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Developing BIM-Based Data Analytics Dashboards for Sustainable Construction and Demolition Waste Management and Environmental Evaluation

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Abstract

Building Information Modelling (BIM) is increasingly mandated worldwide as part of the construction industry's digital transformation. While widely used in design and construction, its potential for managing construction and demolition waste (C&DW) remains underexplored, despite demolition accounting for 70–90% of building-related waste and 30–40% of global solid waste. BIM Revit native models provide rich data but are computationally intensive and require specialist expertise, limiting their direct use for waste quantification and sustainability evaluation. This paper develops a BIM-enabled data integration and visualization framework that automates waste estimation, material classification, and environmental evaluation by linking BIM data with heterogeneous datasets through Speckle connectors and Power BI dashboards. Supplementary datasets included material densities, expansion coefficients, recycling rates, and environmental factors such as CO_2 emissions and energy intensities. A case study of York University's Bergeron Centre illustrates the framework's effectiveness across three demolition stages. The non-invasive dismantling phase highlighted significant opportunities for material recovery, while semi-invasive deconstruction captured recyclable structural components with moderate landfill requirements. The final core demolition stage revealed the greatest potential for recycling, particularly in concrete and steel, though it also underscored the challenges of diverting large volumes of residual waste from disposal. By integrating BIM with environmental datasets and interactive dashboards, the system delivered holistic insights into recovery, landfill diversion, and CO_2 reduction. Findings confirm its scalability, accessibility, and value as a decision-support tool for sustainable demolition and circular economy objectives.

1. Introduction

1.1 Motivation

Building Information Modelling (BIM) has become a central source of information in the construction industry, increasingly mandated across many countries as part of the digital transformation of the built environment (Kalantari et al., 2024). While BIM is traditionally applied in design and construction stages, its potential in automating construction and demolition waste (C&DW) management remains underutilized, despite the sector contributing 30–40% of total solid waste globally (Islam et al., 2024). Given that demolition activities often account for 70–90% of building-related waste (Ding et al., 2016). There is a pressing need for innovative frameworks that leverage BIM for sustainability and circular economy goals.

Beyond waste generation, the broader environmental footprint of the built environment further reinforces the need for more sustainable planning approaches. Urban areas are responsible for nearly 70% of global greenhouse gas (GHG) emissions, while the construction sector, encompassing both operational and embodied impacts, accounts for approximately 38% of these emissions (Ahmed Ali et al., 2020). In 2021, buildings represented nearly one-third of global final energy consumption and generated a comparable share of CO_2 emissions (Camarasa et al., 2022). This challenge is expected to intensify, as building-related energy demand may rise by 46–73% by 2050 relative to 2019 levels, driven by population growth, rising living standards, and increasing energy use intensity in emerging economies (Holechek et al., 2022; Santamouris and Vasilakopoulou, 2021).

Construction and demolition waste is a major environmental challenge. The sector generates 30–40% of global waste, with total C&DW exceeding 10 billion tons annually, and more than 35% ending up in landfills (Islam et al., 2024). In Canada, about 9 million tons of C&D waste are generated each year, but only 16% is reused or recycled, equal to about 1.44 million tons (Shamloo and Hewage, 2010). Figure 1 highlight the need for more effective and data-driven waste recovery strategies.

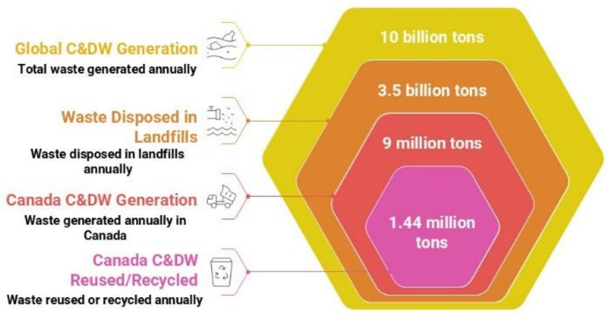

Figure 1-Global Construction and Demolition Waste Generation

1.2 Literature review

Effective construction and demolition waste (C&DW) reduction depends on both modern construction methods and efficient waste management practices. Approaches such as volumetric systems, precast components, steel framing, and insulated panel systems can significantly reduce waste by minimizing off-cuts and unnecessary material handling (Martínez Bertrand and Tomé, 2008). However, effective waste management also requires accurate estimation, source segregation, worker training, digital tracking, and proper logistics planning (Martínez Bertrand and Tomé, 2008). Among these, reliable estimation of waste quantity and composition is especially important because it underpins environmental assessment and recovery planning.

