System Life Cycle Evaluation, SliCE ^{SM}, for Green Building Technologies

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Abstract Current quantitative approaches to valuing green energy and water efficiency retrofits typically provide narrow financial analysis targeted at a limited set of stakeholders. This approach inadequately informs the decision-making process; technologies may be improperly selected or rejected due to insufficient information. Collaborative efforts are underway at the Georgia Tech Research Institute to formalize a systems evaluation methodology that quantifies performance against a broad range of stakeholder requirements. The methodology addresses requirements at each phase of a system's life cycle. The evaluation results are compiled in a decision support tool that enables decision makers to weight each requirement's contribution to an overall score. The methodology was originally conceived for a side-by-side evaluation of water filtration systems. To test for robustness and generate valuable data for a growing field, the methodology is now being applied to an extensive green roof system and a solar photovoltaic system.

Background: Typical Green Technology / Energy Efficiency Retrofit Analysis

Traditional energy efficiency retrofit analysis measures the basic financial impact of proposed investments in energy efficiency for identified facility improvements. Calculators are provided by various agencies, such as Energystar, or other corporate entities to provide organizations with tools to measure the projects viability. Traditional analysis for energy retrofits provide relative evaluation criteria and results including simple payback, net investment cost, reduction in operating expenses, energy savings, Return On Investment(ROI), Internal Rate of Return(IRR), Net Present Value(NPV), Net Operating Income(NOI) and Impact on asset value [1]. Traditional analysis usually covers the basic aspects, such as cost or savings, and is further magnified by other general assumptions such as average utility bill costing or typical performance claims. The basic inputs provides quick, but flawed results as decision maker typically miss the hidden values or cost of a technology selection for emerging systems especially green technologies [2]. Namely this can include social, economic, and environmental impacts which affect critical outcomes including the bottom line.

Comprehensive Decision Support Through Systems Evaluation

Multi criteria analysis (MCA) is commonly considered a best approach for choosing among options when multiple criteria may impact a systems outcome [3]. However, in practice, MCA decisions are constrained by the availability, or lack of data. The criteria for which there is data can be evaluated and rational decisions may be made, however when data is not available the criteria is more likely to be subject to ill-founded criticism.

The diverse set of criteria that is commonly applicable to green technologies falls within the broad sustainability categories: social cultural; environmental; and economic criteria [4]. Current efforts are underway in the green roof industry to enable product selection using the Battelle Method to create an environmental index for energy, acoustic, structural, economic, and code compliance criteria that can be weighted for a specific site. Similar approaches are being developed for renewable energy portfolio selection and water systems selection[5]. Current research needs to increase the data set and develop interactive tools to better inform MCA decisions [6-8]. This paper attempts to develop a broad framework for conducting experimental evaluations of systems based on broad stakeholder requirements throughout a systems life cycle.

Methodology

Overview of Systems Life Cycle Evaluation (SLiCE ^{SM})

A comprehensive evaluation methodology has been developed to test system performance based on identified stakeholder requirements throughout a system's life cycle. An evaluation consists of three stages: evaluation design, implementation, and data processing. In evaluation design the goal is to form an evaluation team, discern stakeholders, define the lifecycle of the system, and identify critical to quality characteristics (CTQs) that can be tested through performance indicators (PIs). The next stage, implementation, test and documents the systems performance and revises performance indicators. In the final stage, data processing, results are compared and packaged for dissemination and decision support.

SliCE Process

EVALUATION DESIGN

In this stage the team, resources, and plans for evaluation are developed. The major steps involve creating an evaluation team that can represent many perspectives; then cross-pollination to collect knowledge through literature review and communication with stakeholders. With this knowledge, the team is able to define the lifecycle of the system and decompose it into discrete phases. Each phase can be evaluated independently by identifying critical-to-quality (CTQ) characteristics that affect the phase's outcome. For each CTQ a unique performance indicator (PI) is generated to measure, through defined experiments, a systems compliance to the CTQ. A rubric for each phase facilitates the collection of PI scores and documentation of lessons learned.

