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Research Article

Digital Sustainability Assessment: A Platform-Based Approach for Transport Infrastructure

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Abstract

The convergence between digital transformation and sustainability, often referred to as Sustainability 4.0, is reshaping the construction and infrastructure sector. Although technologies like Building Information Modeling (BIM), Geographic Information Systems (GIS), Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twins (DT) are increasingly adopted for sustainability assessments, their implementation remains fragmented and uncoordinated. This fragmentation is driven by the partial consideration of sustainability dimensions, the use of multiple digital tools generating isolated datasets, and the lack of lifecycle-oriented integration, limiting holistic decision-making.

This study addresses these limitations by proposing a methodological framework and a platform-based approach designed to manage sustainability assessment in transport infrastructure. The framework is grounded on measurable environmental, social, and operational Key Performance Indicators (KPIs), derived from standards such as Envision and BREEAM and reformulated with a digital-oriented logic. The input data for KPIs calculation are natively generated or stored within heterogeneous digital sources.

The core innovation is a workflow that automatically extracts these data and organizes, stores, and manages them within a relational SQL database (PostgreSQL/PostGIS), subsequently visualized through a web-GIS interface (developed as a web application with Django), helping interpretation and analysis. This integrated digital ecosystem enhances traceability, and lifecycle continuity of sustainability indicators. The framework is applied to a metropolitan railway infrastructure project in Turin (Italy), demonstrating how digitally structured indicators and platform-based workflows can transform sustainability assessment from a static, multiple document-based practice into a dynamic, data-driven process, which can support procurement decisions, long-term asset management, and integrated sustainability governance.

Keywords: Digital Platform, Infrastructure, Sustainability 4.0, Asset Management, Decision Support System

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1 Introduction

1.1 Sustainability 4.0

In an era in which digital transformation is increasingly unavoidable and sustainability has become a fundamental requirement (D. Chen & Wang, 2024), the integration of these two paradigms, often referred to as Sustainability 4.0 (Filgueiras & Melo, 2024), is emerging as a challenge. The sustainability agenda and the introduction of the 17 Sustainable Development Goals (SDGs) has reshaped the concept of sustainability, extending it beyond a purely environmental perspective to also encompass social and economic dimensions. Within this framework, a strong emphasis has been placed on the construction and infrastructure sector (World Green Building Council, n.d.), as more than 40% of the SDG targets are directly or indirectly influenced by activities related to the built environment (Regona et al., 2024). In response to increasing policy demands, numerous initiatives have attempt to translate sustainability principles into measurable performance indicators (KPIs), enabling the assessment, evaluation, and comparison of sustainability outcomes in the built environment. Notable examples include Green Building Rating Systems for residential projects, Envision and BREEAM Infrastructure for infrastructure works, and LEED Neighbourhood Development for urban-scale interventions.

At the same time the built environment, similarly to other industrial domains, has been increasingly shaped by digital transformation. This process has involved the progressive adoption and evolution of digital technologies, starting from more established tools such as Geographic Information Systems (GIS) and Building Information Modelling (BIM), and subsequently extending to the Internet of Things (IoT), Blockchain, Digital Twins (DT) and, more recently, to advanced applications of artificial intelligence (AI) (Regona, Yigitcanlar, Hon, & Teo, 2024).

In this context, digitalization is progressively conceived as a strategic instrument to support the monitoring, control, and improvement of sustainability performance throughout the lifecycle of built assets.