Existing estimation approaches include area-based methods, material stock and flow analysis, software-based tools such as SMARTWaste, and site measurements (Su et al., 2021). While these methods provide useful forecasting capabilities, they also present limitations related to generalization, regional applicability, data complexity, or post-demolition dependency (Building Research Establishment, 2008; Jalali, 2007).

Circular economy (CE) principles have gained increasing attention in the construction sector as a means of shifting from linear waste disposal toward closed-loop resource use (Brambilla et al., 2019; Ranta et al., 2018). CE strategies can reduce virgin material consumption while generating environmental and economic benefits; for example, even a 5% reduction in C&D waste could save the British economy up to £130 million(Ajayi and Oyedele, 2017). Within this context, material reuse, selective deconstruction, and recycling are key strategies for improving sustainability in C&DW management. Reuse of structural components can significantly reduce greenhouse gas emissions and embodied energy (Zheng et al., 2025), while selective deconstruction enables the recovery of valuable materials before final demolition, although it often requires more labour, time, and planning(Gálvez-Martos et al., 2018; Li et al., 2025). Reuse practices can save around 40% of embodied energy, and reusing prefabricated slabs can reduce carbon footprints by more than 60%(Roth and Eklund, 2003). Recycling also offers major environmental benefits, including reductions in life-cycle energy use and embodied energy, particularly for concrete, steel, and aluminum (Bribián et al., 2009; Rimoldi, 2010).

1.3 Research Gaps and Objective

Despite advances in waste reduction strategies and growing interest in circular economy practices, current approaches to C&DW management remain limited in their ability to support integrated, project-level decision-making. Existing waste estimation methods are often either too generalized, region-specific, data-intensive, or dependent on post-demolition measurements, which reduces their usefulness for early planning and environmental evaluation (Building Research Establishment, 2008; Jalali, 2007; Su et al., 2021). At the same time, although reuse, selective deconstruction, and recycling offer clear environmental benefits, their practical implementation is still hindered by financial, structural, legal, and technical barriers (Adams et al., 2016; Association, 2015).

Although BIM provides rich and detailed information on building materials and components, its application in demolition waste quantification and circular economy assessment remains limited. Existing Revit-based BIM models are often complex, data-heavy, and difficult to process without specialized expertise, which restricts their practical use for waste forecasting, recovery planning, and sustainability evaluation (Jayasinghe and Waldmann, 2020). In addition, current approaches often treat material quantification, recovery assessment, and environmental evaluation as separate tasks, resulting in fragmented workflows that are less effective for decision-making. There is still a lack of integrated systems that can efficiently transfer BIM data into accessible analytical environments, automate downstream processing, and support practical interpretation by both technical and non-technical stakeholders.

To address this gap, this study develops a BIM-enabled data integration and visualization framework that links Revit models with external analytical platforms through an automated Speckle–Power BI pipeline. The proposed framework further strengthens decision-making by integrating environmental factors into a visual analytics decision-support system, enabling automated material quantification, recovery-oriented assessment, and sustainability evaluation within a unified and accessible workflow.

2. Method

The proposed system for sustainable C&DW management includes the following components:1) data Transformer, 2) Computational Functions, 3) Environmental Performance Index, 4) Interactive dashboards. A case study of the Bergeron Centre for Engineering Excellence at York University (Toronto, Canada) was used to demonstrate the framework. Though not scheduled for demolition, its 2015 Revit model was selected to test the feasibility of early-stage planning.

2.1 Data Transformer

Using Speckle connectors, architectural and structural BIM data were automatically transferred from Revit into Microsoft Power BI, where the raw model records were cleaned, standardized, and enriched for downstream analysis. This transformation process preserved key BIM attributes, including element categories, material assignments, and geometric quantities such as material volumes, while addressing inconsistencies in naming conventions across families and systems. Within Power BI, the BIM-derived dataset was linked with supplementary reference tables containing material densities, volume expansion coefficients, Ontario recycling rates, CO_2 emission factors, and energy intensity and savings values. This integrated data transformation layer enabled the automatic conversion of model information into a structured analytical dataset capable of supporting demolition waste estimation, material classification, recovery assessment, and environmental performance evaluation.

