



# From Materials to Cities: Understanding Cross-Scale Challenges Affecting Urban Material Flows

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**Abstract.** By promoting a regenerative approach, the Circular Economy has been seen as a pathway to sustainable urban development. As a key component of urban circularity, urban metabolism examines the flows and stocks of resources within cities, including materials and energy. Increasingly, cities are applying this approach within a circular framework to identify opportunities to reduce resource dependence, improve efficiency, and guide more sustainable urban development. However, analyzing materials flows at the city level poses numerous challenges, including technical ones. Among the different categories of technical challenges, the lack of information/data is a relevant one. Understanding the correlations between this challenge at the urban level and challenges at the material and building scales is essential for identifying effective solutions to overcome them.

This study investigates how technical challenges, at the material and building levels, influence the analysis of material flows, particularly in terms of information and data, in urban systems. Furthermore, it explores how digital technologies, namely BIM and GIS, can be enablers and drivers to overcome these challenges. To this end, a desk research approach is employed to detect and map correlations between cross-level technical challenges in the built environment and to identify how digital technologies have been used to overcome the challenges. Finally, based on findings, a conceptual framework is proposed that identifies the use of BIM and GIS at the material and building levels to overcome technical challenges and how these results can be applied to material flow analysis at the urban level.

**Keywords:** Technical Challenges · Circular Economy · Urban Systems · BIM · GIS · Circular Strategies

## 1 Introduction

The transition towards circular and sustainable cities has intensified global interest in understanding the resource dynamics within the urban built environment. In this context, the Circular Economy (CE) has emerged as a central policy and research paradigm, advocating for regenerative cycles that minimize waste, retain material value, and decouple urban development from primary resource extraction [1].

Urban Metabolism (UM) constitutes a structural analytical lens through which cities can be examined as systems that consume inputs, including materials, energy, water, and food, and generate outputs in the form of products, waste, and emissions [2]. Among the different methods to analyze the metabolism of cities, Material Flow Analysis (MFA) enables systematic accounting of material inputs, stocks, and outputs within a defined urban system boundary, serving as a diagnostic tool for identifying material inefficiencies and monitoring progress towards circularity targets [3, 4]. Despite growing methodological advancements, the analysis of materials flows at the urban scale still faces technical challenges. Among these is the scarcity, fragmentation, and inconsistency of data describing material stocks and flows across different spatial and temporal scales [5]. These challenges are not isolated to the city scale but are deeply rooted in upstream deficiencies at the material and building levels, the scales at which the physical characterization of the built environment begins.

Digital technologies, particularly Building Information Modeling (BIM) and Geographic Information Systems (GIS), have been increasingly recognized as transformative enablers that bridge data gaps across scales [6]. Their integration represents a promising approach towards City Information Modeling (CIM), capable of supporting multi-scale urban data aggregation and analysis [6, 7]. However, barriers, including ontological misalignment, data granularity mismatches, and platform interoperability limitations, continue to impede their systematic use in urban MFA. This paper brings material, building, and urban scales information challenges into a single cross-scale framework and examines how BIM and GIS can support the upward translation of data needed for urban MFA.

## 2 Theoretical Background: Technical Challenges Across Scales

The built environment is characterized by an interconnected, scalable structure in which material properties, building components, and urban systems interact in complex, interdependent ways. Technical challenges manifest distinctly, yet correlatively, across these scales, with data and information deficiencies representing a critical cross-cutting constraint [8]. In this paper, the material scale refers to information associated with individual materials, products, and components, such as composition, technical properties, certification, traceability, and passport data. The building scale refers to information related to the aggregation, organization, and lifecycle tracking of those materials and components within assembled building artefacts, including stock indexing, as-built documentation, disassembly records, and building layers. The urban scale refers to information related to resource inputs, stocks, and outputs within defined urban boundaries. The distinction among scales is important because urban MFA depends not only on knowing what materials exist, but also on knowing where and how they are embedded within buildings.

