Research Methodology to Define Sustainability Criteria for Civil Infrastructure Systems

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Abstract

The challenge for the development of innovative engineering systems required for civil infrastructure and its construction is now more complex because of the new demands for a sustainable future. Sustainability has been defined as an alternative to create new technologies and engineering systems that will satisfy the needs of humanity in this generation without placing at risk the ability to satisfy the needs of future generations. The challenge of incorporating sustainability as criteria for the planning, design, construction and operation of civil infrastructure needs to be preceded by sound and rigorous research methodologies that reinforce our confidence in their application in the evaluation of such projects. The results presented in this paper were generated using a research methodology that combines different approaches, including the use of a comprehensive literature review, case studies and Delphi survey to develop a list of sustainability criteria, which allow the integration of sustainable development objectives into the domain of infrastructure projects at the early stages of the planning process. The set of criteria identified provides a sound foundation for the future development of methodologies and tools for the implementation of sustainability across the life cycle of civil infrastructure projects.

Keywords
Sustainability, research methodologies, civil infrastructure systems

1. Introduction

Engineers have continually sought to improve the quality of life, transforming nature to provide better living conditions. Technology has helped to accomplish this transformation and to achieve many humans' goals for economic growth and development. It is undeniable that modern technology has provided enormous benefits to the people around the world, such as longer life-span, increased mobility, improved productivity, and widespread literacy, to name a few. Engineers have played an important role in developing practical applications using available knowledge and technology.
However, the contributions of engineers to a better quality of life have had a profound influence on consumption patterns, the generation of waste, and the resulting environmental impact of modern engineered systems. Today, there is enough evidence to confirm that many innovations created by

humans, combined with an increase in population and consumption patterns, are creating serious environmental problems and limits to growth, in terms of the availability of resources to satisfy basic human needs, and the capacity of nature to assimilate the waste created by human activity. These problems not only affect the economic development and welfare of the current generation, but negatively impact the future generations as well.

Numerous organizations and individuals have proposed sustainable development as an alternative model for global economic development as a result of worldwide recognition of the negative effects of current and potential environmental degradation on social development. The most cited definition of sustainable development is the one proposed by the World Commission on Environment and Development and published on their report *Our Common Future*. In this document, sustainable development is defined as development that meets our needs without compromising the needs of future generations (*Our Common Future* 1987).

There are a number of difficulties in specifying and applying sustainability as a criterion for planning individual construction projects, particularly, civil infrastructure systems. A review of the literature reveals a lack of globally accepted sustainability criteria that can assist planners of infrastructure projects in defining project objectives to guide the delivery process, as well as the ultimate outcome of the project (Maldonado et al., 2002). It is the intention of this document to illustrate a sound and rigorous research methodology used by the authors to incorporating sustainability as criteria for the planning of civil infrastructure systems.

2. The Scientific Method and the Research Process

It is important to state that, among the different ways available for establishing or changing beliefs about phenomenon, science is the one that has great acceptance in today's world. Other ways of knowing like intuition, tenacity, or authority are all less than adequate modes of fixing beliefs primarily because there is a high degree of subjectivity in the individual's judgments about what constitutes truth. Instead, science aims at knowledge that is objective in the sense of being certifiable, independently of individual opinion or preference, on the basis of data obtainable by suitable experiments or observations.

A general framework that is often used for scientific inquiry is based on the scientific method presented on Figure 1.1. This model developed by Stone (1978) represents a contemporary conceptualization of the model for scientific inquiry originated in early seventeenth century, the time that is often considered the birth of modern science. The scientific method has been developed slowly in incremental steps through the work of many other modern scientists, and it continues to develop today. It can be applied in all disciplines of science, including natural and social sciences, but is not limited to the sciences disciplines.

