SCENARIO-BASED MATERIAL-FLOW AND CIRCULARITY ASSESSMENT OF DEEP RENOVATION PROJECTS

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Abstract

Waste generation in deep renovation is driven by onsite activities and their temporal sequencing and scheduling, yet most existing circularity assessment approaches remain scenario and execution agnostic. This paper proposes a schedule-aware BIM-based approach that integrates activity-zone modelling with precedence-constrained scheduling to enable time-based estimation of material flows and waste generation. Implemented through the Circular Intelligent-based Waste Engine (CIWE), the approach supports activity-level waste estimation and onsite circularity assessment. A multi-residential renovation case in Lille, France is used to compare three renovation scenarios. Results show that renovation sequencing significantly influences waste intensity, recovery potential and circularity outcomes.

Introduction

The construction sector is a major contributor to global resource consumption and waste generation, making it a central target for circular economy transitions (dos Santos Gonçalves et al., 2025). In Europe, deep renovation of existing buildings is increasingly promoted to reduce operational energy demand while limiting embodied environmental impacts associated with new construction (Hertwich et al., 2019). However, deep renovation causes substantial material inflows and demolition waste that must be effectively managed to support circular economy goals such as waste reduction, reuse, and recycling (Hossain et al., 2017).

Building Information Modelling (BIM) has significantly advanced construction and demolition waste estimation by enabling element and activity-level quantification and supporting evaluation of renovation and deconstruction strategies (Cheng and Ma, 2013). Recent studies have extended BIM-based approaches toward circularity principles by incorporating material recyclability, reuse potential and whole-life performance indicators (Akanbi et al., 2018). Nevertheless, the literature shows that most BIM-based circularity assessments remain largely static, relying on aggregated material quantities and overlooking the temporal and operational dynamics of renovation execution (Zhao et al., 2025).

Renovation sequencing, spatial dependencies and access constraints influence waste intensity, recovery feasibility and onsite logistics, particularly in multi-storey residential renovation context (Mrema et al., 2023). However, many existing BIM-based frameworks treat renovation activities as temporally independent, failing to integrate scheduling logic with material-flow and circularity assessment (Ashrafi et al., 2025). As summarized in Table 1, prior approaches generally lack zone-based modelling, precedence-constrained scheduling and time-resolved waste profiling. To address these gaps, this paper proposes a scenario-based, schedule-aware BIM-enabled framework integrating activity-zone modelling with precedence-constrained scheduling, implemented through CIWE, and demonstrated on a deep renovation case study in Lille, France.

Table 1: BIM-based waste and circularity frameworks.

Framework	Cheng and Ma (2013)	Akanbi et al. (2018)	Jiang et al. (2025)	This Study
BIM-based material data	✓	✓	✓	✓
Activity-level waste estimation	✓	✓	✓	✓
Zone-based modelling	×	×	×	✓
Execution-aware scheduling (sequencing & precedence)	×	×	×	✓
Execution-level time-resolved waste profiling	×	×	×	✓
Circularity & material-flow assessment	×	✓	✓	✓

Material and Methods

Framework overview

The proposed framework enables schedule-aware circularity assessment by structuring renovation projects around activity-zone execution logic and precedence-constrained scheduling. By integrating BIM-derived quantities with execution sequencing, it supports time-resolved quantification of material inflows, waste outflows and circularity indicators, which captures the influence of renovation sequencing on waste generation and recovery outcomes. The methodological workflow consists of five sequential stages:

1. Definition of renovation activities and scenarios
2. BIM-based activity-zone mapping
3. Precedence-constrained renovation scheduling

