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Towards A Sustainable Engineering of Community Infrastructure (SEI): Theoretical Foundations, Conceptual Framework and Applications to the Beninese Context

Ahonankpon Hubert Frédéric GBAGUIDI
Research Unit on the Sustainability of Urban Infrastructure and Services, Laboratory of Geosciences, Environment and Applications, National University of Science, Technology, Engineering and Mathematics (UNSTIM), Benin,
ORCID: 0009-0008-2064-2701

SUMMARY: The sustainability of community infrastructure is a major strategic challenge in developing countries, particularly in sub-Saharan Africa, where public investment in public facilities does not always translate into a lasting improvement in public services. Despite intensified infrastructure investment programs, many facilities suffer from premature deterioration, poor functionality, and a lack of planned maintenance.

This article proposes the formalization of an integrated theoretical framework entitled "Engineering for the Sustainability of Community Infrastructures" (EIC). This framework aims to overcome the fragmentation of sectorial approaches (civil engineering, infrastructure economics, urban planning, and governance) by offering a systemic reading of the life cycle of community infrastructure.

The methodology is based on a structured critical review of the international literature on asset management, urban resilience and territorial governance, supplemented by the synthesis of empirical work carried out in Benin (Nikki, Porto-Novo), in particular through tools such as the Global Sustainability Index (GSI) and multi-criteria decision support matrices.

The results show that the sustainability of community infrastructure depends less on the initial quality of construction than on the quality of its governance throughout its entire lifecycle. The article proposes an integrated conceptual model based on six dimensions of sustainability and a dynamic infrastructure management cycle.

KEYWORDS: Community infrastructure; sustainability engineering; Global Sustainability Index (GSI); infrastructure governance; life cycle management.

INTRODUCTION

Community infrastructure is a fundamental pillar of territorial development and social cohesion. Whether it be schools, healthcare facilities, drinking water supply networks, sanitation systems, urban roads, or administrative and economic infrastructure, it embodies public action and determines access to essential services for all populations. In developing territories, it plays a crucial role in reducing spatial disparities, improving living conditions, and strengthening community resilience (Sen, 1999; Sachs, 2015; Gbaguidi, 2025). Its availability, functionality, and sustainability are therefore essential conditions for achieving the Sustainable Development Goals defined by the United Nations (United Nations, 2015).

However, the surge in infrastructure investment observed in developing countries over the past few decades reveals a major paradox: the quantitative increase in public assets is not always accompanied by a lasting improvement in the performance of associated services. Many infrastructures experience premature degradation, underutilization, or abandonment just a few years after they are put into operation. This observation reflects a structural weakness in traditional infrastructure production models, which have long focused on design and construction, to the detriment of subsequent phases of operation, maintenance, and renewal.

This issue directly relates to contemporary principles of asset management, which consider infrastructure not as a simple technical object, but as an evolving system requiring an integrated strategy throughout its entire lifecycle (International Organization for Standardization (ISO), 2014; Hastings, 2015). According to this approach, the sustainable performance of a facility depends less on its initial quality of construction than on the ability of the responsible institutions to ensure its monitoring, maintenance, adaptation to evolving needs, and timely renewal. Infrastructure thus becomes a complex system in the sense of Bertalanffy's general systems theory (1968), whose performance results from the interactions between technical, economic, environmental, institutional, and social dimensions.

From this perspective, the sustainability of community infrastructure cannot be assessed solely through physical indicators or one-off technical assessments. It requires a systemic approach that integrates the resilience of territorial systems (Holling, 1973; Meerow et al., 2016), institutional governance capacities (Ostrom, 1990; Healey, 1997), and the use of decision-support tools to objectify public policy choices. Research on composite indicators also shows that evaluating multidimensional phenomena such as sustainability requires structured methodologies that combine standardization, weighting, and aggregation of criteria (Organisation for Economic Co-operation and Development (OECD), 2008; Saaty, 1980).

In sub-Saharan Africa, this issue is of particular importance. Despite increasing public investment supported by governments and technical and financial partners, local authorities continue to face persistent challenges in asset management: insufficient financial resources dedicated to maintenance, limited availability of data on existing equipment, a lack of integrated assessment tools, and fragmented institutional responsibilities. These constraints contribute to maintaining a dominant model based on a reactive approach, in which public interventions often prioritize the reconstruction of degraded equipment rather than its preventive maintenance and long-term optimization.

In Benin, this situation is particularly evident in local communities where community infrastructure is a major factor in local development. Several recent studies have shown that the difficulties encountered stem not only from technical factors, but also from organizational and institutional limitations related to the governance of public facilities. Research conducted by Gbaguidi AHF et al. on the sustainability of municipal infrastructure has notably led to the development of the Global Sustainability Index (GSI), designed as a multi-criteria assessment tool to evaluate the condition, functionality, and sustainability of public infrastructure (Gbaguidi et al., 2025a). Applied to the community infrastructure of Nikki, this tool highlights the importance of an integrated approach that combines physical characteristics, functional performance, and asset management conditions.