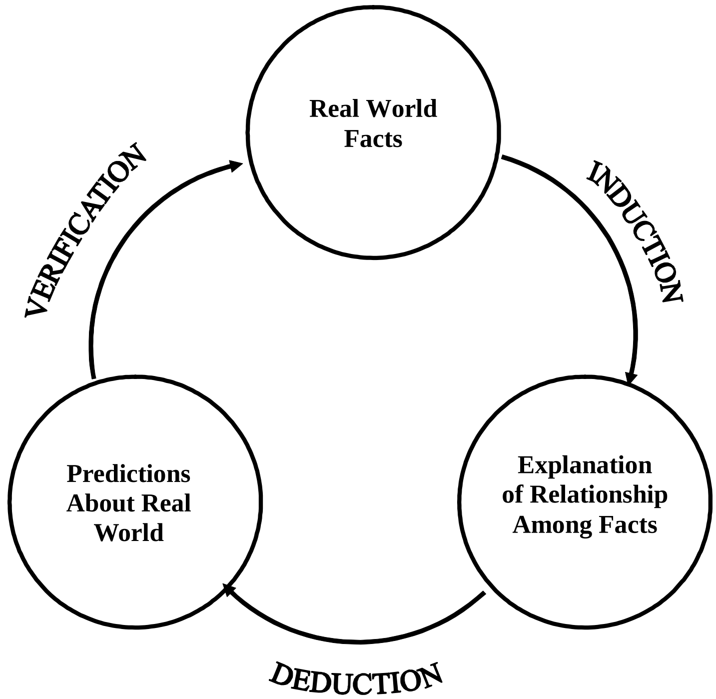

Figure 1: Model of the Scientific Method (adapted from Stone 1978).

The scientific method model consists of the following elements:

- The observation of phenomena or facts in the real world.
- The formulation of explanations for such phenomena, using inductive processes.
- The generation of predictions about phenomena in the real world, using deductive processes.
- The verification of these predictions through systematic, controlled observation.

The scientific method is applied by conducting scientific research. The term scientific research refers to the systematic, controlled, rigorous, empirical, and critical investigation of hypothetical proposition about the presumed relations among phenomena to find the solutions to problems or discover and interpret new knowledge (McCuen 1996). In general, research refers to the rigorous scientific activity aimed at developing new bodies of knowledge. Although many other definitions of scientific research can be found in the literature, the common thread that appears to bind all of these definitions together is that scientific research is the investigation of phenomena via practices consistent with the method of science.

It is important to note that the scientific investigation and verification of beliefs about various real world phenomena involves what is known as empirical research. The term empirical research is based on the belief that "*…all knowledge must originate in experience*" (Stone 1978). In other words, facts are made known to us through our senses; therefore, for a fact to be considered real, it must be capable of being sensed by others, which implies objective reality. Empirical research is research that deals with the facts that have objective reality.

Briefly, empirical scientific research process requires that the researcher first recognizes a problem and/or formulates a question or set of questions that will be addressed by a study. Next, the researcher develops hypotheses that he or she plans to empirically test. A specific strategy or study design is then developed to assess the validity or truth of the hypotheses. The researcher next implements the strategy and observes the values of relevant variables or data during the experimentation step. The resulting data are then analyzed to determine whether or not they provide support for hypothesized relationships. Finally, the study's results are examined by the researcher and used as a basis for conclusions about studied phenomena.

In addition, the process of induction allows the researcher to develop a formal theoretical statement about the phenomenon under study. Because scientist can never develop a theory that describes the researched phenomenon completely, limitations on the verification of scientific theory are inherent. However, completing the induction-deduction-verification cycle of the scientific method strengthens scientific theory.

3. Selection of a Research Methodology to Define Sustainability Criteria for Civil Infrastructure Systems

The research question that guides the selection of a structured methodology was: *How can we develop the criteria to evaluate highway projects alternatives from the sustainable development point of view*? To answer this question, the research focuses on the development of a set of criteria for assessing and analyzing highway infrastructure projects as its fundamental objective.

The motivation for developing these sustainability criteria was to eliminate the gap between public strategic intent, which generate the capital investment, and the planning for performance measurements, which help project stakeholders achieve the expected levels of sustainability. This was accomplished by: (1) investigating the process of planning infrastructure projects, from the owner's point of view; (2) determining the process for defining goals and objectives for highway projects; (3) developing a process to identify sustainability criteria for highway projects and their importance and relationship with the pre-defined objectives; and (4) validating the sustainability criteria with a group of experts with knowledge on sustainable development and experience in the planning, design, construction and operation of highway projects.

There are a number of different approaches to research available to conduct proposed study. There is also a difference in the degree of scientific method adhered to in carrying out the research. For instance, in the physical sciences, it is much easier to have rigid control over an experiment to formulate a hypothesis, design a rigorous research project, control all variables, and look for the answer. In social sciences generally, and in management research in particular, this rigid control is rarely achievable, although it is sometimes possible depending on the kind of research strategy followed.

A common misconception is that the various research strategies should be arrayed hierarchically. Thus, some scientists are taught that case studies are appropriate for the exploratory phase of an investigation; that surveys are appropriate for the descriptive phase; and that experiments are the only way of developing explanations for causal inquires.