Across the three scales of the built environment, lack of data and information constitutes one of the most persistent categories of technical challenges impeding CE implementation [8]. At the material scale, the most frequently reported barrier concerns data availability, accessibility, and accuracy, including unreliable data, outdated material passports, and limited information on salvaged components. These are followed by deficiencies in traceability and certification, which weaken the capacity to verify the quality

and performance of reused materials throughout the value chain. At the building scale, the challenge shifts from characterizing individual products to aggregating and tracking information in assembled artefacts. Key barriers include incomplete material stock indexing, absence of as-built documentation, insufficient tracking of reused materials across lifecycle phases, and lack of disassembly records. These limit the reuse of products elsewhere when buildings or components are dismantled. At the urban scale, barriers include limited data capabilities, insufficient integration across information sources, and restricted data availability for CE monitoring and planning [9]. Together, these challenges constrain the reliability, granularity, and temporal depth of urban MFA.

### 3 Methodology

This study adopts a desk-research approach grounded in a structured literature review and thematic synthesis. The analysis builds on previous review-oriented works addressing technical challenges to circular strategies in the built environment and the role of digital tools in supporting circularity and urban-scale material analysis [7, 8]. The first study [7], critically reviewed 19 papers, from a total of 75, from 2018 to 2025. By addressing the question: “*Is City Information Modeling currently defined and used in the context of Material Flow and Stock Analysis?*”, the study aimed to understand the relationship between digital tools, namely City Information Modeling (CIM), and urban material analysis (MSA and MFA). The second study [8], on which this research is built, identifies and analyzes the primary technical barriers impeding the transition to a circular economy in the built environment, examining challenges across the urban, building, and material scales and exploring the potential of digitalization, design for disassembly, and BIM as enabling strategies to overcome them. The research approach of the present study was designed to: (i) identify and classify technical challenges related to data and information across the three scales; (ii) map correlations between challenges across scales in the lens of the analysis of the materials flows; and (iii) identify documented applications of BIM and GIS that respond to these challenges.

Building on these sources, the present paper conducted an interpretive cross-scale synthesis to propose a framework, constructed through iterative thematic synthesis, in which technical challenges were systematically mapped against documented applications of BIM and GIS technologies and organized into a hierarchical structure reflecting the scalar progression from material characterization to urban-level MFA. Challenge priorities were established based on frequency of mentions in the literature; they represent research relevance, not validated real-world priorities, and further validation is needed.

### 4 Cross-Scale Technical Challenges and Enablers in the Built Environment

Data and information deficiencies do not operate in isolation at each scale but exhibit a structural propagation pattern: gaps in material-level data, particularly regarding traceability, passport completeness, and quality documentation, cascade upward to constrain building-level material stock assessments, which in turn limit the reliability and resolution of urban-scale MFA inputs. This cross-scale propagation is further intensified

by the absence of standardized data schemas capable of ensuring semantic consistency across scales, a condition at the intersection of information deficiencies and the lack of technical standards that directly conditions the effectiveness of digital technology interventions. Similarly, at the urban scale, limited knowledge of UM methodologies and digital analytical tools constrains practitioners' capacity to deploy GIS-based platforms for spatiotemporal material flow mapping, even where underlying data are partially available. Table 1 maps these cross-scale correlations.

These literature-derived correlations indicate the principal points at which BIM and GIS may act as cross-scale enablers: at the material scale, through structured digital capture of material properties and passport data; at the building scale, through interoperable BIM models aggregating component-level information; and at the urban scale, through GIS-based platforms integrating building stock data for city-level flow analysis. As enablers, BIM and GIS address different but complementary dimensions of the cross-scale information problem: BIM supports structured representation and life-cycle tracking of materials and components, whereas GIS supports spatial aggregation, territorial analysis, and urban-scale interpretation.