Similarly, research applied to the urban road network of Porto-Novo has demonstrated the value of combining sustainability assessment with tools for prioritizing interventions. Integrating the Integrated Management of Degradation (IMD) approach with multi-criteria prioritization matrices allows us to move beyond a purely descriptive approach to infrastructure deterioration and develop operational strategies for the maintenance and sustainable management of infrastructure (Gbaguidi et al., 2025b). This work confirms the need for a paradigm shift: moving from engineering focused on the construction of structures to engineering oriented towards their overall sustainability.

In this context, the lack of a unified conceptual framework remains a significant limitation. Approaches from civil engineering, infrastructure economics, land-use planning, public governance, and environmental management generally address the issue in a fragmented manner. However, the increasing complexity of contemporary challenges (climate change, budgetary constraints, rapid urbanization, environmental requirements, and digital transformation) necessitates a cross-cutting approach capable of integrating all the dimensions influencing the sustainable performance of infrastructure.

This article proposes to formalize a new approach called Community Infrastructure Sustainability Engineering (CIE). This proposal aims to build a theoretical and methodological framework that integrates contributions from systems theory, asset management, territorial resilience, composite indicators, and digital tools into a sustainable management perspective for community infrastructure.

The central scientific question guiding this research is therefore: How to move beyond sectoral and fragmented approaches to community infrastructure management in order to build an integrated sustainability engineering framework capable of assessing, managing and optimizing their performance throughout their entire life cycle, particularly in the context of developing territories?

To answer this question, the article pursues three main objectives:

(i) to establish the theoretical foundations of IDIC based on systemic, heritage and territorial approaches;

(ii) to propose an integrative conceptual framework linking multi-criteria assessment, governance and life cycle management and

(iii) discuss its applicability to the Beninese context based on experiences developed around the Global Sustainability Index (GSI)

1. Literature Review

International literature on physical asset management (ISO 55000, Hastings, 2015) highlights the importance of integrated infrastructure lifecycle management. This approach is based on the planning, operation, maintenance, and renewal of assets according to their overall performance. However, these models have primarily been developed in industrial contexts or in countries with robust institutional systems, limiting their direct transferability to local authorities in developing countries. The work of Ostrom (1990), Healey (1997), and Lascoumes & Le Galès (2004) shows that infrastructure performance is highly dependent on institutional arrangements and public governance instruments.

However, these approaches often remain focused on the governance of common resources or public policies without systematically integrating the technical lifecycle of infrastructure. Resilience theory (Holling, 1973; Meerow et al., 2016) introduces the capacity of urban systems to absorb disturbances and reorganize themselves. This approach is particularly relevant in the context of climate change and rapid urban growth. However, it remains insufficiently operationalized to directly guide the management of community infrastructure. Three major limitations emerge:

i. disciplinary fragmentation between engineering, economics and governance;
ii. weak contextualization in the local context;
iii. lack of systemic integration of the complete infrastructure lifecycle.

2. PROBLEM STATEMENT AND HYPOTHESES

2.1. Problem Statement

In a context marked by the scarcity of public resources and increasing pressure on infrastructure, how can we design an integrated framework to guarantee the sustainability of community infrastructure through systemic management of its life cycle?

2.2. Assumptions

The following hypotheses are put forward to support this issue:

H1: The sustainability of community infrastructure is determined more by the quality of its governance than by its initial quality of construction.

H2: The lack of life cycle integration is a major structural cause of premature infrastructure degradation.

H3: The use of multi-criteria tools improves the rationality of maintenance and renewal decisions.

H4: A multi-dimensional, systemic approach improves the overall performance of community infrastructure.

2.3. Methodology

This research adopts a qualitative and conceptual approach structured into three complementary components.

A systematic analysis of research in asset management, territorial governance, and urban resilience identifies the main existing theoretical frameworks and their limitations. This article draws on several findings from previous research conducted in Benin:

- Global Sustainability Index (GSI) applied to urban infrastructure;
- Nikki infrastructure assessment tool;
- diagnosis of road infrastructure in Porto-Novo;
- studies on the financing and maintenance of community infrastructure.

The theoretical and empirical results are synthesized to produce an integrated conceptual framework of a systemic type.

3. RESULTS: CONCEPTUAL FRAMEWORK OF THE IDIC

3.1. Definition and dimensions of sustainability

IDIC is defined as an interdisciplinary field focused on the design, management, and optimization of community infrastructure throughout its entire lifecycle, with a view to territorial sustainability. It addresses the six (6) dimensions listed below.