Yin (1989) believes that this hierarchical view or research strategies is incorrect. Experiments with an exploratory motive have certainly always existed. In addition, the development of causal explanations has long been a serious concern of historians, reflected by the sub field known as historiography. Finally, case studies are far from being only an exploratory strategy. Some of the best and most famous case studies have been both, descriptive and explanatory.

In order to conduct research in sustainable infrastructure systems it is believed that the appropriate view of these different strategies is a pluralistic one. Each research strategy can be used for all three purposes in science, namely, exploratory, descriptive, or explanatory. What distinguishes each strategy is not this hierarchy, but other conditions. These conditions consist of the following according with Yin (1993):

- The type of research question posed
- The extent of control an investigator has over actual behavior events
- The degree of focus on contemporary as opposed to historical events

The first condition for differentiating among the various research strategies is to identify the type of research question being asked. Therefore, if the research question stated before was a "*how*" question the research strategy is likely to favor the use of case studies. To conduct the research study proposed in this document, a case study research strategy was selected, not only because the intention was to answer a "*how question*," but due to the fact that the other conditions for selecting that research strategy, according with Yin(1993), were valid as well. These conditions include no requirement of control over behavioral events and a focus on contemporary events.

The case study is preferred in examining contemporary events, especially when the relevant behavior of the phenomenon being studied cannot be manipulated, contrary to experiments. Even though the case study relies on many of the same techniques as a history analysis, it adds two sources of evidence not usually included in the historian's repertoire: direct observation and systematic interviewing. The case study's unique strength is its ability to deal with a full variety of evidence like documents, artifacts, interviews, and observations.

Finally, if little is currently known about the nature of the variables involved in the research problem, which is the case in planning for sustainable development, then it is likely that more qualitative, exploratory research methods will be needed. For that reason, an exploratory case study was more appropriate to answer the research questions formulated before in this section.

The case study approach to research can be described as an intensive examination of a single unit, where data are often collected by multiple means, and no attempt is made to exercise experimental or statistical controls. Case studies enable the researcher to explore, unravel, and understand problems, issues, and relationships in a particular situation. Also, the case study is the empirical research strategy most common when the boundaries between phenomenon and context are not clearly evident. Exploratory case studies seek to discover significant variables and relations between them, and to lay the foundations, perhaps, for more scientific work aimed at testing more theory-based propositions.

Additional advantages of the case study strategy are:

- The opportunity to study the full complexity of the unit under study
- A flexible data collection
- Is a useful vehicle for the generation of hypothesis and insights
- Generally, is less expensive research strategy compare with other research strategies

4. Description of the Research Methodology Developed to Define Sustainability Criteria for Civil Infrastructure Systems

The overall research plan developed to define sustainability criteria for civil infrastructure systems includes:

1. A clear understanding of the problem to study.
2. A definition of the research objectives and contribution.
3. Description and justification of the point of departure.
4. The identification of the fundamental research issues.
5. A definition of all the elements and components that comprise the investigation.
6. A clear methodology to perform the investigation.

The research plan was organized in three phases: Problem Definition and Research Design, Data Collection and Analysis, and Validation of the Results

The main activities for the investigation are presented in Figure 2. The following is a detailed explanation of the research progress based on the three phases of the overall plan.

