents and examples from building construction, and factors from theory on diffusion of innovations to suggest what may be important design considerations when developing a measurement approach for CIS.

Future research in this domain must include both human considerations and technical considerations when evaluating sustainability, even as sustainability itself represents a balance between human needs and aspirations and the impacts of the solutions we design to meet those needs and aspirations. Specific areas meriting additional study include further investigation of the stakeholders and organizations involved in the equation of sustainability for CIS, and the roles and resources they offer toward achieving sustainability. A measurement system must take into account the roles, resources, and ultimate motivations of stakeholders who use it. Better understanding of the organizational context of use will enable a system to be designed that provides maximally useful knowledge to people with the power to make better decisions.

Selection of metrics to measure the impacts and performance of CIS will necessarily vary by system type, although at a systems-based scale, those metrics may look quite the same across different types of infrastructure systems. In defining what makes a CIS sustainable, we must achieve broad agreement on what constitutes the failure of these systems, including technological, ecological, economic, and social failure. Together, these considerations define the sustainability of the human-technology-ecology system that we ultimately seek to sustain as a way of meeting human needs and aspirations. While we may be able to conceive of the ideal way to measure system sustainability from a results standpoint, we must also carefully consider how such a tool will be used to ensure that it meets its desired goals.

References

Abrahamson, E. (1991). "Managerial fads and fashions: The diffusion and rejection of innovations," *Academy of Management Review,* 16(3), 586-612.

Ahn, Y.H. and Pearce, A.R. (2007). "Green Construction: Contractor Experiences, Expectations, and Perceptions," *Journal of Green Building,* 2(3), 106-122.

Amekudzi, A.A. and Khisty, C.J. (2008). "Sustainability Footprints, Calculus, and Infrastructure Systems Evaluation," *Proceedings, Transportation Research Board 2008 Annual Meeting*, Washington, DC.

ASCE – American Society of Civil Engineers. (2005). *2005 Report Card for America's Infrastructure*. Available online at http://www.asce.org/reportcard/.

Bosch, S.L. and Pearce, A.R. (2003). "Sustainability in Public Facilities: Analysis of Guidance Documents," *Journal of Performance of Constructed Facilities,* Special Issue on Facilities Design and Management, 17(1), 9-18.

Bray, J., and McCurray, N. (2006). "Unintended Consequences: How the Use of LEED Can Inadvertently Fail to Benefit the Environment," *Journal of Green Building,* 1(4), 152–165.

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

Denis, J., Hebert, Y., Langley, A., Lozeau, D., & Trottier, L. (2002). "Explaining diffusion patterns for complex health care innovations," *Health Care Management Review,* 27(3), 60-73.

Doyle, M.W., Stanley, E.H., Havlick, D.G., Kaiser, M.J., Steinbach, G., Graf, W.L., Galloway, G.E., and Riggsbee, J.A. (2008). "Environmental Science: Aging Infrastructure and Ecosystem Restoration," *Science*, 319(Jan 18), 286-287.

DuBose, J.R., Bosch, S.J., and Pearce, A.R. (2007). "Analysis of Statewide Green Building Policies," *Journal of Green Building,* 2(2), 161-177.

Elliott, M.L. (1981). "Pulling the Pieces Together: Amalgamation in Environmental Impact Assessment," *Environmental Impact Assessment Review,* 2(1), 11-38.

Gray, J. and Baird, G. (1996). "How to Plan and Conduct Evaluations," in Baird et al., eds. *Building Evaluation Techniques.* McGraw Hill, New York, NY.

Gustafsson, S. (2000). "Optimization and simulation of building energy systems." *Applied Thermal Engineering*, 20, 1731-1741.

Heller, M. (2001). "Interdependencies in Civil Infrastructure Systems," *The Bridge*, National Academy of Engineering, 31(4), Winter. Available online at http://www.nae.edu/nae/bridgecom.nsf/weblinks/KGRG-573PLA?OpenDocument.

Hendrickson, C.T. and Horvath, A. (1997). "Discussion: Infrastructure Obsolescence and Design Service Life," *Journal of Infrastructure Systems*, 3(3), 127.

Jeon, C.M. and Amekudzi, A.A. (2005). "Addressing Sustainability in Transportation Systems: Definitions, Indicators, and Metrics," *Journal of Infrastructure Systems,* 11(1), 31-50.

Keysar, E. and Pearce, A.R. (2007). "Decision Support Tools for Green Building: Facilitating Selection Among New Adopters on Public Sector Projects," *Journal of Green Building*, 2(3), 153-171.

Lemer, A.C. (1996). "Infrastructure Obsolescence and Design Service Life," *Journal of Infrastructure Systems*, 2(4), 153-161.

Moore, G.A. (1991). Crossing the Chasm: Marketing and Selling High Tech Products to Mainstream Customers. Harper Collins, New York, NY.

Morcous, G. (2005) "Performance Prediction of Bridge Deck Systems Using Markov Chains", *Journal of Performance of Constructed Facilities.*

Morcous, G., and Lounis, Z. (2005a). "Maintenance optimization of infrastructure networks using genetic algorithms and Markovian models." *Automation in Construction,* 14(1), 129-142.