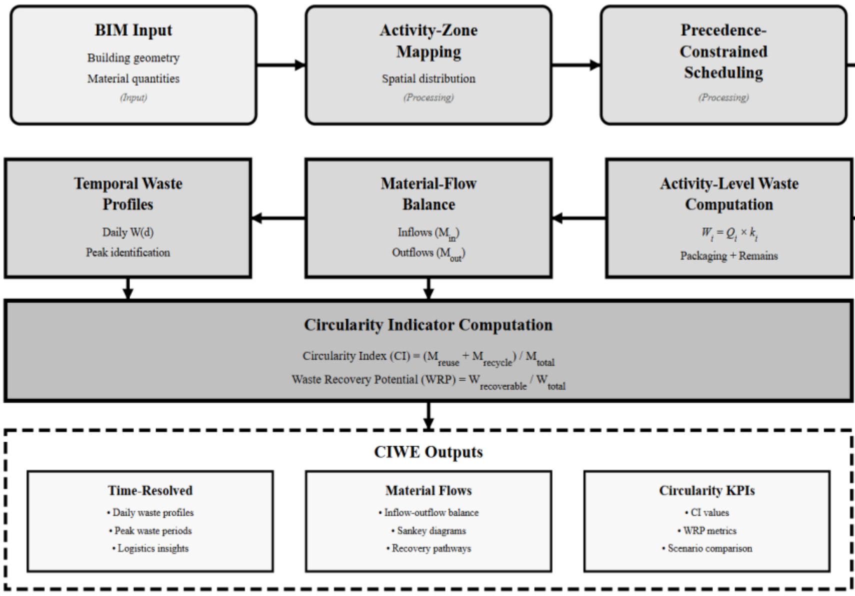

Figure 1: Overview of the CIWE framework for schedule-aware material-flow and circularity assessment

4. Activity-level waste and material-flow estimation
5. Computation of circularity indicators

Figure 1 illustrates the overall workflow and highlights the interaction between BIM data, activity sequencing, and temporal material-flow modelling implemented through CIWE. The CIWE, developed in this study, is implemented as a plug-in tool within Autodesk Revit, enabling automated extraction and activity-level quantification of material flows and waste generation during renovation projectsParts of the paper.

Case study

The proposed framework is demonstrated using a multi-residential building undergoing deep renovation in Lille, France, representative of a typical European multi-storey residential typology targeted by current renovation and circular economy policies (Figure 2). The building includes five floors, envelope elements, circulation areas, and external zones, enabling analysis of both vertical and horizontal renovation sequencing. A BIM model was developed as the primary source of geometric, material, and zoning data, supporting activity-zone mapping and consistent definition of renovation activities within CIWE. The model enables extraction of activity-level quantities required for material-flow and waste estimation. Three renovation scenarios with increasing intervention depth are analysed. All scenarios share identical geometry and zoning to ensure comparability, with differences arising only from renovation scope and system upgrades. Scenarios vary in envelope insulation levels, window specifications, HVAC configurations, ventilation systems and renewable energy integration, including photovoltaic and solar-thermal installations (see Table 2). It should be noted that the three scenarios are defined as alternative renovation strategies rather than sequential extensions of one another. Differences in waste generation arise primarily from variations in activity composition and execution logic, particularly the balance between demolition-intensive and installation-based interventions.

Activity-zone execution model

Renovation works are structured using an activity-zone execution model that explicitly links each renovation activity to the building zones where it is performed. The defined activities include envelope insulation, window and door replacement, HVAC and ventilation installations, internal insulation measures, pipe insulation, and renewable energy systems. This structure enables consistent allocation of material inflows and waste outputs at activity level while preserving spatial differentiation across the building.

Figure 2: Case study building in Lille, France, corresponding BIM model and CIWE GUI

Table 2: Summary of renovation scenarios applied to the Lille demonstration case

Element / System	External-wall insulation	Roof insulation	Basement-ceiling insulation	Windows	Heating /Cooling	Ventilation	RES electricity	RES thermal	Lighting
Scenario 1	EPS 12 cm (U= 0.25 W/m²K)	EPS 20 cm (U = 0.20 W/m²K)	--	Double-glazed Low-E	Decentralised ASHP	Natural	--	--	--
Scenario 2	EPS 12 cm (U= 0.25 W/m²K)	EPS 20 cm (U = 0.20 W/m²K)	--	Triple-glazed Low-E	Decentralised ASHP	Decentralised MVHR	Roof PV 15 kW	--	LED partial
Scenario 3	EPS 12 cm (U= 0.25 W/m²K)	EPS 20 cm (U = 0.20 W/m²K)	EPS 3 cm (U = 0.83 W/m²K)	Triple-glazed Low-E	Decentralised ASHP	Decentralised MVHR	Roof PV 20 kW	Solar-thermal 12 m²	Full LED replacement