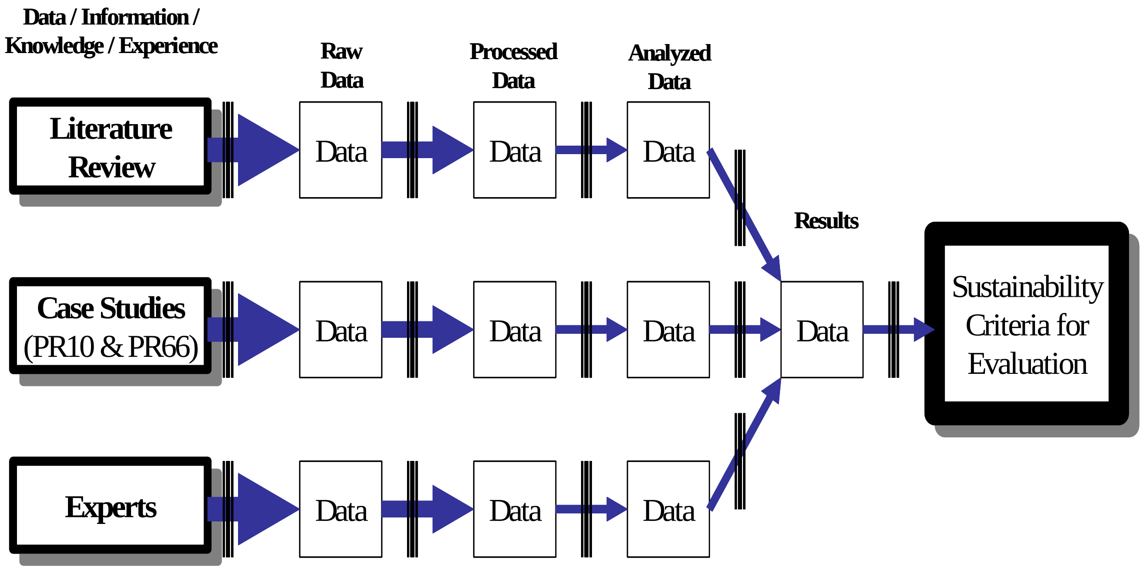

Figure 2: Research Methodology to Define Sustainability Criteria for Civil Infrastructure Systems

4.1 Phase 1: Problem Definition and Research Design

This phase includes the following activities:

- *Identify the problem*: Create a clear understanding and description of the problem.
- *Formulate the study questions, objectives and propositions*: Create a description of the research questions and its objectives based on the problem identified, and the possible solutions and propositions to that problem.
- *Conduct preliminary literature review*: Consolidate and extract information from the main areas of investigation including: highway planning; sustainable evaluation tools; and current practice for the evaluation of highway systems. Sources of information for this activity included books, journal publications, magazine articles, research source documents from the Construction Industry Institute (CII), and proceedings from conferences, workshops and seminars.
- *Identify units of analysis*: Use units of analysis and the point of departure for this investigation from previous scientific research, based on the results of the literature review.
- *Develop research methodology*: Generate a literature review on general research methodologies and strategies, and their possible application in construction research. The research strategy was selected based on the following three conditions: (1) the type of research question posed; (2) the extent of control and investigator has over actual behavioral events; and (3) the degree of focus on contemporary as opposed to historical events. Examples were selected as means for data collection and analysis.
- *Prepare and present a complete project proposal*: Generate a proposal that establishes overall project objectives, research contribution, and a preliminary research methodology.

4.2 Phase II: Data Collection and Analysis

The core of activities in this phase includes a continuing literature review, the selection of the case studies, the data collection, and the analysis of the data.

- *Perform an additional literature review*: Continue with the review of information that is more relevant to the investigation as the research progresses and the scope is reduced.

- *Definition of the selection criteria for the case studies and data collection and analysis of the cases*: Use select Environmental Impact Statements from infrastructure projects as a basis for the data collection.
- *Develop the sustainability criteria for the evaluation of highway projects.*

4.3 Phase III: Documentation and Validation of the Sustainability Criteria for the Evaluation of Highway Projects

Based on the results of from the analysis of the case studies, a set sustainability criteria was developed and validated using a two round Delphi survey. This phase is an iterative process where the proposed list of sustainability criteria is presented, tested and improved until consensus is reached among a selected group of experts. The specific activities for this phase are:

- *Prepare a Participation-Release Agreement form, and the first and second questionnaires*
- *Conduct the first round of the Delphi survey*
- *Analyze the results from the first round of the Delphi survey*
- *Conduct the second round of the Delphi survey*
- *Revise and improve the list of sustainability criteria for highway projects model*: Analyze the data collected to identify trends, similarities, and differences to modify and improve sustainability criteria.
- *Prepare final report*: Document all previous research activities, and develop a set of conclusions and suggestions for future research.

4.4 Delphi Survey Methodology

The Delphi method was first developed by the US RAND Corporation in the 1950's to pool expert judgment primarily with reference to military planning and new technology. Many different types of Delphi survey have been developed, though they all have several distinguishing features:

- They elicit the views of panels of experts
- They employ an iterative process of summarizing, averaging and recycling panel members' views to encourage convergence on a consensus view. Participants are given the opportunity to revise earlier answers in the light of the general opinions expressed by the group as a whole.
- Information is collected by questionnaire and does not involve interviews or discussion
- Members of the panel are guaranteed anonymity

Linstone and Turoff (1975) have defined a Delphi survey as "…*a method of structuring a group communication process, to that the process is effective in allowing a group of individuals, as a whole, to deal with complex problems*." They see an important role for Delphi surveys where:

- A problem does not permit the application of precise analytical techniques but can "benefit from subjective judgments on a collective basis."
- The relevant specialists are in different fields and occupations and not in direct communication.
- The number of specialists is too large to "effectively interact in a face-to-face exchange" and too little time and/or funds are available to organize group meetings.