1.2 Digital tools for the sustainability in the built environment

The current landscape is dominated by BIM (Abbasnejad, Soltani, Ahankoob, Kaewunruen, & Vahabi, 2025), which is increasingly used during the design phase to perform Life Cycle Assessments (Potrč Obrecht, Röck, Hoxha, & Passer, 2020), energy and water performance analysis (Durdyev, Dehdasht, Mohandes, & Edwards, 2021; Z. Liu, Zhang, Guo, Osmani, & Demian, 2019), and material waste reduction (C. Chen, Zhao, Xiao, & Tiong, 2021; Y. Liu, Van Nederveen, Wu, & Hertogh, 2018). Although its application is more mature in residential buildings, it is also widely used in infrastructure, with a particular focus on transportation infrastructure (Benzidane et al., 2025). Another fundamental tool is GIS, which enables to analyse land use, ecosystems, environmental constraints supporting sustainable planning and decision-making (X. Liu, Antwi-Afari, Li, Zhang, & Manu, 2025). GIS is predominantly applied at the infrastructure scale, as infrastructures are inherently spatial. Complementing BIM and GIS, IoT technologies and sensors are deployed for the real-time monitoring of structural health, tracking of operational energy consumption, air quality, and on-site worker safety. IoT systems are applied in both buildings and infrastructures (T. Chen, Wang, Su, Ikram, & Li, 2023; Jawad & Ali, 2025). AI and machine learning-based predictive analytics are increasingly used for predictive maintenance, resource optimization, automated damage detection, and supporting evidence-based decision-making through the identification of patterns in large datasets (Abbasnejad et al., 2025; Rasheed O. Ajirotutu et al., 2024, Mozafarian, Desiderio, Ye, Cavallaro, Villa, & Ninić,

2025). Blockchain is used to enhance supply chain transparency, ensure data integrity for ESG reporting, and support the tracking of construction waste (Kumar & Shah, 2025).

Consequently, several studies investigate the integration of multiple technologies (X. Liu et al., 2025; Piras, Muzi, & Zylka, 2024). In particular, the integration of BIM and GIS has proven essential for linear infrastructures, as it enables the contextualization of detailed asset information within a broader geospatial framework (Caldera, Mostafa, Desha, & Mohamed, 2021). This evolution has led to the development of DT, which integrate real-time data from IoT sensors to support continuous monitoring and proactive maintenance.

Although numerous digital tools are available, their application remains fragmented across sustainable thematic domains (Raouf & Al-Ghamdi, 2019) and lifecycle phases. These limitations highlight the need for platform-based approaches capable of orchestrating heterogeneous data sources and providing consistent sustainability evidence across lifecycle phases.

1.3 Digital-Platforms State of the Art

Based on recent literature current digital platforms for infrastructure aim to reduce fragmentation among stakeholders by providing shared environments for data access, analytics, and visualization. These solutions are often framed as layered architectures (Zhou et al., 2022). An information management layer, typically implemented as a Common Data Environment (CDE), supports storage, versioning, and controlled sharing of heterogeneous project and asset data through relational/graph databases and standard formats (such as: IFC, CityGML, RailML). An analytics layer then turns design and operational data into actionable insights via engineering simulations and data-driven methods (Afshari, Lee, & Besenski, 2025; Pawar & Khan, 2025; Xu et al., 2026). A visualization layer then exposes data and results through decision-oriented interfaces, such as interactive WebGIS dashboards and, in some cases, immersive environments of augmented reality.

Recent contributions can be grouped in the following recurring platform archetypes. BIM- and CDE-oriented platforms support design coordination, information governance, and model-based extraction of sustainability-relevant data (Jang, Kim, Ju, & An, 2021). Geo-enabled platforms couple BIM with GIS/WebGIS to situate assets within their territorial and network context, enabling corridor-scale visualization and spatial reasoning for linear infrastructures (Xu et al., 2026). Operation-centric platforms integrate IoT streams and Digital Twin concepts to support condition monitoring and the shift from reactive to predictive maintenance (Zhou et al., 2022). Federated or traceability-oriented architectures, sometimes including blockchain-enabled mechanisms (Romani et al., 2025), aim to facilitate multi-actor data exchange while strengthening provenance and accountability (Organisation for Economic Co-operation and Development [OECD], 2019). While these approaches provide clear benefits in monitoring, collaboration, and analytics, the reviewed literature also highlights three recurrent limitations that motivate further development.

First, lifecycle coverage and data continuity remain inconsistent (Zhou et al., 2022). Many platforms are optimized for a specific segment, making it difficult to maintain representations that remain comparable over time (Nübel, Bühler, & Jelinek, 2021). The effort required to align heterogeneous models and verify field updates can therefore undermine lifecycle-wide usability (Jang et al., 2021). Second, platform functionality tends to prioritize techno-economic performance and environmental monitoring, whereas integrated sustainability assessments that include social dimensions are less consistently operationalized (Triantafyllidis, Koppelaar, Wang, Van Dam, & Shah, 2018). Third, expert-

oriented usability can limit adoption, reducing accessibility. This is particularly critical for procurement and delivery governance, where decision-makers need interpretable, comparable, and easy to consult information.