Table 1: Dimensions of the IDIC

Dimension	Components
Technical dimension	Physical condition, structural performance, pathologies, material durability
Economic dimension	Investment costs, maintenance costs, allocative efficiency
Social dimension	Accessibility, usability, user satisfaction, territorial equity
Environmental dimension	Environmental impacts, resource consumption, climate resilience
Institutional dimension	Capacity of local institutions, planning, coordination
Political dimension	Decision-making process, continuity of public action, rationality of choices

3.2. Lifecycle management process and integrated conceptual model

The model is based on a continuous cycle:

Observe → Diagnose → Evaluate → Decide → Maintain → Renew

Each step is powered by multidimensional data.

The IDIC model illustrated below can be represented as a dynamic system where the infrastructure constitutes the central system, the six dimensions represent evaluation subsystems, the life cycle constitutes the temporal mechanism, the IGD tools ensure measurement and governance ensures regulation.

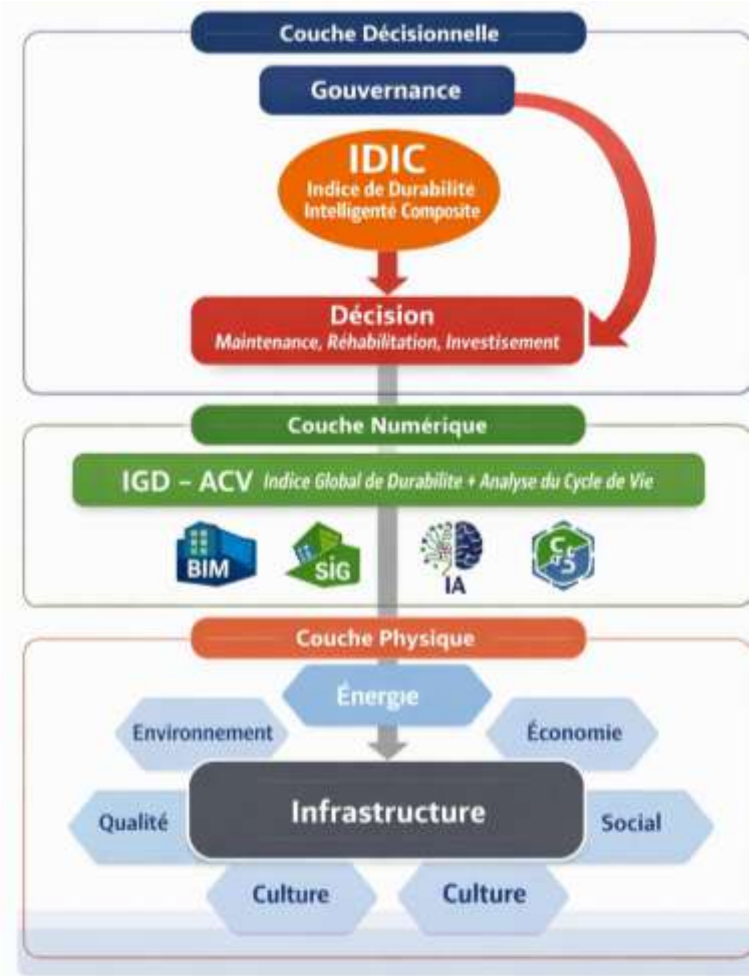

Figure No. 01: Conceptual architecture of the IDIC

4. CRITICAL DISCUSSION

4.1. Epistemological status and risk of disciplinary redundancy

IDIC is not yet a stable discipline but rather an integrative research program aimed at structuring a fragmented field. Although closely related to asset *management* and urban *governance,* IDIC is distinguished by its territorial grounding in the community infrastructures of countries with constrained governance.

4.2. Model complexity and empirical limitations

The complexity of the framework reflects the true nature of infrastructures as hybrid socio-technical systems. The model requires multi-context quantitative validation. Furthermore, the political dimension is reformulated as a dimension of governance and decision-making rationality.

4.3. Formalization and general structure of the Global Sustainability Index (GSI)

Within the framework of Community Infrastructure Sustainability Engineering (CIIE), the Overall Sustainability Index (OSI) is a central tool for multi-criteria assessment and decision support. It allows for the synthesis of the overall state of an infrastructure based on multiple and interdependent dimensions.