The Delphi survey method was selected for this research study to validate a list of sustainability criteria for the evaluation of highway projects using a two round approach to answer the questionnaire.

4.5 Selection Criteria for the Case Studies

Infrastructure projects are essential for economic prosperity and development. These projects demand a high level of technical proficiency due to their complexity and scope and generally have an impact on many people during a long period of time, which goes beyond several decades. Infrastructure projects include, but are not limited to: highways; dams; railroads; water supply systems; sanitary sewers; storm water drainage and flood control; electrical and gas systems; and telephone communication systems.

Although major development projects can benefit significantly from associated infrastructure systems, the provision of such needed infrastructure can also generate adverse, and in some cases irreversible, environmental and social impacts. For instance, large-scale ecosystems as well as relocation of people may be required for major highway projects in urban, suburban, and rural areas.

Based on the effects infrastructure projects have on society and the environment, they were selected as a basis to compare projects objectives resulting from infrastructure planning in developing countries, with the sustainable engineering design objectives found in the literature. Among all the different types of infrastructure projects available, various highway projects were selected. These two projects are located in the Island of Puerto Rico, a Commonwealth with the United States since 1952.

The Commonwealth of Puerto Rico is a tropical island located in the Caribbean with a surface area of 3,515 miles^2 (9,104 km^2). The population of Puerto Rico, based on the census in 2000, was more that 3.8 million. The Gross National Product (GNP) of Puerto Rico was $35,160.6 million in 1998. Based on historical data of Puerto Rico’s population and economic activity, the World Bank classified Puerto Rico during the period of the study as an upper middle income economy. In other words, using the World Bank’s classification by income, Puerto Rico has a developing economy during the when the research was conducted.

The two projects selected for the study are: the PR-66 Highway (also known as Route 66) located within the municipalities of Carolina and Canovanas; and the PR-10 Highway located within the municipalities of Arecibo, Utuado, Adjuntas, and Ponce. Each project was selected on the basis of the following selection criteria:

- Highway infrastructure project in Puerto Rico
- Projects included in the 1982's Strategic Transportation Plan of Puerto Rico
- The need of the Environmental Impact Statement or an equivalent requirement due to the significant environmental impact of the project
- The lands in question are of Commonwealth or local significance

The following is a description of each selection criteria with details of how the chosen projects comply with each criterion.

4.5.1 Highway Infrastructure Projects in a Country with a Developing Economy

The selection of highway infrastructure projects for the study proposed in this document was based on the needs for a comprehensive transportation network in a country with a developing economy. The classification selected to make a distinction between developed and developing economy was the group divisions used by the World Bank. The World Bank is an international source of assistance for development. This organization, founded in 1944, provides information and financial assistance to more than 100 countries with developing economies.

The World Bank developed a classification of countries, for operational and analytical purposes, that is based on the country Gross National Product (GNP) per capita. The GNP represents the economic activity in a country. Every country is classified as a low income economy, middle income economy (subdivided into lower middle and upper middle), or high income economy. Low-income and middle-income economies are sometimes referred to as developing economies or countries. The World Bank states that classification by income does not necessarily reflect development status.

4.5.2 Projects Included in the 1982's Strategic Transportation Plan of Puerto Rico

The Planning Board of Puerto Rico, created by the Law number 75 of June 24, 1975 is the government agency with the responsibility of defining the public policy for the development of the land. In 1982 the Planning Board of Puerto Rico derogated the Land Use Plan created in 1971, and adopted a new Strategic Transportation Plan, which is still in effect at the time this document is prepared. The 1982 Strategic Transportation Plan included the design and construction of 115 miles (185 km) of new roads and highways all across Puerto Rico to stimulate the economic development of the island.

The infrastructure projects included in the Strategic Transportation Plan of 1982 represent the cornerstone of future development of Puerto Rico, and that itself constitutes the primary reason for selecting projects included in that Plan. Both projects selected, PR-10 and PR-66 highways, are parts of this important strategic development plan.