These gaps indicate that, beyond integrating technologies, platforms should be designed around decision needs and lifecycle comparability. This study therefore develops a web-based decision-support platform that operationalizes a project-focused sustainability assessment framework for linear transport infrastructure.

2 Aim of the study and background

In response to these gaps, this study has two linked goals: define a project-focused key performance indicators (KPI) framework for integrated sustainability and build a digital platform that applies it across asset lifecycle phases. The overall aim is to support sustainability-informed contractor selection for linear transport infrastructure by incorporating consideration on both environmental and social aspects. The KPI framework evaluates sustainability at the project level, using indicators tied to design choices. The governance dimension is not included, because the focus is the sustainability and delivery performance of the project, not the contractor's wider corporate practices. While the KPI framework is introduced only to define the data and functions the platform must support, this paper focuses on the digital implementation. It presents the design and development of a web-based decision-support platform that collects, computes, and visualizes KPI data across project phases to support procurement and delivery decisions.

2.1 Background: Digital KPIs Development

The KPI framework was developed to be assessable and monitorable in a digital environment, so that it could be directly operationalized within the proposed platform. To ground the framework in practice, the initial indicator set, and data assumptions were refined through consultations with professionals from Infra.TO s.r.l., the company responsible for the design, tendering, construction supervision, and operational management of the new Turin metro line (Italy). These consultations helped identify the main sustainability challenges and possible areas of positive value creation in the case of a linear infrastructure. During this phase four macro-areas were defined: Project (asset-related characteristics), Community (responses to local needs and social value co-creation), Construction site (impacts of construction activities), and Territory (relationship between the project and its surrounding area).

New digital-ready KPIs were then derived through a comparative mapping of two established assessment systems in the infrastructure sector: Envision (Institute for Sustainable Infrastructure, 2018) and BREEAM Infrastructure (BRE Global, 2022), using a matrix to assign and filter indicators according to the case-study relevance. Within each macro-area, selected indicators were clustered by content affinity, and merged in a reduced KPI set with associated sub-indicators. As mentioned previously, a key design principle was digital compatibility, ensuring that each KPI could be linked to identifiable data sources and explicit computation rules. For examples, KPI inputs may include: material-related data extracted from BIM models; community engagement information collected through online questionnaires; changes in public transport accessibility or property value proxies derived from GIS layers; energy consumption and environmental impacts, captured through IoT monitoring systems or camera-based observations.

Once a first set of indicators was defined, it was revised to ensure that, where possible, the KPIs can be determined throughout all project phases. The assessment is designed to evolve across the project lifecycle phases and KPIs are recalculated at four key stages: Feasibility Design (FD), Detailed Design (DD), As-Built (AB), and Operation & Maintenance (O&M), enabling formal progress checks.

Each indicator is assessed on a scale from 1 to 5. When sub-indicators are defined, they are also rated on the same five-point scale, and their arithmetic mean provides the overall score of the indicator.

The following table provides an overview of the developed indicator set: 15 KPIs, which are then computed through 49 sub-indicators. Overall, the KPI framework provides the methodological starting point for the digital platform by defining its information requirements.