At the material scale, BIM-based material passports offer a structured mechanism for encoding and updating material properties throughout the building lifecycle, directly addressing the data availability and traceability deficiencies. At the building scale, existing BIM models have been applied for material stock and material intensity assessment [9, 10], deconstruction planning, and selective demolition, supporting end-of-life material recovery and reuse strategies [11, 12]. At the urban scale, GIS has been extensively applied to address deficiencies in spatial resolution and temporal coverage. Applications include hotspot analysis to identify spatial concentrations of building material stocks, 4D GIS models to characterize urban building metabolism and construction and demolition waste flows, and integrated GIS–MFA–LCA frameworks to analyze the spatiotemporal dynamics of building stocks [13]. These studies collectively establish GIS as the primary tool for spatially aggregating and analyzing distributed material data at the city level, directly responding to the data integration and accessibility barriers identified at the urban scale.

The integration of BIM and GIS represents the most direct technological response to the cross-scale data propagation problem. Parezanović et al. (2025) [9] combined BIM models with GIS cadastral data to assess building material stocks, while Triantafyllidis et al. (2025) [10] demonstrated that linking georeferenced BIM models with GIS enhances spatial analysis capacities. The convergence of BIM and GIS capabilities through CIM frameworks represents a promising trajectory for cross-scale data integration. By enabling the translation of building-level material data into spatially referenced urban datasets, BIM–GIS integration holds the potential to substantially improve the granularity and consistency of urban MFA inputs [7]. An explicit articulation of this integration is proposed by Schiller et al. (2024) [6], who developed a materiality-based City Information Model (mCIM) applying MFA principles to construct a material cadastre map, positioning GIS as the urban-scale modeling framework and BIM as the source of detailed building-level material data.

Critically, the reviewed literature demonstrates that BIM and GIS are predominantly applied in isolation, with their integration remaining partial and rarely framed within a

**Table 1.** Cross-scale mapping of information/data technical challenges in the built environment.

| Challenge/ category            | Material Scale                                                                                            | Building Scale                                                                                              | Urban Scale                                                                                                 |
|--------------------------------|-----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|
| Data Availability and Accuracy | Unreliable material data; incomplete material passports; limited data on salvaged components              | Lack of material stock indexing; absence of as-built documentation; inaccurate building component databases | Limited georeferenced building stock data; insufficient data for CE monitoring and planning                 |
| Traceability and Certification | Lack of certification for reused products; absence of component-level traceability across the value chain | Insufficient tracking of reused materials across lifecycle phases; absence of disassembly records           | Limited provenance data for urban material flow attribution                                                 |
| Standardization                | Absence of standardized material data schemas; incompatible material classification systems               | Lack of open BIM data standards (e.g., IFC); inconsistent Level of Development (LOD) specifications         | Absence of harmonized urban material accounting frameworks; incompatible spatial data standards             |
| Spatial Resolution             | Material-level spatial referencing largely absent; components not georeferenced                           | Building-level spatial data inconsistently captured; georeferencing dependent on GIS integration            | Spatially inconsistent datasets; difficulty attributing material flows to specific urban zones or functions |
| Temporal Coverage              | Limited longitudinal data on material performance and degradation over time                               | Lifecycle phase data fragmented; design-stage data rarely updated through construction and use phases       | Temporally misaligned datasets; absence of dynamic stock inventories for urban monitoring                   |
| Interoperability               | Incompatible material data formats; absence of machine-readable material passports                        | Lack of interoperability between BIM platforms; data exchange barriers across project stakeholders          | Insufficient integration among urban data sources; limited BIM-to-GIS data translation capacity             |

**Cross-scale propagation:** data availability gaps cascade upward from material to building to urban scale, constraining MFA resolution at each level. Traceability gaps undermine flow accounting reliability. Absence of shared standards limits semantic interoperability. Spatial and temporal deficiencies at lower scales reduce disaggregation capacity in urban MFA.

unified cross-scale analytical structure [7]. This gap, compounded by the identified barriers to semantic interoperability and standardization, motivates the conceptual framework proposed in Sect. 5, which explicitly structures the roles of BIM and GIS across the material, building, and urban scales to support city-level MFA.

## 5 Proposed Conceptual Framework

The proposed conceptual framework explains how interventions at the material and building scales can improve the data foundations required for urban MFA, as shown in Fig. 1. The framework operates across three interdependent layers.