4.5.3 The Need of the Environmental Impact Statement

The United State's National Environmental Policy Act (NEPA) of 1969, which became effective on January 1, 1970, was a very important piece of legislation that ensures balanced decision making regarding the environment, in the total public interest, during the planning and development of capital projects. One of the most important outcomes from NEPA was the creation of the Environmental Impact Assessment (EIA) process as a device to compel the examination of environmental consequences of such projects.

The Environmental Impact Assessment is defined as the systematic identification and evaluation of the potential impacts, or effects, of proposed projects, plans, programs, or legislative actions relative to the physical-chemical, biological, cultural, and socioeconomic components of the total environment (Canter 1996). The action-forcing mechanism in the NEPA is that Environmental Impact Statements (EIS) must be prepared such that they describe the environmental consequences of major actions that significantly affect the quality of the human environment.

In Puerto Rico the government created in 1970 the Environmental Public Policy Act under the Law 9 of June 18, 1970. This Act also created the Environmental Quality Board as the statewide government agency responsible for the local implementation of the NEPA requirements and the creation of the rules and the mechanisms for the control of contaminants and negative impacts to the air, water, land, and other natural resources, including the provisions for solid waste disposal and noise contamination. Article 4 of the Puerto Rico Environmental Public Policy Act established that all departments agencies, public corporations, municipalities, and any dependency of the Commonwealth of Puerto Rico has to conduct an Environmental Impact Assessment for any action taken that can affect significantly the quality of the existing environment.

The two infrastructure projects selected for data collection to conduct this study are both proposed actions from the Commonwealth of Puerto Rico Department of Transportation and Public Works, in conjunction with the Highway and Transportation Authority. Therefore, both projects have to comply with both Puerto Rican and United States federal regulations on elements of the infrastructure projects that can impact significantly the environment. The Environmental Impact Statements of both projects include the type of information and analyses that are required of any project under the United States federal jurisdiction; however, in these two projects the context is a developing country with a different economic, social, and political structure.

4.5.4 The Lands in Question are of Commonwealth or Local Significance

Construction in a tropical island like Puerto Rico with a surface area of 3,515 miles^2 (9,104 km^2) and a population of more than 3.8 million is always a challenge. The limited space available, the scarcity of building materials and systems produced locally, and the richness of natural ecosystems and resources due to the tropical environment creates a situation where engineered facilities has to comply with the highest standards of conservation and resource efficiency and effectiveness to fulfill present and future societal needs. That is why major infrastructure projects in small developing countries are so important and receive the attention of all different project stakeholders, including politicians, the community, and the business sector.

The two infrastructure projects selected for the research study confronted great environmental challenges. When the PR-66 Highway was presented in the Preliminary Environmental Impact Statement in 1992 and before the public hearings, the project proposed a 15.09 miles (24.3 km) highway from the municipality of San Juan to the municipality of Canóvanas. This alignment was exactly as the one conceived for the 1982 Strategic Transportation Plan, even though there was an attempt to extend the route beyond Canóvanas all the way to the east part of the Island ending in the municipality of Fajardo. But the extension of the PR-66 Highway to Fajardo was rejected by the Planning Board of Puerto Rico when Pablo Cruz, the supervisor of the Caribbean National Forest El Yunque (which is under the jurisdiction of the U.S. Forest Service) opposed to the extension of the PR-66 Highway to Fajardo due to its impact to a national preserved area.

But the troubles of approving the construction of PR-66 were not finished. After the public hearings held in October of 1992, the community and other organizations, including the University of Puerto Rico (UPR), expressed their opposition to the project for its imminent impact to approximately 10.7 acres of the UPR Botanical Garden located in the project alignment. Further environmental studies were requested by the Environmental Quality Board after the hearings, and in June 1996, the proponents of the PR-66 Highway submitted a Supplement of the Preliminary Environmental Impact Statement and celebrated public hearings. In January of 1997 the Environmental Quality Board gave their approval to the project that has a reduction from 15.09 miles (24.3 km) of highway to 8.9 miles (14.3 km), excluding the alignment through the UPR Botanical Garden located in the municipality of San Juan, and keeping only the route from the municipality of Carolina to Canóvanas. The previous sequence of events shows how the PR-66 Highway suffered several design changes as a result of the planning process. This happens when land that is considered very valuable is at risk if the proposed action is implemented.