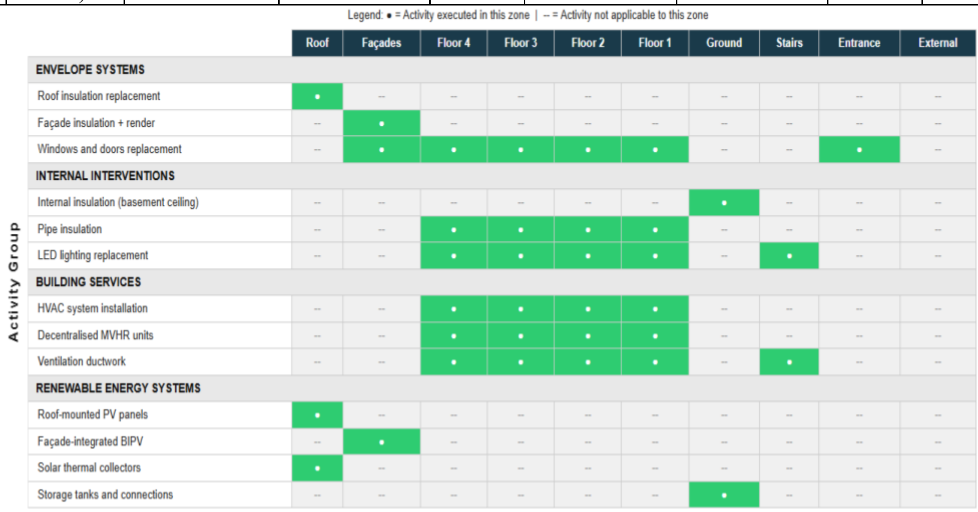

Figure 3: Activity-zone execution matrix defining the spatial distribution and repetition of renovation activities across building

Repetitive activities, such as internal insulation, HVAC installations and pipe insulation are replicated across the building floors, reflecting vertical execution patterns typical of multi-storey renovation projects. In contrast, envelope-related and renewable energy activities are assigned to specific zones, including roofs, external façades, and external areas, capturing horizontal differentiation in renovation execution. Figure 3 presents the activity-zone execution matrix, which links spatial activity allocation with BIM-derived quantities to support consistent material-flow and waste estimation.

Precedence-constrained renovation scheduling

Renovation execution is governed by a zone-level precedence logic that defines spatial and temporal dependencies between activities, reflecting access, safety, and coordination constraints typical of multi-storey deep renovation projects. This ensures feasible sequencing while maintaining operational continuity.

Three categories of precedence constraints are applied. Vertical precedence enforces a top-down execution order for internal works, requiring upper-floor activities to be completed before lower-floor interventions. Horizontal precedence coordinates envelope and internal activities, ensuring façade insulation and window replacement are completed before internal installations commence, while preserving functional access routes.

Controlled parallelisation allows selected activities to proceed concurrently across zones once prerequisite conditions are satisfied. All precedence relationships are formalised as a directed scheduling network integrated with BIM-derived activity-zone mappings and activity durations. This enables CIWE to generate feasible renovation schedules that underpin time-resolved allocation of material inflows, waste generation, and circularity assessment. Figure 4 illustrates the zone-level precedence network applied in this study.

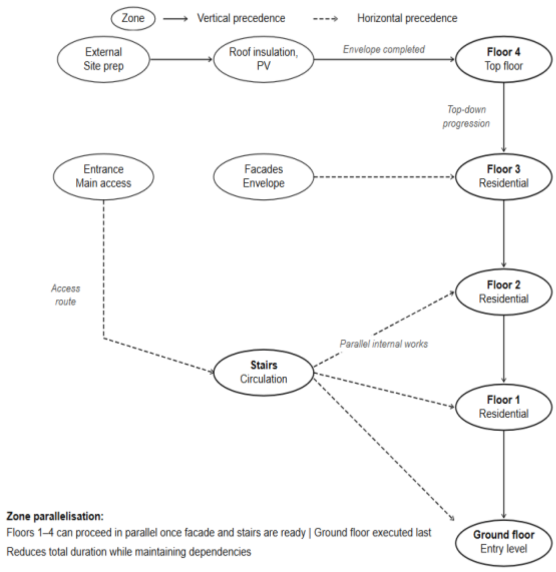

Figure 4: Zone-level precedence network governing spatial and temporal renovation sequencing in CIWE.