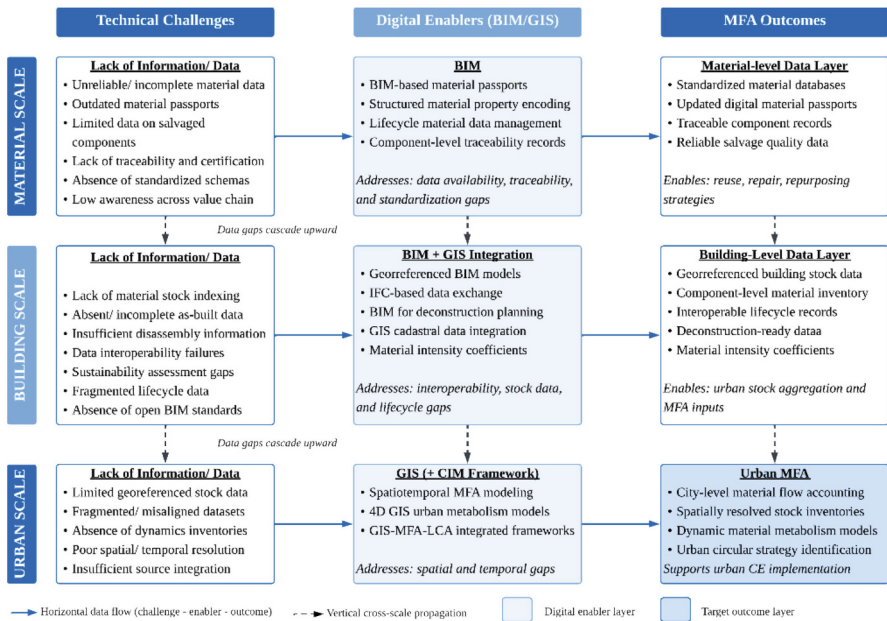


**Fig. 1.** Conceptual Framework: BIM and GIS as Cross-Scale Enablers for Urban Material Flow Analysis

At the material scale, BIM-embedded material passports and standardized product data libraries provide the foundational input data. At the building scale, BIM models enriched with material attributes, complemented by GIS-based spatial registration, enable characterization of the building stock. At the urban scale, spatially aggregated building stock data, processed through GIS-enabled MFA platforms, support city-level resource flow quantification and circular strategy identification.

This framework contributes to operationalizing CIM as a data infrastructure for urban circularity, emphasizing the importance of upward data flow from material characterization to urban analysis. Furthermore, the framework highlights that the resolution of urban-scale data challenges is conditional upon addressing their antecedent causes at lower scales.

## 6 Conclusions and Future Research Directions

This paper has discussed the cross-scale technical challenges that impact material flow analysis at the urban level, with particular focus on data and information deficiencies. Through a structured desk research approach, it has mapped correlations between challenges at the material, building, and urban scales, and identified how BIM and GIS technologies have been employed, individually and in integrated form, to address these challenges. The proposed conceptual framework offers a structured perspective on how digital technologies, when applied at lower scales, can generate upward data flows that enhance urban MFA capacity. By positioning BIM and GIS as cross-scale enablers within

a CE framework, the study underscores the need for integrated digital strategies that span from material characterization to city-level resource governance.

Several limitations should be acknowledged. First, the study is based on desk research and is therefore subject to publication bias and limited coverage of practitioner-driven or grey literature. Second, the relevance levels assigned to challenges are based on frequency of mention in the reviewed literature; they indicate prominence in research, not validated real-world priority. Third, the cross-scale correlations proposed in this paper are literature-informed analytical relationships and should not be interpreted as empirically confirmed causal links. Future research should focus on validating the relevance of challenges in real-world applications, developing and testing data pipelines that operationalize the proposed framework, including integrating material passport systems with BIM platforms and GIS-based urban stock databases. Comparative case studies across different urban contexts will be instrumental in refining the framework and assessing its transferability.

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