Table I. KPIs overview

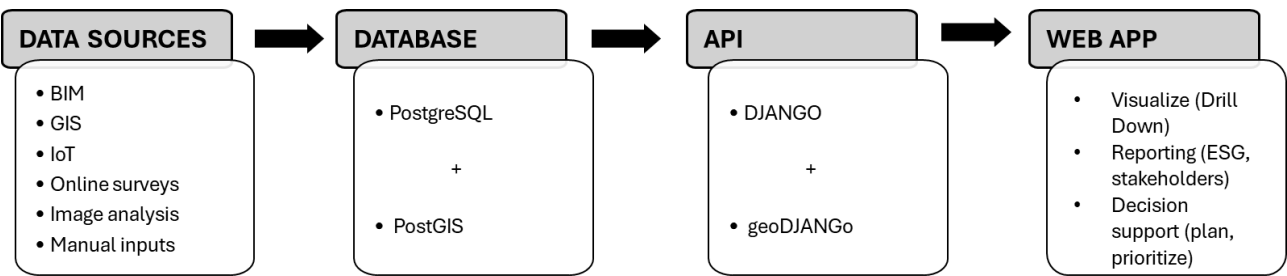
PROJECT (PR)	COMMUNITY (CO)	CONSTRUCTION SITE (CS)	TERRITORY (TE)
PR1_Recycled Materials	CO1_Local Community Involvement	CS1_Environmental Impacts	TE1_Heritage and Landscape Management
PR2_Embodied Carbon		CS2_Resource Efficiency and Reuse	
PR3_Energy Management	CO2_Economic Growth	CS3_Logistics	TE2_Soil Protection
PR4_Operational Carbon	CO3_Transport Network Integration		TE3_Water Protection
PR5_Water Management			TE4_Biodiversity

Moreover, the KPI system was structured as a hierarchical (tree-like) model to enable multi-level sustainability assessment. KPIs are computed within each macro-area and for each relevant asset component of the metro system (individual stations and tunnel segments). This structure allows results to be aggregated and disaggregated along two dimensions: by sustainability domain (macro-area → KPI → sub-indicators) and by asset breakdown (project → station/tunnel). Therefore, the assessment is meant to enables partial aggregation through user-defined selections. This “mix-and-match” capability is a key requirement for decision support, as it allows stakeholders to tailor the assessment scope based on their needs.

3 Proposal of a Web-Based Decision-Support Platform

This section describes the technical methodology adopted to implement the proposed decision-support platform. The system automatically collects required data, perform KPI-related computations, and present results through a web-based interface. By structuring and storing data consistently, the platform enables multi-level navigation and phase-based comparisons, allowing users to explore results at different levels of aggregation. Figure 1 shows a simplified schematic of the main components of the platform and the related technologies used.

Figure 1. Platform schematic flowchart



3.1 Identification of Heterogeneous Data Sources

The first step in developing the digital platform was to formalize the information requirements implied by the KPI framework and to identify the data sources that can provide such information across lifecycle phases. Each indicator (or sub indicator where available), was decomposed into its required input variables, and, for each variable, the most appropriate source(s) were defined for each lifecycle phase.

As an illustrative example of the workflow described above, Table 2 focus on the PR3_Energy Management indicator (Project macro-area).

Table 2. Example of an environmental indicator (PR3_Energy Management)

PHASE:	FD	DD		AB	O&M	
Sub indicators	-	PR3.1_ %Primary Energy	PR3.2_ Renewable Energy	-	PR3.1_ %Primary Energy	PR3.2_ Renewable Energy
Calculus	-	$PR3.1 = \frac{EN_p[kWh/a]}{EN_b[kWh/a]} * 100$	$PR3.1 = \frac{EN_r[kWh/a]}{EN_p[kWh/a]} * 100$	-	$PR3.1 = \frac{EN_p[kWh/a]}{EN_b[kWh/a]} * 100$	$PR3.1 = \frac{EN_r[kWh/a]}{EN_p[kWh/a]} * 100$
Data Required	-	EN _p Primary Energy	Baseline (EN _b) ¹ Renewable Energy (EN _r)	-	Primary Energy (EN _p)	Baseline (EN _b) ¹ Renewable Energy (EN _r)
Sources	-	BIM (IFC)	BIM (IFC)	-	IoT	BIM (IFC)/IoT

¹ Baseline definition adapted from Envision (Institute for Sustainable Infrastructure, 2018)

The table outlines the sub-indicators composing the main indicator, the project phase in which each sub-indicator is computed, the calculation method, the required input data and the sources from which the inputs data are retrieved. In the case of the primary energy consumption (EN_p), it is a BIM-based data in the early design stages, whereas during O&M it is computed using IoT sensor data, demonstrating that this mapping process represents a required step since KPI inputs may vary across project phases.