Activity-level waste and material-flow estimation

Waste generation is estimated at activity level using predefined waste and demolition coefficients applied to BIM-derived quantities. For each activity ($\boldsymbol{i}$), total waste generation is calculated as:

$$W_i = Q_i \cdot k_i \quad (1)$$

where (W_i) is the total waste generated by activity ($\boldsymbol{i}$), (Q_i) is the BIM-derived quantity of the activity ($\boldsymbol{i}$), and (k_i) is the corresponding waste coefficient of activity ($\boldsymbol{i}$).

The activity-level waste coefficients, packaging shares, reuse, recycling and recovery assumptions applied in this study are derived from literature (Llatas and Osmani, 2016; Quiñones et al., 2022) and expert-informed calibration (Table 3). To account for the temporal distribution of waste, activity-level waste is evenly allocated over the scheduled duration of each activity:

$$W_i(d) = \frac{W_i}{D_i} \text{ for } d \in [S_i, E_i] \quad (2)$$

Where ($W_i(d)$) is the waste generated on day (d), (D_i) is the activity duration, and (S_i) and (E_i) are the scheduled start and end days respectively for activity **($\boldsymbol{i}$).**

Daily project-level waste generation is then computed as the sum of waste contributions from all active activities:

$$W(d) = \sum_{i=1}^{n} W_i(d) \quad (3)$$

Waste outputs are divided into packaging waste and remains waste. Packaging waste corresponds to installation and transport losses, while remains waste represents demolition debris and residual materials.

For each activity ($\boldsymbol{i}$), packaging and remains waste are calculated respectively as follows:

$$W_{i,pack} = W_i * p_i \quad (4)$$

$$W_{i,rem} = W_i * (1 - p_i) \quad (5)$$

where (p_i) is the packaging share in Table 3. In parallel, material inflows associated with new installations are quantified, allowing the construction of material inflow-outflow balances:

$$M_{\text{net}} = \sum M_{\text{in}} - \sum M_{\text{out}} \quad (6)$$

Where (M_{in}) represents materials introduced through new installations and (M_{out}) represents materials removed as waste.

Circularity indicator computation

Circularity performance is evaluated using two indicators derived from CIWE outputs. The Circularity Index (CI) quantifies the share of material flows directed towards reuse and recycling pathways relative to total material throughput:

$$CI = \frac{\text{Recovered Material}}{\text{M}_{throughput}} = \frac{\sum_{i=1}^{n} \text{W}_i\left(r_i^{reuse} + r_i^{recycle}\right)}{\sum_{i=1}^{n} M_i^{in} + \sum_{i=1}^{n} \text{W}_i} \quad (7)$$

where $W_i$is the waste generated by activity i, $M_i^{in}$is the material inflow associated with activity i, $r_i^{reuse}$and $r_i^{recycle}$are the reuse and recycling coefficients assigned to activity i, respectively, and $M_{throughput}$represents the total material throughput of the renovation system, defined as the sum of all material inflows and waste outflows across renovation activities.The Waste Recovery Potential (WRP) represents the proportion of total generated waste that can be directed to recovery pathways. In this study, material-specific recovery routes refer to the predefined post-generation pathways assigned to each activity-related waste stream, namely reuse, recycling, and landfill disposal, based on the recovery assumptions reported in Table 3. Accordingly, WRP captures the share of generated waste that is recoverable through reuse and recycling pathways:

$$WRP = \frac{\sum_{i=1}^{n} \text{W}_i \times r_i^{recover}}{\sum_{i=1}^{n} \text{W}_i} \quad (8)$$

Where, $r_i^{recover} = r_i^{reuse} + r_i^{recycle}$represents the total recoverable fraction of waste for activity i. Both indicators are computed at scenario level by aggregating activity-level results using the recovery coefficients reported in Table 3.