2.2 Computational Functions

A set of computational functions was developed to convert BIM-derived material quantities into demolition waste indicators relevant for circular economy assessment. First, material volumes extracted from the BIM models were converted into mass values using representative density factors for each material type. Expanded waste volumes were then estimated using material-specific bulking coefficients to reflect post-demolition behaviour and support waste handling and logistics planning. The quantified materials were subsequently classified into reusable, recyclable, and residual waste streams, enabling estimation of recoverable fractions and landfill-bound residues. By applying Ontario-specific recycling rates to the recyclable portion of each material stream, the framework generated realistic projections of recovery potential, recycling residues, and diversion from landfill, thereby providing a more regionally grounded basis for demolition planning.

2.3 Environmental Performance Index

To extend waste quantification into sustainability assessment, environmental performance indicators were integrated into the analytical workflow. The framework linked BIM-derived material streams with external carbon and energy coefficients to estimate the environmental implications of recycling and recovery scenarios. Carbon-related indicators included emissions associated with recycling activities, avoided emissions from displacing virgin material production, and transportation-related CO_2 impacts. Energy-related indicators captured both the energy required for recycling processes and the energy savings achieved through material recovery. By incorporating these measures, the framework enabled a project-specific comparison of environmental burdens and benefits across material categories, supporting more informed evaluation of demolition strategies from both resource recovery and environmental perspectives.

2.4 Interactive Dashboards

A series of interactive dashboards was developed to communicate the outputs of the BIM-RISE framework in an accessible and decision-oriented format. These dashboards combined BIM-derived quantities with supplementary datasets, including material densities, volume expansion coefficients to account for post-demolition bulking behaviour, Ontario recycling rates, and environmental performance indicators such as carbon emissions and energy demand. Implemented in Microsoft Power BI and supported by Speckle's 3D Viewer and query tools, the dashboards allowed users to filter results by material category, building system, and demolition stage, while also exploring recovery potential and associated environmental outcomes. By linking quantitative metrics to the spatial BIM model, the dashboards improved transparency and enabled both technical and non-technical stakeholders to interpret material flows, identify high-impact recovery opportunities, and evaluate sustainability-oriented demolition scenarios more effectively.

3. Result and Discussion

3.1 Results

The results demonstrate the capacity of the proposed BIM-RISE framework to process BIM-derived geometric and semantic building information together with external material, recovery, and environmental datasets within an integrated spatial decision-support workflow. Across the three demolition stages, the framework quantified both recoverable and landfill-bound material streams and translated these into project-specific indicators of recovery potential, carbon implications, and energy performance. This confirms that BIM-RISE moves beyond conventional volumetric estimation by combining spatial data processing, sustainability assessment, and visual analytics to support circular demolition planning.

In the non-invasive dismantling stage, which focused on the removal of fixtures, finishes, and equipment, approximately 13.92 million kg of material were identified as recoverable, while 9.84 million kg remained directed to landfill. In the semi-invasive structural deconstruction stage, the system estimated 1.55 million kg of recyclable material, primarily metals, compared with 1.04 million kg of non-recyclable waste. The core structural demolition stage produced the highest material quantities and the greatest recovery opportunity, with approximately 21.7 million kg of recyclable material and 11.54 million kg destined for disposal. These results indicate that although later demolition stages generate the largest waste streams, they also contain the greatest opportunity for diversion when supported by material-specific recovery planning. In particular, the structural stage highlights the importance of targeting high-volume materials such as concrete and steel to achieve significant landfill reduction.

Beyond waste quantification, the framework linked recyclable material streams to environmental coefficients to evaluate net CO_2 impacts, recycling energy demand, energy savings, and transportation-related CO_2 emissions. The results show that environmental performance is strongly influenced by material composition rather than waste quantity alone. Metals, especially steel and aluminum, generated the greatest environmental benefits because the avoided impacts of virgin material production substantially outweighed the burdens of recycling. By contrast, mineral-based materials such as concrete, brick, and mortar tended to produce smaller benefits or even net positive impacts due to their lower recycling credits relative to processing burdens. As a result, the overall environmental balance of the case study was driven primarily by the recoverable fraction of high-value metals, which offset a substantial share of the impacts associated with bulk concrete and masonry streams.

The energy results followed a similar pattern. Recycling process energy demand varied considerably across materials, with aluminum showing the highest recycling energy intensity and steel also requiring substantial processing energy. However, these same materials also delivered the greatest energy savings because recycling displaced highly energy-intensive virgin production. In contrast, concrete contributed comparatively low energy savings despite its large mass, reflecting the lower energy intensity of virgin concrete production. This distinction is important because it shows that the most abundant material is not necessarily the one with the highest environmental leverage. Therefore, if the objective is to maximize sustainability benefits, demolition planning should prioritize the recovery and segregation of high-impact metals while also improving the recovery quality of concrete and masonry through enhanced sorting and reduced contamination.