Once the processes were extended to all the indicators, the findings were consolidated into relational conceptual models, which were subsequently simplified into a more readable representation explicitly linking each entity and attribute to its corresponding data source(s). This step established a clear basis for designing the spatial database and the subsequent data integration workflow.

3.2 Automated Data Extraction and Cleaning

To make the platform scalable across lifecycle phases and data sources, data ingestion was designed as an automated Extract–Transform–Load (ETL) workflow, that converts heterogeneous inputs into a consistent, database-ready format. Automation is essential because KPI computation relies on repeatable updates over time: as the project progresses, the same KPI may transition from being estimated using design information to being updated using measured or externally collected data. As an illustrative example of the automated workflow, the system ingests BIM data exported from the model, in IFC format. All ingestion and processing steps are implemented in Python: during ingestion, the extraction is performed programmatically, and the pipeline applies cleaning and normalization. In addition, units and quantity measures are standardized to enable KPI computation.

While BIM/IFC is used here as an illustrative case, the same ETL logic can be designed to be extensible to the other sources.

3.3 Relational Spatial Database Implementation

A relational spatial database was adopted as the main core of the proposed platform in order to manage heterogeneous KPI inputs and enable consistent querying, aggregation, and visualization across asset components and lifecycle phases. The backend was implemented using PostgreSQL with the PostGIS extension, which provides native support for spatial geometries and geospatial operations, while database administration and inspection were performed through pgAdmin.

The database schema was derived from the information requirements defined during KPI decomposition. Because the same asset evolves across multiple project stages, the data model explicitly supports phase-dependent versions of the same entities. Unique identification relies on a composite key combining project ID and project phase, allowing comparisons across phases. Spatial datasets are stored as PostGIS tables and linked to the same project/phase identifiers to ensure coherence with non-spatial data. QGIS was used as a supporting tool to prepare and quality-check geospatial layers.

KPI computation is implemented at the database layer through SQL views which transform and join raw tables into indicator-ready datasets, ensuring a centralized and auditable workflow. Rather than storing only final KPI scores, the database preserves the normalized input variables required for each computation. This design improves transparency and reproducibility: KPI values can be recalculated as new data become available, and intermediate variables can be inspected to support results interpretation. Another important feature is the ability of the system not only to flag when an indicator cannot be computed, but also to report the underlying reason (such as which required inputs are unavailable), thereby supporting transparency and iterative data completion by stakeholders.

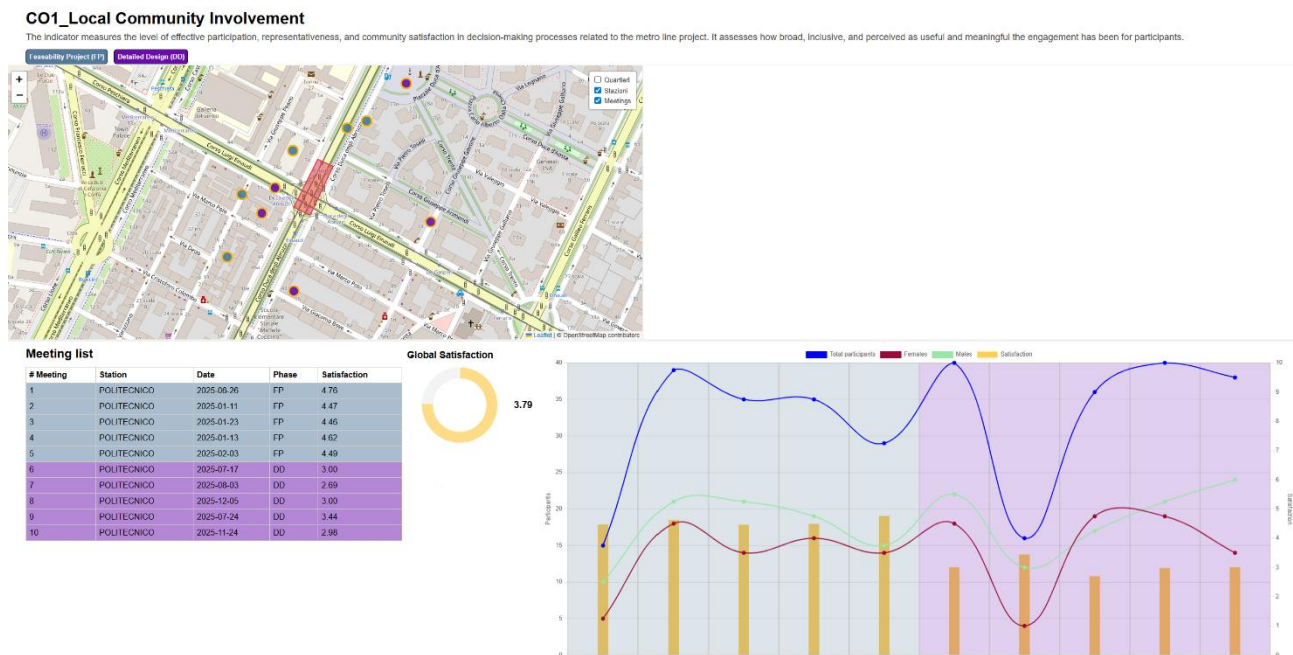
3.4 Web-Based User Interface for Decision Support