Table 3: Activity-level waste coefficients, waste fractions, and recovery assumptions

Activity Category	Activity	Unit	Waste Coefficient (k)	Packaging Share (%)	Reuse Potential (r_i^{reuse}) (%)	Recycling Potential (r_i^{recycle}) (%)	Total Recovery Potential (r_i^{recover}) (%)
Envelope	Roof insulation replacement	dm³/m²	23	35	20	50	70
	Façade insulation + render	dm³/m²	28	25	15	50	65
	Window replacement	dm³/unit	30	40	30	45	75
Internal works	Internal insulation	dm³/m²	18	30	20	48	68
	Pipe insulation	dm³/m	8	45	25	55	80
	LED lighting replacement	dm³/unit	5	65	20	65	85
Building services	HVAC system installation	dm³/unit	30	70	18	60	78
	MVHR unit installation	dm³/unit	25	75	17	65	82
	Ventilation ductwork	dm³/m	12	55	20	55	75
Renewable energy	Roof PV panels	dm³/kW	15	80	15	70	85
	Solar thermal collectors	dm³/m²	10	75	15	65	80
	Storage tanks	dm³/unit	20	60	25	50	75

$W_i$represents the total waste generated from activity i, and the recovery coefficients $r_i^{reuse}$and $r_i^{recycle}$are applied to the total waste, not limited to the packaging fraction. Adapted from Llatas and Osmani (2016); Quiñones et al. (2022), with expert-informed calibration.

Recovery coefficients are applied to the total waste generated from each activity, not limited to the packaging fraction, and are defined at the aggregated activity level to ensure modelling consistency.

Results and Discussion

This section presents a schedule-aware assessment of renovation waste on the Lille case study. It examines how material inflows, waste generation, spatial execution, and temporal sequencing interact across the three renovation scenarios. Waste is analysed as a time-dependent and activity-driven process rather than a static cumulative outcome, to enable explicit evaluation of waste intensity, recovery potential, and circularity trade-offs.

Scenario-level material inflows and waste generation

Table 4 summarises scenario-level material inflows and waste outputs for the Lille renovation case study. As renovation depth increases, total new materials installed rise from 18,500 kg in Scenario 1 to 24,100 kg in Scenario 3, primarily due to the introduction of renewable energy systems and expanded building services. In contrast, material inflows associated with insulation and window replacement remain relatively stable across scenarios, indicating that envelope upgrades constitute a baseline intervention independent of renovation depth.

Table 4: Scenario-level material inflows and waste outputs for the Lille renovation case.

Indicator	Unit	Sc. 1	Sc. 2	Sc. 3
Material Inflows				
Total new materials installed	kg	18,500	21,200	24,100
Insulation materials (EPS)	kg	4,200	4,200	4,850
Windows and doors	kg	3,100	3,600	3,600
HVAC systems	kg	2,800	3,400	3,400
Renewable energy systems	kg	--	1,850	3,200
Other building services	kg	8,400	8,150	9,050
Material Outflows (Waste)				
Total waste generated	dm³	50,664	42,127	33,736
Packaging waste	dm³	13,173	11,796	10,121
Remains waste	dm³	37,491	30,331	23,615
Packaging fraction	%	26	28	30
Remains fraction	%	74	72	70

Across the scenarios, higher material inflows do not translate into higher waste quantities, indicating a clear decoupling between material throughput and waste generation. This outcome reflects differences in renovation activities rather than overall material volumes, as scenarios with greater emphasis on system installation generate proportionally less demolition-related waste. The results highlight that waste generation in deep renovation is primarily driven by activity composition and execution logic, rather than by the magnitude of material inflows alone. At the same time, waste composition shifts toward packaging-dominated streams as renovation depth increases. This qualitative change reflects the growing contribution of packaged building services and renewable energy systems and has direct implications for on-site handling and recovery strategies. These findings demonstrate that scenario-level waste performance cannot be evaluated solely through cumulative waste quantities, motivating analysis at activity, spatial and temporal levels.

While Table 4 provides a scenario-level summary of material inflows and total waste outputs, it does not explicitly reveal the origin of waste generation across renovation systems. To improve interpretability, Table 5 presents a disaggregated breakdown of waste by renovation system and activity for each scenario.