Evaluation Team (E.T.)

To start the SLiCE methodology a multi-disciplinary evaluation team (E.T.) should be formed. A SLiCE E.T. should encapsulate diverse perspectives on the systems in question. Specifically, the members of the team should include a domain expert, an end user, and an original equipment manufacturer (OEM), as well as a SLiCE methodology facilitator. Once team members are selected, this is recorded on the roster provided in the SLiCE documentation, citing the name, contact information, and qualifications of each team member.

Cross-Pollination

To facilitate collaboration, the evaluation team should share perspectives and expertise within the team and collect general domain knowledge with the intent that participants may adapt and broaden their beliefs. Presentation of team members' respective areas of expertise should be given. Then the team may allocate responsibility of identifying the current body of knowledge in the form of a literature review. This literature review should define the technology landscape, identify prior system comparisons, and review previous case studies. This process should facilitate the understanding of the following parameters: implementation scenarios, stakeholders, research questions, critical to quality characteristics.

Stakeholder identification is intended to capture the diverse set of participants who may share differing views and values [9]. Given the wide set of possible stakeholders, stakeholder identification may utilize the SLiCE a stakeholder identification worksheet based on Table 1. The E.T. should list a contact person representative of each category of stakeholder suggested on the form. These representative stakeholders are engaged in conversation through in-person meetings or correspondence. The E.T. should use this interaction to learn CTQs perceived by stakeholders and evidenced by stakeholder anecdotes. It is important to identify the different types of stakeholders, their importance and influence on the final product. For example the opinion of the end-user is extremely important in determining the success of the product but most often the end-user has the least influence on the how the system is evaluated. Figure 1 represents the relationship of different stakeholders and their influence and importance on the evaluation of a system.

Table 1: Stakeholder Identification

Category	Sub-Category
Decision Maker	Capital Investor
Financiers	O&M financer
	Other financers
Producers	Designers/Engineers
	Manufacturers
	Salespeople
End Users	Beneficiaries
	Installers
	Operators
	Maintainers
	Consumables Providers
Community	Municipality/Government
	Policy Makers
	Owns/Operates within Physical Proximity
Other Participants	Displaced Product/Service
	Opposition
	Future Markets
	Others