Morcous, G., and Lounis, Z. (2005b) "Prediction of Onset of Corrosion in Concrete Bridge Decks Using Neural Networks and Case-Based Reasoning", *Journal of Computer-Aided Civil and Infrastructure Engineering*, 20, 108-117.

NAHBRC – National Association of Home Builders Research Council. (2002). "List of Local Residential Green Building Programs." April 17, Washington, DC. http://www.nahbrc.org/tertiaryR.asp?TrackID=&CategoryID=1801&DocumentID=2858

OFEE (Office of the Federal Environmental Executive). (2003). *The Federal Commitment to Green Building: Experiences and Expectations*, Office of the Federal Environmental Executive, Washington, DC. Available online at: http://ofee.gov/sb/fgb.html.

O'Hare, M. (1980). "Improving the Use of Information in Environmental Decision Making," *Environmental Impact Assessment Review,* 1(3), 229-250.

Panzano, P.C., Roth, D., Crane-Ross, D., Massatti, R., and Carstens, C. (2004). "The innovation diffusion and adoption research project (IDARP): Moving from the diffusion of research results to promoting the adoption of evidence-based innovations in the Ohio Mental Health System," *New Research in Mental Health, Vol. 15.,* Roth, D., ed. Ohio Department of Mental Health, Columbus, OH, 149-156.

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

Pearce, A.R. (2001). "Sustainable vs. Traditional Facility Projects: A Holistic Cost Management Approach to Decision Making," White paper prepared for U.S. Army Forces Command, Fort McPherson, GA.

Pearce, A.R. (2003). *An Online Knowledge Base for Sustainable Military Facilities & Infrastructure.* Final Project Report to Region IV Department of Defense Pollution Prevention Partnership, University of South Carolina.

Pearce, A.R. (2008a). *Systems-Based Sustainability Analysis at the Installation Scale: Proof of Concept and Demonstration at Fort Belvoir.* National Defense Center for Environmental Excellence, Concurrent Technologies Corporation, Inc., Washington, DC.

Pearce, A.R. (2008b). "Sustainability at the Installation Scale: A Comparison of LEED-Based and Systems-Based Sustainability Assessment for Military Bases," *Proceedings of the International Conference on Sustainability Engineering and Science*, New Zealand Society for Sustainability Engineering and Science, Auckland, New Zealand, December 9-12, 2008.

Pearce, A.R., DuBose, J.R., and Bosch, S.J. (2007). "Green Building Policy Options in the Public Sector," *Journal of Green Building,* 2(1), 156-174.

Pearce, A.R., Fischer, C.L.F., and Jones, S.J. (2000). *A Primer on Sustainable Facilities & Infrastructure.* Text prepared for continuing education public offering, February 6 and 9, Atlanta, GA.

Pearce, A.R. and Fischer, C.L.J. (2001). Systems-Based Sustainability Analysis of Building 170, Ft. McPherson, Atlanta, GA. Summary analysis report to the Army Environmental Policy Institute, Atlanta, GA, May.

Pearce, A. R., and Vanegas, J. A. (2002). "Defining sustainability for built environment systems." *International Journal of Environmental Technology and Management*, 2(1), 94–113.

Rogers, E.M. (2003). *Diffusion of Innovations, 5th ed.* Free Press, New York, NY.

Turner, C. (2006). *LEED Building Performance in the Cascadia Region: A Post Occupancy Evaluation Report*. Cascadia Region Green Building Council, January 30. Available online at http://www.cascadiagbc.org.

Ugwu, O.O., Kumaraswamy, M.M., Wong, A., and Ng, S.T. (2005a). "Sustainability appraisal in infrastructure projects (SUSAIP): Part 1: Development of Indicators and computational methods," *Automation in Construction,* 15(2), 239-251.

Ugwu, O.O., Kumaraswamy, M.M., Wong, A., and Ng, S.T. (2005b). "Sustainability appraisal in infrastructure projects (SUSAIP): Part 2: A Case Study in Bridge Design," *Automation in Construction,* 15(2), 229-238.

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

USGBC – United States Green Building Council. (2002). "State and Local Government Toolkit" USGBC, November, Washington, DC.

USGBC – United States Green Building Council. (2004). "Leadership in Energy and Environmental Design – New Construction, v. 2.1". http://www.usgbc.org.

USGBC – United States Green Building Council. (2008). "LEED for New Construction 2009 – First Public Comment," USGBC, Washington, DC, July. http://www.usgbc.org.

Wang, W., Rivard, H., and Zmeureanu, R. (2005a). "An object-oriented framework for simulation-based green building design optimization with genetic algorithms." *Advanced Engineering Informatics*, 19, 5-23.

Wang, W., Zmeureanu, R., and Rivard, H. (2005b). "Applying multi-objective genetic algorithms in green building design optimization." *Building and Environment*, 40, 1512-1525.