In the case of PR-10 Highway, the project included three alignment alternatives namely, Alternative 2A, 2B, and 3, which were presented in the Preliminary Environmental Impact Statement. After the dissemination of the Preliminary Environmental Impact Statement proposing Alternative 2B, and the conclusion of the public hearings, the project was modified and a new alignment, Alternative 2B Revised, was the one presented in the Final Environmental Impact Statement. The controversial corridor was finally approved even though the project crosses through agricultural and forest lands, including 1.7 miles (2.8 km) of highway construction over the Río Abajo State Forest, home of an extensive 34 acres of forest, and fascinating sinkholes and underground cavities, some with natural water.

The PR-10 also constitutes a major infrastructure project that will have a direct impact on land that has great environmental value. These facts have produced many controversies and oppositions from the affected community and the public in general.

4.6 Data Collection Using Environmental Impact Statements

The Environmental Impact Statement was the document used for data collection to conduct the analysis of objectives for infrastructure projects. The focus was on identifying objectives defined as part of the planning process of the project and comparing those objectives with the ones found in the literature for sustainable design. It is imperative to present here the basic structure of the Environmental Impact Statements used for data collection to be able to understand where the data came from and why it is relevant to the research study presented here.

In the United States, the Council on Environmental Quality Guidelines (CEQ) is the reference for the preparation of Environmental Impact Statement to comply with NEPA. Although, the Environmental Quality Board of Puerto Rico approved in June 1, 1984 the "Regulations for Preparing Environmental Impact Statements," the structure of the documents prepared in Puerto Rico under this law follows the same guidelines established by the Council on Environmental Quality that are applicable to all federal agencies for their compliance with the NEPA.

The five major areas that any Environmental Impact Statement should cover include the following (Canter 1996):

- The environmental impact of the proposed action
- Any adverse environmental effects that cannot be avoided should the proposal be implemented
- Alternatives to the proposed action
- The relationship between local short-term uses of the human environment and the maintenance and enhancement of long-term productivity
- Any irreversible and irretrievable commitments of resources that would be involved in the proposed action should it be implemented

4.6.1 Basis for the Comparison

The data to make the comparison between highway infrastructure objectives and the objectives for sustainable design was obtained directly from the Environmental Impact Statements of each project. Each Environmental Impact Statement was carefully read to identify objectives. Every objective was extracted every time an action verb was identified related with something that was done, or will be done in the course of the project.

One of the purposes of this research was to study the objectives for the complete project life cycle. To accomplish that purpose a matrix was created to categorized the objectives found in the Environmental Impact Statements based on the phases of the project life cycle, namely: Pre-design, Design, Construction, Commissioning, Operation & Maintenance, and Deconstruction or Rehabilitation. The matrix was a good tool to organize the information in such a matter that categories for each project objective were easy to apply. The following section includes a description of each of the categories selected to construct the matrix.

4.6.1.1 Construct of the Matrix for Data Collection

The objective of the developing a matrix with the objectives for the highway infrastructure projects was to collect data specifically related with the project objectives and organize that data with respect with the sustainable development principles, heuristics and specifications to find out how the current practice to minimize the impact to the environment compares with the suggestions from the literature on how to incorporate sustainability into construction projects.

To achieve the objective presented above, the Environmental Impact Statement was selected as the source of data as stated before. To be able to organize the objectives for highway PR-66 and for highway PR-10 in a way they can be analyzed and compared with sustainable development objectives a matrix was created with the following columns headings: ID, Project Phase, Issue, Project Objective, Sustainability Variable, Scale and Class.

The ID was used to assign specific objectives to a specific PROJECT PHASE, across the life cycle of the project, including: Life Cycle; Pre-design; Design; Construction; Commissioning; Operation and Maintenance; and Deconstruction and Rehabilitation. The goal was to categorize the objectives found in the Environmental Impact Statement for each project phase, and also, those objectives that affect the entire project life cycle. A number ID was assigned to each objective that corresponds to a specific project life cycle phase. The number ID's were assigned using the following as a reference: 1.0 Life Cycle, 2.0 Pre-design, 3.0 Design, 4.0 Construction, 5.0 Commissioning, 6.0 Operation & Maintenance, and 7.0 Deconstruction/Rehabilitation

The other column headings selected for the matrix were found in the literature as descriptive parameters of knowledge in the fields of engineering design and sustainable development. They are:

- ISSUE: This column refers to any matter, concern, question, topic, proposition, or situation that demands a design response in order for the infrastructure project to be successful for its clients and users.
- PROJECT OBJECTIVE: This column refers to objectives associated to a given issue extracted directly from the Environmental Impact Statement for each of the highway projects.
- SUSTAINABILITY VARIABLE: This column refers to the sustainability variable to which a project objective can be assigned. The sustainability variables were taken from previous analysis of the literature in sustainable development for evaluation tools and assessment that can be applied to whole systems and development projects.
- SCALE: This column refers to the level of impact of a specific objective: Material, Building System, Project, Community/Regional, and Global levels.
- CLASS: This column classifies specific project objectives as Principles; Heuristics; or Specifications.