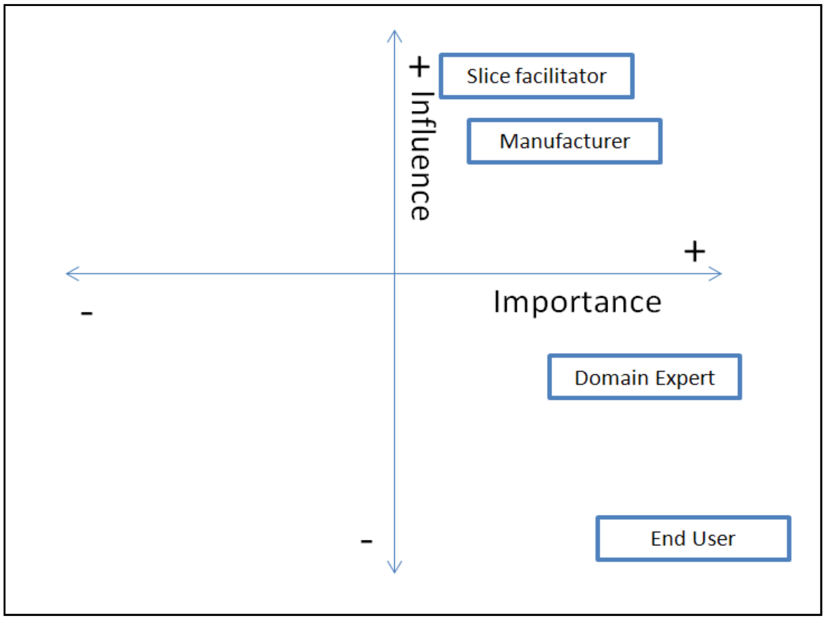

Figure 1: Stakeholder Mapping

In parallel to stakeholder identification the system life-cycle should be defined. These efforts feedback on each other, for example as new life cycle phases are identified new stakeholders may be recognized then those stakeholders may further expand the life-cycle. A typical life-cycle scope incorporates part or all of the following life cycle stages: material acquisition; manufacturing; distribution; product use; recycle; waste management[10]. For the purpose of systems evaluation the evaluation team may refine the scope to suite the resources of the analysis and to ensure stakeholder requirements are addressed [11]. A *phase* may be divided into multiple phases to provide the appropriate level of fidelity. A common example may be division of product use into operations phases and maintenance phase. A draft set of the life cycle phases for evaluation should be examined for applicability by a range of the stakeholders. Applicability scoring may be conducted as a means to pass the scope or require revision.

Critical To Quality Characteristics (CTQs)

Through the combination of the literature search and stakeholder focus group meetings, system processes and outputs occurring in each life-cycle phase are identified. Subsequently, the critical to quality (CTQs) characteristics associated with the processes and outcomes are identified for each phase of the project as shown in Figure 2 [12, 13]. To increase the likelihood comprehensively evaluating the systems, CTQs of each

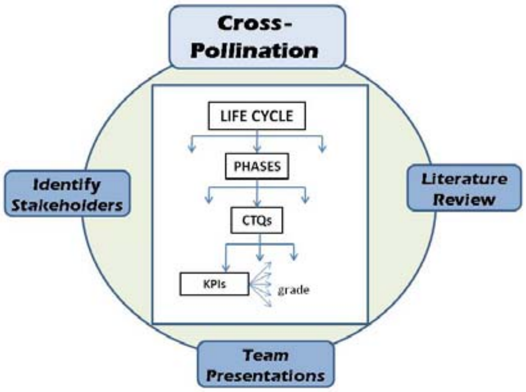

Figure 2: Evaluation Design

phase are considered in the sustainability categories: economic; environmental; and social..

Performance Indicators

Once CTQs have been identified, the E.T. establishes specific performance Indicators, PIs, that can be used to measure fulfillment of each CTQ and entail experimental procedures and scoring functions that normalize results. The experiments conducted may be mixed mode and result in both qualitative and quantitative results [14]. The scoring function developed by the E.T. aids the transformation by mapping the results onto a 1-5 scale. While the scale should accommodate the full range of expected results the min and max of the data set do not define a 1 and 5 respectively. To ensure consistency, a 1 is based on the most detrimental yet still feasible outcome while a 5 is based on the most beneficial and feasible outcome. The intermediate scores, 2, 3, and 4 may be defined at this point as well or be left to the discretion of the evaluation team to generate during implementation and review for consistency during data processing.

IMPLEMENTATION

During implementation the evaluation team runs the system through each lifecycle phase under conditions that simulate field conditions. During each lifecycle phase testing is conducted as prescribed by the PIs. Once adequate data has been collected a phase may be completed and the evaluation team may proceed to the next phase. However, in some cases, such as operation and maintenance, overlap between phases may occur.

With the definition of how the systems will be evaluated complete, the E.T. should proceed with implementing the life cycle phase by phase. The most effective way to glean a variety of insights and develop a robust systems review is to have a consistent set of diverse evaluators from the E.T. participate in the data collection. Often the evaluator will realize that a certain CTQ is not being captured by the evaluation plan. New CTQ's are likely to be identified during implementation and alternative PI experiments may need to be performed. As a result, evaluation rubrics should be considered living documents that may accommodate revision when accompanied by detailed documentation. An evaluation rubric for each phase can facilitate documentation of experimental results and the PI score. Evaluator notes specific to each PI can be used to ensure consistency across systems and can be mined to