Table 5: Waste generation by renovation system and activity across scenarios (dm³)

Renovation System	Activity	Sc. 1 (dm³)	Sc. 2 (dm³)	Sc. 3 (dm³)
Envelope		**48396**	**18363**	**1883**
	Flat roof insulation	**21302**	**0**	**0**
	Façade insulation	**27094**	**0**	**1883**
	Windows & doors replacement	**0**	**18363**	**0**
Internal works		**0**	**3794**	**0**
	Internal insulation (all floors)	**0**	**3794**	**0**
Building services		**2268**	**19975**	**31448**
	Pipe insulation (all floors)	**0**	**19975**	**0**
	Wall-mounted HVAC / storage	**2268**	**0**	**0**
	Radiant floor installation	**0**	**0**	**24511**
	Mechanical ventilation	**0**	**0**	**2320**
	Mini split installation	**0**	**0**	**2368**
	Condensing boiler installation	**0**	**0**	**2249**
Renewable energy		**0**	**0**	**405**
	Photovoltaics (roof)	**0**	**0**	**405**
Total waste generated		**50664**	**42127**	**33736**

Table 5 clarifies the origin of waste generation across scenarios. Scenario 1 is dominated by envelope-related activities, particularly façade and roof insulation, which are associated with demolition-intensive processes and therefore generate high waste volumes. In Scenario 2, part of this contribution shifts toward windows and internal works, resulting in a more distributed waste profile.

In contrast, Scenario 3 shows a significant reduction in envelope-related waste and a shift toward building services and renewable energy systems. These activities are primarily installation-based and generate lower waste per unit compared to demolition-driven processes. Additionally, the integrated execution of multiple systems within the same intervention cycle reduces redundant removal and rework operations. This explains why Scenario 3 generates lower total waste despite involving a broader scope of interventions.

Activity-level and zone-level waste generation

Figure 5 indicates that waste generation across all scenarios is dominated by envelope-related and building services activities, with broadly consistent contribution patterns as renovation depth increases. Envelope insulation and window replacement remain major contributors, although their relative importance decreases as renovation strategies shift toward more system-based interventions. Internal insulation and HVAC-related activities contribute a stable share of total waste across scenarios, reflecting the influence of spatial repetition across residential floors rather than renovation depth. In contrast, renewable energy systems introduce a distinct pattern, increasing the share of installation- and packaging-related waste as renovation depth increases.

From a spatial perspective, activities repeated across floors generate substantial cumulative waste, while envelope and roof-related works produce more localised concentrations. Overall, these results confirm that waste generation is driven primarily by activity composition and spatial execution logic rather than by renovation scope alone, underscoring the value of activity-zone modelling for effective waste management planning.

Temporal waste profiles and schedule-induced intensity effects

Figure 6 and Table 6 illustrate the temporal waste intensity patterns across the three renovation scenarios, revealing substantial differences driven by activity sequencing and scheduling logic rather than total waste quantities. Although cumulative waste generation decreases from Scenario 1 to Scenario 3, the timing and concentration of waste generation vary markedly across scenarios. Scenario 1 exhibits the highest waste intensity, with an average daily waste generation of 160 dm³/day and a peak of 377.7 dm³/day, resulting in a peak-to-average ratio of 2.36. These pronounced peaks coincide with extensive activity overlap, generating elevated operational pressure on on-site waste handling, storage capacity, and collection logistics. Scenario 2 presents a more balanced temporal profile. Reduced parallelisation and more sequential execution of major activities lower the average daily waste generation to 113 dm³/day and the peak-to-average ratio to 1.38. This smoother distribution indicates improved alignment between execution sequencing and on-site waste management capacity.

Table 6: Daily waste generation intensity indicators across renovation scenarios.

Indicator	Sc. 1	Sc. 2	Sc. 3
Project duration (working days)	321	376	317
Total waste generated (dm³)	50,664	42,127	33,736
Average daily waste (dm³/day)	160	113	108
Peak daily waste (dm³/day)	377.7	156	136.2
Peak-to-average ratio	2.36	1.38	1.26

Despite the highest material inflows, Scenario 3 achieves the lowest waste intensity, with an average daily waste generation of 108 dm³/day and a peak-to-average ratio of 1.26. This demonstrates that extended execution durations and controlled activity overlap can substantially mitigate waste intensity, even in deeper renovation scenarios. Overall, these results confirm that waste intensity is primarily a scheduling-driven phenomenon rather than a function of cumulative waste volume. Peak waste formation, driven by execution overlap, represents a critical determinant of operational feasibility and directly influences the effectiveness of on-site logistics, labour coordination and waste segregation strategies.