The IGD is defined as a weighted aggregate function of the six dimensions of sustainability:

$$IGD=f(T,E,S,Env,I,P) \quad (1)$$

Or :

T = technical dimension

E = economic dimension

S = social dimension

Env = environmental dimension

I = institutional dimension

P = political dimension (decision-making governance)

Each dimension is measured by a set of standardized indicators on a scale:

$$x_i \in [0,1] \quad (2)$$

The IGD is then expressed as a weighted average:

$$IGD=\sum_{k=1}^{6} w_k \cdot D_k \quad (3)$$

Or :

- D_k = normalized score of dimension k
- w_k = weight of dimension k
- $\sum w_k = 1$

In detail, the expression can be rewritten as follows:

$$IGD = w_T T + w_E E + w_S S + w_{Env} Env + w_I I + w_P P \quad (4)$$

Therefore, three classes allow us to interpret the IGD.

Table 2: Interpretation of the IGD

IGD value	Interpretation
IGD<0.4	unsustainable infrastructure (critical risk)
0.4 ≤ IGD < 0.70	Average durability (maintenance required)
IGD≥0.7	sustainable infrastructure

Based on these findings, the IGD constitutes both a diagnostic tool, a prioritization tool, a tool to aid public decision-making and a life cycle monitoring instrument.

4.4. Applications to the Beninese context and scientific contributions

Case studies in the context of Nikki and the road heritage of Porto-Novo demonstrate as pitfalls, through calculated rates, the sustainability of the infrastructure heritage, weak maintenance integration, institutional fragmentation, lack of life cycle planning and strong utility of IGD tools for public decision-making.

Based on the results obtained, the implementation of the Integrated Management System (IMS) provides solutions along four (4) lines: theoretically, it structures a new integrated field; methodologically, the IMS offers the development of multi-criteria tools; operational applicability demonstrates improved asset management; and from a public policy perspective, this new tool facilitates objective decision-making.

CONCLUSION

This contribution has proposed the theoretical and methodological foundations of a new approach called Community Infrastructure Sustainability Engineering (CIIE), designed as an integrative framework for rethinking how public infrastructure is assessed, managed, and transformed in developing territories. Unlike traditional approaches, often limited to analyzing technical performance or conducting one-off assessments of infrastructure condition, CIIE considers infrastructure as an evolving socio-technical system embedded in a territory, subject to multiple constraints, and requiring dynamic management throughout its entire lifecycle.

The main contribution of this research lies in proposing a paradigm shift: moving from a reactive approach to heritage management to a proactive approach to sustainability engineering. This shift is based on the fundamental assumption that the long-term viability of community infrastructure depends not only on its structural characteristics, but also on its ability to maintain its functions, limit its environmental impact, adapt to territorial changes, and benefit from appropriate governance.

From this perspective, the proposed conceptual framework articulates several complementary dimensions: the technical dimension, which provides information on the physical condition and functional performance of structures; the environmental dimension, integrating the impacts associated with the life cycle; the economic dimension, relating to investment, operating, and maintenance costs; the institutional dimension, linked to governance and management capacities; and the digital dimension, based on data analysis, modeling, and intelligent decision-support tools. This multidimensional approach constitutes the scientific foundation of the IDIC.

The integration of the Global Sustainability Index (GSI), developed as a multi-criteria infrastructure assessment tool, represents a major contribution to this approach. The GSI makes it possible to objectify sustainability levels and identify vulnerability factors in community facilities, opening a new perspective: that of intelligent asset management based on knowledge, measurement, and anticipation.

Application to the Beninese context demonstrates the relevance of this approach in addressing the specific challenges faced by local authorities, such as the accelerated aging of equipment, insufficient preventive maintenance programs, weak asset management information systems, and persistent financial constraints. Observations of public infrastructure highlight that technical problems are often the visible manifestations of deeper issues related to governance, maintenance organization, and the lack of integrated monitoring and evaluation tools. Therefore, the Infrastructure Development Index (IDIC) should not be considered simply another indicator, but rather a decision-making engineering system that connects scientific knowledge, public action, and the operational management of infrastructure. It serves as a decision-support tool capable of assisting local stakeholders in prioritizing interventions, optimizing available resources, and developing resilient asset management strategies.

However, several research avenues remain open. Empirical validation of the model across a wider range of infrastructures and territories is essential to refine the weighting coefficients, test the robustness of the indicators, and improve the transferability of the proposed framework. The gradual integration of artificial intelligence, connected sensors, digital twins, and collaborative platforms could also enable the evolution of the Infrastructure Diagnostic

Information System (IDIC) into a predictive system capable of anticipating failures and optimizing maintenance strategies in real time.

Ultimately, Community Infrastructure Sustainability Engineering (CIE) aims to structure a new scientific field at the interface of civil engineering, land-use planning, environmental engineering, decision sciences, and digital technologies. In the Beninese and broader African context, it offers a renewed perspective for transforming public infrastructure into genuine drivers of territorial resilience, collective performance, and sustainable development.

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