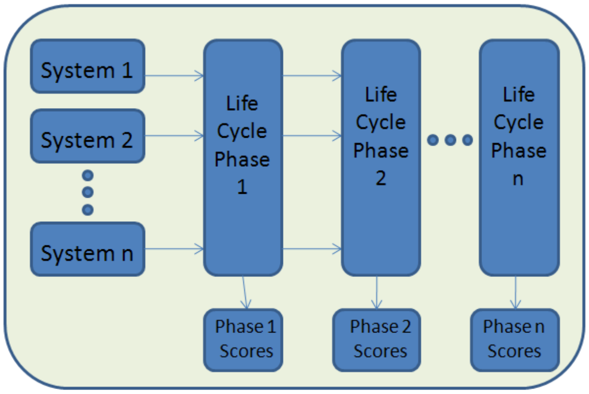

Figure 3: Implementation

compile as a lessons learned database.

The experimental conditions have the dual purpose of facilitating execution of PI experiments and simulating typical conditions. Stakeholders commonly impacted by a life cycle phase should continuously monitor conditions, propose modification as necessary, and document limits of applicability. As shown in Figure 3, Performance Indicator experiments define the duration of a life cycle, once the PIs have been evaluated for a phase, the next phase may begin. Completion of implementation coincides with completion of the last life cycle phase.

DATA PROCESSING

Data Processing entails reviewing the scoring of PI's to ensure consistency between systems and then specifying the PI's to the systems being reviewed to better differentiate between alternatives and inform end users. Finally scores can be packaged to facilitate side by side comparison and stakeholder PI weighting for multi-criteria decision support.

Once the life-cycle has been completed for each test system, researchers process the data, verifying, normalizing, and packaging it to enable dissemination and stakeholder support. To verify the data, scores for the system(s) are compared for each individual PI. The E.T. ensures that scores have been assigned consistently across PIs and systems, when applicable, adjusting for any discrepancies. At this point, if the intermediate scores, 2, 3, and 4, have not been fully defined, the E.T. should do so. System scores are then adjusted to this scale if necessary. A high level of evaluator integrity is required in this process to minimize the impact of experimenter bias. Bias is likely to exist due to a pre-existing relationship or experience with a system or due to the evaluation experience. Participation of multiple E.T. members who represent varying stakeholder groups is likely to reduce the experimental bias.

Once finalized, PI scores and lessons learned are packaged for dissemination. The system selection tool (SST) compiles PI scores with the associated CTQ to facilitate weighted or un-weighted comparisons. This enables users to see system differences, and also provides a tool to aid system selection in a given deployment scenario, allowing users to rank PIs and life-cycle phases most important in their project. Experimenter observations may form the basis for a best practices manual or reference guide for stakeholders who are responsible for selecting or designing a system.

Conclusions: SLiCE Utilization

The SLiCE methodology was developed to enable a side by side comparison of small scale water treatment systems that facilitates selection of new technologies by relief agencies [15-18]. The methodology was employed by a team of researchers to compare seven systems side by side at a Georgia Tech pond in Cobb County Georgia. The collocation of multiple systems attracted and facilitated the engagement of stakeholders. Throughout the evaluation phase, new CTQ's were identified through stakeholders and through direct data experience. This illustrated the importance of maintaining the rubrics as a living document.

Recently, SLiCE studies have been initiated on green roofs and solar panels. Early engagement of stakeholders has enabled identification of CTQ's for which there is little published data and in many cases has hindered adoption. Future work is intended to quantify and disseminate data that can facilitate the selection process of these green technologies. In addition to the end users, we have already seen examples where manufacturers have utilized our SLiCE evaluation results to guide product development. The collections of CTQs, quantified performance indicators as well as the testing of specific systems have added value to product developers. Finally, given the broad nature of the stakeholder CTQs public policy makers may utilize SLiCE evaluations to understand the broad impact of technology incentives.

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