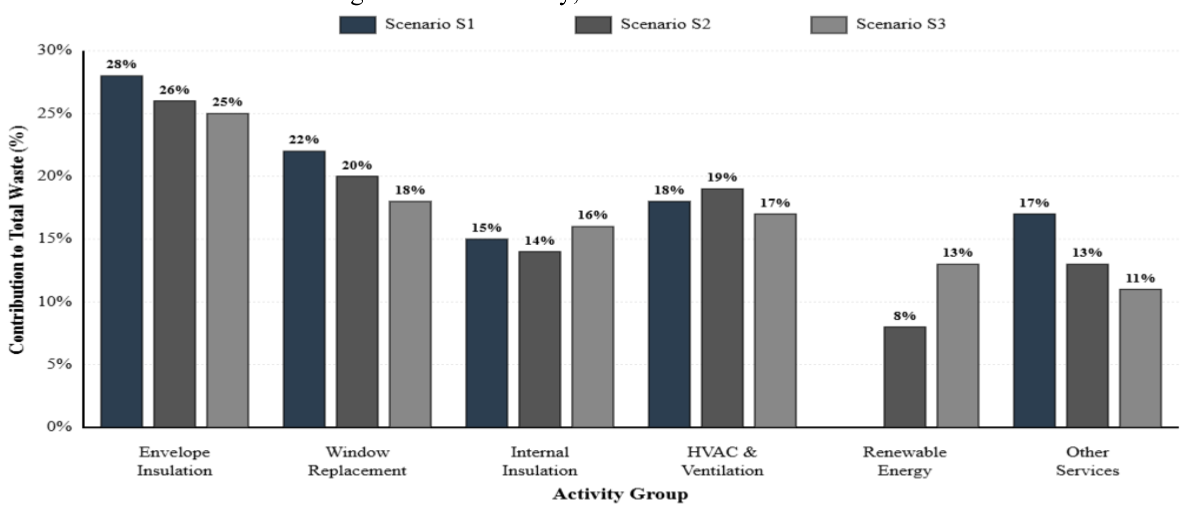

Figure 5: Waste contribution by activity group across the three renovation scenarios

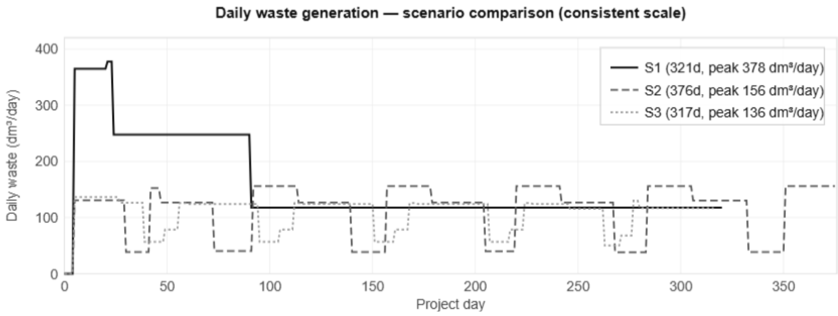

Figure 6: Daily waste generation profiles across the three renovation scenarios plotted on a consistent scale (0-400 dm³/day).

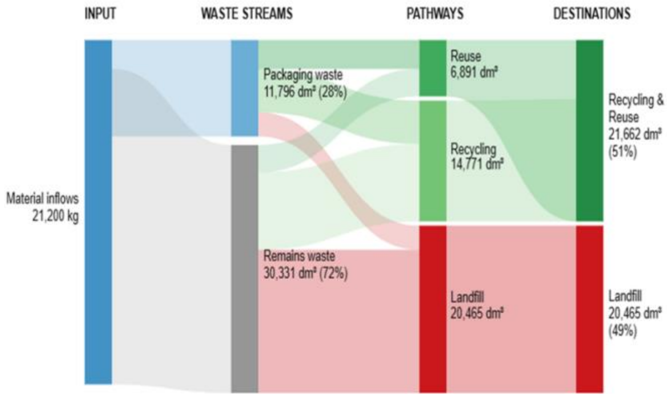

Figure 7: Material-flow pathways and recovery routes (Scenario 2)