5. Results

The list of sustainability criteria for the evaluation of highway projects was created based on the objectives for sustainable development found in the literature and the analysis of two case studies. The application of the sustainability criteria for project evaluation was beyond the scope of the research study presented in this document. However, it will be hard to accept such a list without a rigorous validation by experts. To achieve a final validation of the sustainability criteria for highway projects, a Delphi survey was conducted among experts in the area of highway planning, design, construction and operation.

The first and second round of the Delphi survey were analyzed using a distribution frequency table to annotate first the frequency of responses for each sustainability evaluation criteria to the Frequency and Importance columns in the first round, and subsequently to the Importance column in the second round. The frequencies of responses for the importance column of the first round were averaged and presented to the survey's participants.

The same procedure was applied to analyze the responses to the second round using a distribution frequency table with the average of the responses to the Importance column. Graphics of the results of the second round were used for the final analysis.

When the charts with the results from the first and second round of the Delphi survey are compared, it can be observed that the average for the importance was the same or increased a little fraction in the second round. Table 8.2 shows the averages of the importance for the first and second round of the Delphi Survey.

Table 1: Average of Frequency for Primary Sustainability Parameters

Sustainability Parameter	Average of Frequency
Resources	2.5
Ecology	2.6
Humans	2.6
Materials	2.0
Environmental Impact	2.3
Energy	1.8
System Efficiency	1.9
Project Delivery	2.2
Facility Indoor Quality	1.6

Table 2: Average of Importance for Primary Sustainability Parameters

Sustainability Parameter	Average of Importance First Round	Average of Importance Second Round
Resources	4.0	4.1
Ecology	4.1	4.2
Humans	3.9	4.0
Materials	3.8	4.1
Environmental Impact	4.3	4.3
Energy	3.8	4.1
System Efficiency	3.7	4.0
Project Delivery	4.1	4.1
Facility Indoor Quality	4.0	4.2

6. Assumptions and Limitations in the Use of the Proposed Research Methodology

In interpreting the results of this research using a case study methodology and the Delphi survey method, one should be aware of its assumptions and limitations. One assumption regarding the objective function for the participants of the Delphi survey was that the participants had to judge the expected criteria for a sustainable future. One of the shortcomings of the Delphi survey method is that it can exaggerate the concept of expertise and over value the opinions of the panel. Therefore, the final list of sustainability criteria developed in this research study is applicable in the context of highway construction in Puerto Rico, the place from where the experts were selected.

The anonymity of the participants relieves them of accountability and can lead to careless responses. However, in this particular research study, the Delphi questionnaire was distributed during a workshop for project managers at the Highway and Transportation Authority of Puerto Rico, which allowed the researcher to interact with the participants and increase their enthusiasm in the study and their commitment to give the best information possible.

One of the main shortcomings of the Delphi survey method is that it offers little insight in the reasoning underlying the participants' responses. To reduce the negative impact of this condition, the participants had the opportunity to comment about the sustainability criteria in a face to face discussion with the researcher and the rest of the group.

Although, all the participants were able to ask questions about the definitions of the sustainability criteria list, the time constraint did not allow the opportunity to verify if each expert understood the description of the sustainability criteria, therefore, it was assumed that all participants of the Delphi survey had a good understanding of all the criteria in the questionnaire.

7. Conclusion

The use of a comprehensive literature review combined with case study research strategy and a Delphi survey was a good technique to define a list of sustainability criteria for the planning of civil infrastructure systems in Puerto Rico

The research methodology presented in this document can be used for the development of sustainability criteria in other regions and countries where there is a need of simultaneous considerations of environmental, social, technological, and economic goals. With the help of consultants or interdisciplinary teams, sustainable development criteria can be evaluated and compared among alternatives to make informed decision on which projects are more sustainable than others. The final evaluation tool where the sustainability criteria developed using the research methodology presented in this document can be developed with further research studies. However, knowing that this set of criteria has been created, it will be easy to move into the development of the specific evaluation tool.

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