Figure 2 and figure 3 illustrate examples of the developed visual analytics interface, where BIM-derived material quantities are linked with environmental coefficients to generate project-level sustainability indicators. The dashboard enables users to interpret CO_2 impacts, energy demand, and energy savings across material streams in an accessible format, supporting comparison of recovery scenarios and improving transparency in demolition planning.

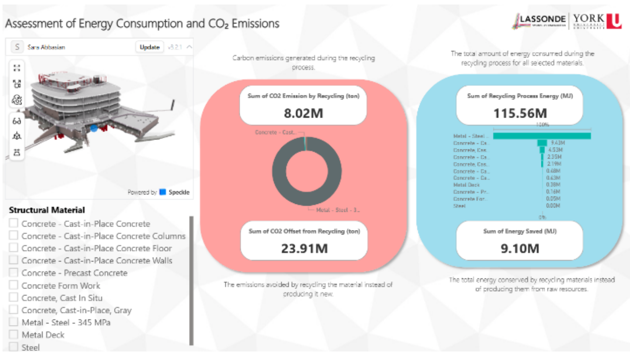

Figure 2 - Energy consumption and CO2 emission in the structural model

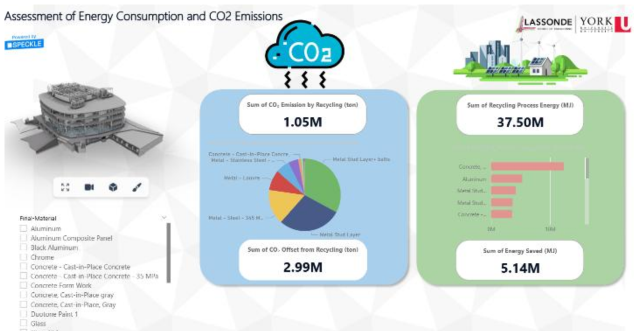

Figure 3 - Energy consumption and CO2 emission in the architectural model

Table 1 shows a summary of CO_2 and energy indicators generated from the BIM-RISE dashboard for the architectural and structural models.

Table 1-Environmental impact results from the dashboard visualizations

Model	CO_2 Emission by Recycling (ton)	CO_2 Offset from Recycling (ton)	Recycling Process Energy (MJ)	Energy Saved (MJ)
Architectural Model	1.05M	2.99M	37.50M	5.14M
Structural Model	8.02M	23.91M	115.56M	9.10M

Table 2 provides a qualitative interpretation of the major material categories in terms of their environmental contribution within the proposed BIM-RISE framework. By comparing net CO_2 effects and energy savings potential, the table highlights how different materials influence the overall sustainability performance of demolition and recovery strategies. This comparison helps clarify why materials with smaller quantities may still generate greater environmental benefits, while high-volume materials may contribute more limited gains despite dominating the waste stream.

Table 2- Environmental interpretation of major material categories

Material Category	Net CO_2 Effect	Energy Savings Potential	Discussion
Steel	Strong benefit	High	High avoided virgin production impact
Aluminum	Strong benefit	Very high	High recycling burden but even larger avoided production benefit
Concrete	Limited benefit	Low	Large mass but low environmental leverage per kg
Brick / Mortar	Net burden or limited benefit	Low to moderate	Lower recycling credits relative to processing impacts

3.2 Discussion

The discussion of this study centers on how the proposed BIM-RISE framework addresses the research objective of developing an integrated and accessible system for demolition waste quantification, recovery planning, and environmental assessment. Rather than functioning as a standalone estimation tool, the framework was designed as a complete decision-support system that connects BIM-derived building information with external sustainability datasets through a structured digital workflow. This system-oriented design is important because one of the major limitations in current practice is not the lack of data itself, but the difficulty of transforming complex BIM data into usable knowledge for planning and evaluation.

A key contribution of the framework lies in its architecture as an automated Speckle–Power BI pipeline, which bridges BIM authoring and analytical interpretation. In many conventional workflows, Revit models remain difficult to interrogate outside specialist environments, and their practical use in demolition planning is limited by manual extraction steps, fragmented calculations, and dependence on expert users. By contrast, the proposed system was designed to preserve element- and material-level BIM information while transforming it into a structured analytical environment where waste, recovery, and environmental computations can be performed consistently. This directly supports the study objective of reducing the technical barrier associated with BIM-based waste assessment and improving the usability of model-derived information.