Material-flow pathways and recovery routes

Figure 7 illustrates the material-flow pathways and reuse and recycling routes for Scenario 2 by linking material inflows, waste streams, and final destinations. From total material inflows of 21,200 kg, the renovation process generates 42,127 dm³ of waste, consisting of 11,796 dm³ of packaging waste (28%) and 30,331 dm³ of remains waste (72%). The Sankey diagram indicates that a substantial share of both waste streams is directed toward reuse and recycling pathways. In total, 29,910 dm³ (71%) of generated waste is directed toward recycling and reuse, while 12,217 dm³ (29%) is sent to landfill. Packaging waste exhibits high reuse and recycling potential due to its relatively homogeneous and uncontaminated nature, making it well suited to established reuse and recycling processes. In contrast, remains waste constitutes the primary contributor to landfill disposal, reflecting the presence of mixed, damaged, or contaminated materials generated during removal and demolition activities

It should be noted that recovery coefficients for remains waste are literature-derived estimates representing theoretical potential under optimized sorting conditions, and actual rates may be lower in practice due to material contamination and heterogeneity. Although remains waste dominates total volumes, its relatively lower recoverability drives landfill dependency, underscoring the need to distinguish waste streams at activity and scheduling levels. Scenario 2 illustrates how structured material flows aligned with reuse and recycling pathways can enhance overall recovery performance.

Circularity performance and scenario trade-offs

Circularity performance across the three renovation scenarios is evaluated using the Circularity Index and the Waste Recovery Potential, which together capture the balance between material recovery and overall waste generation. These indicators provide an integrated view linking material inflows, waste composition, and recovery outcomes. Circularity performance improves consistently with increasing renovation depth (Table 7).

Table 7: Scenario-level circularity indicators for the Lille renovation case.

Indicator	Sc. 1	Sc. 2	Sc. 3
Circularity Index (CI)	0.58	0.62	0.65
Waste Recovery Potential (WRP)	0.67	0.71	0.74
Total material throughput (kg)	28,400	31,800	35,200
Recoverable waste fraction (%)	67	71	74
Landfill fraction (%)	33	29	26

CI improves from 0.58 to 0.65 and WRP from 0.67 to 0.74 across scenarios, alongside a rise in total material throughput from 28,400 to 35,200 kg. Recoverable waste rises from 67% to 74% and landfill fraction decreases from 33% to 26%, confirming that deeper renovation strategies enhance circularity when recovery pathways are effectively integrated. However, as relative indicators can mask absolute flow increases, results should be interpreted alongside the absolute waste quantities in *Tables 4 and 5*.

Implications, limitations, and outlook

The results demonstrate that schedule-aware waste modelling provides actionable decision support beyond cumulative assessments by capturing activity-level, spatial, and temporal waste dynamics. This enables more informed planning of onsite logistics, waste segregation, and recovery strategies, particularly through identifying waste-intensity peaks and their scheduling drivers during renovation execution. Limitations include fixed waste coefficients, uniform daily waste distribution assumptions, and fixed recovery coefficients that reflect theoretical pathways rather than dynamic site conditions. In practice, packaging waste may occur in short bursts, and sorting efficiency may vary under peak generation. Another limitation concerns the use of relative circularity indicators. While CI and WRP improve consistently across scenarios, relative indicators can mask increases in absolute material flows. As total material throughput grows from 28,400 kg in Scenario 1 to 35,200 kg in Scenario 3, absolute landfill quantities may not decrease proportionally despite improved relative indicators. This rebound-effect risk suggests that the results should be interpreted alongside the absolute waste quantities reported in Tables 4 and 5, not solely through relative indicators. These findings should therefore be considered in light of the underlying modelling assumptions. Future work will focus on calibrating the framework using empirical site data and extending it to capture dynamic execution conditions through real-time sensing and digital twin integration, thereby strengthening its robustness and applicability for execution-aware circular renovation planning.

Conclusions

This paper introduced a schedule-aware, BIM-based approach linking activity-zone modelling with precedence-constrained scheduling to enable time-resolved assessment of material flows, waste generation and circularity performance in deep renovation. Application to a multi-residential case in Lille demonstrated that scenarios with comparable material throughput can exhibit markedly different waste intensity profiles and recovery outcomes, confirming that activity sequencing, spatial repetition and controlled parallelisation are decisive drivers of circularity performance. Deeper renovation strategies can enhance circularity despite increased material inputs when execution logic is appropriately managed. These findings position scheduling as a central lever for circular renovation performance, underscoring the need to integrate execution planning into material-flow and circularity assessment.

Acknowledgements

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