

GIUSEPPE PIRAS

Integrated Methodologies for the Built Environment

Digital Modelling, Energy
Assessment and Multi-Scale
Frameworks for the Production
and Management
of Built Environment

preface by Zoubeir Lafhaj

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Preface

The research that this volume collects and systematizes originates from an observation that anyone working in the field of construction recognizes immediately, yet which the scientific literature struggles to address directly: the structural gap between the sophistication of digital tools available for the design, management, and assessment of the built environment, and the average quality of their use in current professional practice. This gap is not simply a technological lag destined to close spontaneously over time: it is the symptom of a deeper methodological problem, concerning the understanding of the validity conditions of instruments, awareness of their limitations, and the capacity to combine them coherently in response to real decision-making questions.

The architecture, engineering, and construction sector, commonly designated by the acronym AECO, finds itself at a moment of accelerated transformation on two simultaneous fronts. The first is the digital transition: the progressive replacement of analogue processes with digital ones that affect not only the design phase, already broadly involved, but the entire value chain from construction to operational management through to renovation. The second is the en-

ergy transition: the need to drastically reduce the energy consumption of the existing building stock and to integrate production from renewable sources, in response to European climate objectives that impose emission reductions of 55% by 2030 and carbon neutrality by 2050. These two transitions are not parallel and independent: they interweave deeply, because digital tools are a necessary condition for effectively realizing the energy transition at scale, and the energy transition is one of the main drivers of demand for digital innovation in the sector.

Responding to this dual challenge requires not only new tools, but new methodologies: new ways of combining available instruments, new criteria for evaluating their quality and reliability, new conceptual frameworks for integrating information from different disciplinary domains into coherent assessments that support well-founded decisions. This represents the space of integrated methodologies for the dual transition in the built environment, and the present volume intends to explore it with scientific rigour and systematic ambition.

The original motivation for this research is not theoretical but empirical: it derives from direct observation of how digital tools are used in real operational contexts, and from the recognition that their effectiveness is frequently limited not by the technical quality of the tools themselves, but by a lack of methodological reflexivity on the part of those who use them. A BIM model constructed without awareness of the level of development required for the analyses for which it is intended produces unreliable results regardless of the quality of the software. A machine learning model for predicting energy consumption trained on insufficient data

produces misleading predictions regardless of the sophistication of the algorithm. An economic assessment of investments in energy efficiency conducted with an unjustified discount rate produces distorted recommendations regardless of the precision of energy savings estimates.

In all these cases, the problem is not the technology: it is the methodology. And methodology cannot be improved simply by adding more powerful tools: it requires a specific investment in the critical understanding of the validity conditions of existing instruments, in the systematic documentation of their limitations, and in the design of frameworks that combine instruments in ways that amplify their strengths without multiplying their weaknesses.

This awareness oriented the research design choices from the outset towards an explicit methodological perspective. The application cases that appear in the volume relates to the renovation of an office building in Rome, the monitoring of workplace environments with IoT systems, the prediction of energy consumption in Roman residential buildings, the assessment of the photovoltaic potential of a Campanian motorway, the critical analysis of environmental product declarations for photovoltaic modules, are not the protagonists of the text: they are the instances through which methodological problems become concrete and verifiable. The question this volume intends to answer is not “how does one carry out an energy renovation of an office building” or “which machine learning algorithm is most accurate for energy consumption prediction”, but higher-order questions: what are the validity conditions of the methods used in each of these contexts, how do uncertainties propagate through analytical chains, and how are frameworks built that main-

tain their coherence when transferred from one context to another.

The originality of the scientific contribution of this volume articulates along three distinct dimensions that deserve to be made explicit.

The first is the systematicity of the methodological stress-test. The existing literature on the application of digital tools to the building sector is predominantly optimistic: it documents the results that tools produce when applied under favourable conditions, with abundant data, well-defined contexts, and specialized expertise available. This volume deliberately adopts the opposite perspective: it asks how tools behave when conditions are difficult due to data scarcity, or when they are incomplete, or noisy; when standard assumptions are not satisfied; when the application context differs from that for which the tools were designed. The systematic stress-test framework developed for evaluating ML models for energy prediction varies the historical depth of data, introducing missing values and Gaussian noise, and measures performance degradation in a quantitative and replicable manner. This is the most elaborate example of this perspective, but the same logic pervades the entire research: the validation of aeraulic calculations in a BIM environment through comparison with the manual method, the critical analysis of hidden assumptions in EPDs, the explicit documentation of conditions under which clustering models produce reliable segmentations and those under which they do not.