A web-based user interface was developed to translate the underlying database content and KPI computations into an interpretable decision-support environment accessible to different stakeholders. The interface was implemented using Django, which provides the application layer connecting the PostgreSQL/PostGIS backend to interactive web views. Because the platform includes spatial information, the web stack was configured using GeoDjango and supporting geospatial libraries (such as: OSGeo4W/GDAL stack) to enable geospatial queries and map-based visualization within the application. A key design choice was to decouple computation from presentation. The web application consumes KPI outputs exposed by the database (via dedicated views) as stable interface layers, which keeps the application logic lightweight and ensures that updates to computation rules remain centralized and traceable at the database level.

The main methodological challenge concerned the structure of user interaction: the interface had to support both synthesis and exploration without overwhelming users with technical details. To address this, the navigation logic was designed around the hierarchical assessment model. Users can access results at multiple levels of aggregation through interactive controls such as filters and zoom-in/zoom-out functions, which dynamically adjust the level of detail and reveal nested information. This structure supports flexible decision-making during procurement and project delivery, as stakeholders may require either high-level summaries or diagnostic views highlighting performance drivers and missing inputs. At the current stage, the web application should be considered work in progress: the core functions, data retrieval from database views, phase/component navigation, and map-based visualization, have been implemented to validate the decision-support concept, while further

development will extend interaction features, refine usability, and strengthen support for additional data sources and lifecycle monitoring. The following figure shows an example screenshot of the web page regarding the CO1_Local Community Involvement indicator.

Figure 2. Web Platform page example



4 Conclusions

The main contribution of this work lies in showing how a KPI-based sustainability assessment can be made operational in day-to-day project practices through a digital workflow that connects data acquisition, structured storage, automated calculations, and GIS-oriented communication. Rather than treating KPIs as a static reporting exercise, the proposed setup supports an updateable monitoring logic, where indicator values can evolve as new information becomes available and remain interpretable thanks to the traceability of input variables.

The system is conceived around a concrete case-study context, namely a new metro line in Turin (Italy), which is used in this study to ground requirements, data typologies, and user needs. While the paper presents the design and implementation choices in that setting, the intention is not to limit the approach to a single project. On the contrary, the architectural principles adopted (geospatial core, lifecycle-aware structure, and modular ingestion and computation) are meant to be transferable and scalable to other linear infrastructures. It should be noted that the platform is still under development and is not yet a finalized product. As such, it presents several aspects that can be improved, both technically and in terms of usability and data governance.

Nevertheless, the work intends to illustrate a key point: making sustainability information transparent and readable also to non-technical stakeholders can turn regulatory compliance from a purely burdensome requirement into a meaningful process. By structuring, connecting, and visualizing data that are already produced for design, reporting, and permitting, yet are often archived and rarely used afterwards, the platform can help transform “documentation” into actionable knowledge, supporting continuous monitoring and more informed decisions over the infrastructure lifecycle.

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