The integration of environmental factors into the visual analytics decision-support system further strengthens the methodological contribution of the framework. Existing approaches often separate waste quantification from environmental evaluation, which limits their usefulness for circular economy decision-making. In the proposed system, material quantities, recycling rates, carbon coefficients, energy factors, and transport assumptions are brought together within one unified workflow. This design allows the framework to support not only measurement of waste flows, but also interpretation of their broader sustainability implications. As a result, the system aligns more closely with the real needs of demolition planning, where decisions must account for both material recovery potential and environmental trade-offs.

Another important strength of the system design is its emphasis on accessibility. The dashboards were not developed merely as reporting interfaces, but as an operational layer of the framework through which the outputs of the analytical modules become interpretable to a wider range of stakeholders. This is especially relevant to the study objective of supporting both technical and non-technical users. In practice, demolition and deconstruction planning involves multidisciplinary actors, including engineers, project managers, contractors, and sustainability practitioners, many of whom do not work directly within BIM software. By translating BIM-derived data into interactive and queryable dashboards, the system broadens access to complex material and environmental information and improves transparency in decision-making.

From a design perspective, the staged structure of BIM-RISE also reflects the logic of circular demolition planning. The framework organizes the workflow from data acquisition and transformation, through waste quantification and classification, to environmental evaluation and dashboard communication. This modular design improves traceability because each stage of the computation remains connected to the original BIM data while also allowing the system to be adapted as new coefficients, recovery rates, or policy assumptions become available. In this sense, the framework is not only a case-specific implementation, but also a scalable methodology that can be extended to different project contexts and regional conditions.

The discussion also highlights that the value of the framework lies in its integrative capability. Many previous studies address waste estimation, recycling assessment, or environmental analysis separately, resulting in fragmented outputs that are harder to operationalize. The proposed system responds to this gap by embedding these components within a single analytical environment. This integrated design is closely aligned with the research objective and represents the main advancement of the study: the creation of a practical BIM-enabled system that supports circular economy evaluation through automated data flow, structured computation, and accessible visual analytics.

Overall, the study demonstrates that effective demolition waste management requires more than accurate quantity estimation; it requires a system capable of linking building information, recovery logic, and sustainability metrics in a form that supports real planning decisions. The BIM-RISE framework contributes to this need by offering a professionally structured, data-driven, and user-oriented decision-support system. Its design shows how BIM can move beyond static information storage and become an active platform for circular demolition planning and environmental assessment.

4. Conclusion

This study presented BIM-RISE as an integrated system design for demolition waste quantification, recovery planning, and environmental evaluation. Rather than using BIM only as a source of building information, the framework was designed as a complete digital workflow that connects Revit-based model data with external sustainability datasets through an automated Speckle–Power BI pipeline. This system architecture enables the transformation of complex BIM information into a structured analytical environment where waste, recovery, carbon, and energy indicators can be calculated and communicated in a consistent and accessible way.

A key contribution of the research is therefore not only the estimation of demolition waste, but the design of a practical visual analytics decision-support system that reduces dependence on manual extraction and specialist BIM expertise. By integrating data transformation, computational assessment, and dashboard-based communication within a single framework, BIM-RISE supports both technical and non-technical stakeholders in interpreting demolition scenarios and their sustainability implications. Overall, the study shows that system-oriented BIM integration can play an important role in advancing circular economy objectives by turning data-rich building models into actionable knowledge for more transparent, scalable, and sustainability-driven demolition planning.

Despite these contributions, the study has several limitations. The framework was demonstrated on a single case study building and therefore serves primarily as a proof of concept rather than a universally validated solution. The reliability of the outputs also depends on the completeness and quality of the BIM model, as well as the regional assumptions embedded in the recycling rates, environmental coefficients, and transport parameters. In addition, the current framework emphasizes environmental and recovery-based indicators, while economic feasibility, uncertainty analysis, and real-time demolition constraints were not fully incorporated.

Future research should expand the framework across multiple building types and demolition scenarios to strengthen validation and generalizability. Further development could also integrate cost analysis, sensitivity analysis, and region-specific policy or market factors to support more realistic decision-making. In addition, enhancing the system with scenario comparison capabilities and broader material recovery datasets would improve its usefulness as a scalable decision-support platform for circular demolition planning.

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