The second dimension of originality is the integrated multi-scale perspective. Research on the built environment tends to organize itself by scale: researchers working at the

product scale rarely interact with researchers working at the building scale, who rarely interact with researchers working at the neighbourhood or infrastructure scale. This volume deliberately crosses this separation, analyzing the methodological discontinuities encountered when moving from one scale to another: how legitimate assumptions change, what data is required, what techniques are appropriate, what conditions of transferability hold. This multi-scale perspective is not a catalogue of applications at different scales: it is an analysis of the methodological transformations that scale changes imply, and of the coherence conditions that must be guaranteed so that assessments at different scales can be articulated into an integrated system.

The third dimension of originality is the explicit integration of the three evaluative dimensions> energetic, environmental, and economic, with a critical awareness of their difficult management. The existing literature tends either to treat them separately, each with its own tools and standards, or to aggregate them into composite indicators that conceal tensions between dimensions. This volume adopts a third approach: it analyses the conditions under which the three dimensions are mutually coherent, identifies the structural tensions that emerge when they are not, and proposes methodological strategies for managing these tensions transparently rather than concealing them through arbitrary aggregations.

The scientific rigour of the volume is founded on precise methodological choices that must be made explicit so that readers can critically assess their solidity.

The first choice concerns the documentation of assumptions. Every method analysed is examined not only in its

results, but in its premises: the assumptions that must be true for the method to produce reliable results (Nwodo & Anumba, 2019), and the consequences that occur when these assumptions are violated. This documentation of assumptions, even if they are often absent in applied literature, which tends to present results without discussing the conditions that make them valid, is the necessary condition for a critical use of tools rather than an uncritical use that applies standard procedures without verifying their adequacy to the specific context.

The second choice concerns the distinction between generalizable results and contextual results. The volume systematically identifies, for each result, which portion constitutes a methodological principle with general validity and which portion is specific to the case study in which it was produced. This distinction is epistemologically necessary but practically challenging. It requires resisting the temptation to generalize results produced in specific contexts too widely, and being honest about the limitations of the transferability of one's contributions. Specific numerical results as the R^2 values of ML models, unit costs of retrofit measures, photovoltaic production estimates for the A3 motorway etc., are not generalizable outside their context. The methodological principles that emerge from the analysis of these results are the need for at least 12 months of data for complete seasonality (a threshold that, as discussed in Chapter 3, should be understood as context-dependent rather than as a universal rule), the priority of disaggregation over aggregation in EPDs, coherence between system boundaries across the different dimensions of integrated assessment, that have broader validity.

The third choice concerns replicability. The data, code, and workflows used in computational analyses are made available in open form on public repositories. This choice is not only a gesture of transparency: it is a necessary condition for cumulative scientific production that allows the community to build on existing results rather than having to start from scratch. Replicability does not guarantee the truth of results, but is the necessary condition for their critical verification by the scientific community.

The volume is organized in five chapters that follow a logical progression from the micro scale to the macro scale, and from the analytical perspective of individual tools to the synthetic perspective of integrated frameworks. The first chapter addresses the problem of informational modelling of the built environment, analysing the validity conditions and limitations of the chain that runs from physical survey to the georeferenced digital twin. The second chapter addresses the problem of data, examining the epistemological characteristics of measured, declared, and estimated data in the different contexts of energy and environmental assessment. The third chapter addresses machine learning models for energy prediction, with a systematic focus on robustness under conditions of limited data. The fourth chapter addresses integrated assessment in its three dimensions, energetic, environmental, economic, analyzing available methodologies, their limitations, and the coherence conditions between different dimensions. The fifth chapter synthesizes the cross-cutting methodological principles that emerge from the analysis of the preceding chapters, formulating the replicability conditions and structural limits of integrated frameworks.

The conclusions, which follow the five chapters, do not repeat already-presented results: they propose a reading of the overall corpus that identifies the original methodological contributions as a coherent system, discusses their position in the international research landscape, and formulates a future development agenda rooted in identified limitations rather than abstract ambitions.

This volume is addressed to a plurality of readers: researchers in the AECO sector seeking not only results but a critical reflection on the methodologies that produce them; designers and technicians who use digital tools in professional practice and want to understand the conditions for their correct use; public and private decision-makers who must assess the reliability of the analyses on which they base their choices; advanced students preparing for research or professional work at the boundary between the digital domain and the energy-environmental domain. For each of these readers, the value of the volume lies not in the specific numerical results of case studies, which age with markets, materials, and regulations, but in the methodological principles that emerge from their analysis, and which maintain their validity independently of technological evolution.

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Chapter 1

Informational Modelling of the Built Environment

From BIM to the Georeferenced Digital Twin

This chapter examines the conceptual and methodological foundations of informational modelling in the built environment, tracing the progression from physical survey to georeferenced digital twin. It moves from geometric model to informational model, from BIM to GIS integration, from static snapshot to adaptive system, and each step in this chain introduces specific validity conditions, new sources of uncertainty, and distinct epistemological implications. The aim is not to catalogue tools, but to make explicit the conditions under which each level of representation can be legitimately used, and where its reliability ends.

1.1. The Informational Model as an Epistemological Construct

The informational model functions as a knowledge tool, but only within the validity conditions defined by the data and hypotheses on which it is based. Understanding what a model can and cannot know (and why) is the prerequisite for any methodologically sound use of BIM-based analytical workflows.

1.1.1. *Difference Between Geometric Model, Informational Model, and Digital Twin*

The history of the representation of the built environment is, in large measure, a history of progressive abstraction. From the two-dimensional technical drawing, that translates the three-dimensional complexity of a building into orthogonal projection, to parametric solid modelling, through to the distributed informational architectures that today go by the name of Digital Twin, each step has entailed not only an expansion of representational capacities, but a qualitative transformation of the relationship between the model and the reality it intends to describe. Understanding this transformation is not an exercise in the history of technology: it is a necessary condition for correctly evaluating the validity, limitations, and operational implications of any methodology founded on digital modelling of the built environment.

The starting point is a distinction often neglected in applied literature, but epistemologically decisive: the difference between a geometric model, an informational model, and a digital twin. The three concepts share the word *model*, but refer to structurally different cognitive objects, with different validity conditions and different methodological implications.

A geometric model is a representation of form. It describes the position, dimensions, and spatial relationships of the elements that compose an object. In its most elementary form, as it is the three-dimensional CAD drawing, the geometric model lacks semantics: a wall is a solid, not a wall. It has no thermal properties, no cost, no

supplier, it does not age. Its relationship with reality is of a mimetic type: it reproduces the appearance, not the behavior. This makes it a powerful tool for visualization and certain types of spatial analysis, but insufficient for any assessment that requires reasoning about the physical, economic, or environmental properties of the represented elements.

An informational model, in the technical sense introduced by the BIM (Building Information Modelling) paradigm, is something structurally different. It does not merely describe the form of elements: it treats them as objects with identity, properties, and relationships. A wall in a BIM model is an entity that has a thickness, a stratigraphic composition, a thermal transmittance, a manufacturer, a scheduled installation date and unit cost. It has relationships with other elements as happens with the floor slab it rests on, with the window that penetrates it, with the room it helps to delimit. This semantic richness transforms the model from a representation tool to a knowledge tool: it allows information to be extracted, calculations performed, coherences verified, documents generated, behaviors simulated.

The distinction is not, however, merely quantitative intended as for the information present in the model, but qualitative. An informational model introduces an ontological structure: each element belongs to a category, each category has defined attributes, each relationship has a type and a direction. It is this structure that makes interoperability between different software possible through open formats such as IFC (Industry Foundation Classes), and that constitutes the technical precondition for any form of automation

or advanced computational analysis. Without ontological structure, data remains data; with it, data becomes information in the technical sense of the term: data organized in such a way as to answer questions.

The digital twin adds a third dimension that neither the geometric model nor the informational model possesses: dynamics. A Digital Twin is not a digital photograph of a building at a given moment; it is a representation that updates in real time or near-real time to maintain its correspondence with the physical state of the object it represents. This continuous update capability is made possible by the integration of the reference model, typically a BIM model, with a real-time data acquisition infrastructure, realized through networks of IoT (Internet of Things) sensors (Li et al., 2025)). The result is a system that not only describes how a building is made, but monitors how a building behaves, and, in the most advanced implementations, predicts how it will behave in the future.

This conceptual progression has profound methodological implications. The first is that the three levels are not interchangeable: using a geometric model to answer questions that require an informational model, or a static informational model to answer questions that require a dynamic twin, produces invalid results regardless of the quality of the tools used.