Towards Urban-Scale Renovation: Integrating Multi-Agent Urban Digital Twin Framework with the RINNO Suite

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Abstract

Deep building renovation requires integrated digital solutions spanning entire project lifecycles and scaling to urban deployment. This paper presents the RINNO Suite, a comprehensive Building Information Modelling (BIM)-enabled platform combining specialised tools for renovation planning and execution, demonstrated through a residential building case study in Lille, France. The Techno-Economic Assessment (TEA) tool automates Planning and Design phase assessment, whilst the Retrofitting Manager (RRM) platform manages Retrofitting phase execution. Building on this foundation, the paper introduces Multi-Agent Urban Digital Twin (MAUDIT), a framework that enables city-wide renovation prioritisation, building pathology assessment, and circular economy coordination, representing the evolutionary pathway for scaling building-level tools to massive urban renovation programmes.

Keywords: Deep Renovation, Multi-Agent System, Urban Digital Twin

1 Introduction

1.1 The urban renovation challenge

The European building stock accounts for approximately 40% of primary energy consumption and 30% of greenhouse gas emissions, presenting a significant challenge to achieving carbon neutrality by 2050 (Lynn et al., 2021). Current annual renovation rates hover around 1%, far below the 2 to 3% required to achieve the EU's decarbonisation goals. Lynn et al. (2021) identify a range of human, technological, organisational, and environmental barriers across the renovation value chain, including inadequate planning, communication failures, and coordination challenges. Building Information Modelling (BIM) and digital twins (DT) offer potential to address these barriers through integrated digital workflows and data-driven monitoring that support collaborative decision-making across project phases (Bolpagni et al., 2022; Sacks et al., 2025). Beyond individual building challenges, the transition to urban-scale deployment presents distinct coordination difficulties that remain inadequately addressed. Most European cities contain extensive pre-1970s building stock requiring deep renovation, yet current approaches proceed largely ad-hoc, building-by-building, without systematic prioritisation. Municipal authorities and large estate owners lack comprehensive assessment capabilities to prioritise interventions based on energy performance, structural condition, and strategic value. Individual building renovations proceed without visibility into neighbouring projects that could enable material reuse, equipment sharing, or sequential workforce deployment. These coordination failures constrain achieving renovation rates necessary to meet climate targets within available resources.

1.2 Research objectives and contributions

This paper addresses the critical gap between building-level renovation tools and urban-scale deployment strategies through integration of the RINNO Suite, a validated platform for individual building renovation, with MAUDIT (Multi-Agent Urban Digital Twin), a framework enabling city-wide coordination. The RINNO Suite, developed under the EU's Horizon 2020 programme, integrates several software tools, including the TEA (Techno-Economic Assessment) tool for

Planning and Design phase evaluation with the RRM (RINNO Retrofitting Manager) platform for Retrofitting phase execution. Demonstration through a residential building in Lille, France validates lifecycle integration whilst revealing urban-scale coordination limitations.

Building on this validated foundation, the paper's primary contribution introduces MAUDIT, a framework enabling city-wide renovation coordination that complements RINNO Suite building execution capabilities. MAUDIT employs a multi-agent architecture encompassing drone-based building condition assessment, scheduling modelling (4D) of building stock evolution, strategic prioritisation algorithms, and circular economy material flow coordination. The integration creates a multiscale system addressing both "which buildings to renovate in what sequence" (MAUDIT urban planning layer) and "how to optimise individual building renovation" (RINNO Suite execution layer), providing a comprehensive approach to the massive urban renovation programmes necessary for achieving EU 2050 targets. The paper thus demonstrates not merely two independent tools but their necessary integration within hierarchical architecture where urban strategic planning informs and coordinates building-level execution whilst feedback from completed projects enhances future prioritisation and assessment accuracy.

2 The RINNO Suite: building-level foundation

2.1 Platform capabilities and lifecycle integration

The RINNO Suite addresses building-level renovation management through integration of BIM and specialised tools spanning the complete project lifecycle. The platform's architecture employs web-service technologies enabling distributed collaboration across geographically dispersed teams whilst maintaining data consistency through a shared BIM (Building Information Modelling) repository. This integrated approach recognises that effective renovation delivery requires seamless information flow from initial assessment through renovation completion, avoiding the fragmentation that characterises current tool landscapes.

The TEA tool automates Planning and Design phase assessment through BIM-based multi-scenario simulation (Doukari et al., 2023). The tool enriches information models with semantic data and renovation activity definitions, then simulates alternative intervention strategies to generate comprehensive performance profiles. Scenarios range from targeted envelope improvements to comprehensive deep renovation incorporating heating system replacement, mechanical ventilation, and renewable energy installations. For each scenario, the tool employs Resource Constrained Project Scheduling Problem optimisation (Blazewicz et al., 1983) to generate optimal activity sequences whilst quantifying duration, cost, resource requirements, and multi-dimensional disruption impacts across six categories including noise, dust, vibration, utilities, physical space, and traffic. The multi-scenario comparison enables systematic evaluation of trade-offs between renovation ambition and practical constraints of time, finance, and occupant disruption, transforming abstract renovation options into quantified alternatives that stakeholders can evaluate against their specific priorities.

The RRM platform coordinates Retrofitting phase execution through distributed web-based workflow management implementing Lean construction principles (Doukari et al., 2024). The platform architecture comprises six integrated components providing role-based user interfaces connected to remote services performing specialised processing via REST API. Role-based authentication across eleven user profiles ensures appropriate information access for diverse stakeholders from construction directors through site workers to building owners. The Planning Component implements a three-level scheduling approach operationalising principles established by Ballard's (2000) Last Planner System, progressively refining plans from strategic project baselines through tactical look-ahead schedules to operational weekly commitment plans that release constraint-free work to production crews (Heigermoser et al., 2019). The Monitoring Component tracks actual progress through BIM-based visualisation overlaying completion status onto 3D building models, enabling spatial coordination between on-site teams and proactive management intervention when performance trends suggest potential problems.

2.2 Phase integration and urban-scale limitations

The critical integration between TEA and RRM operates through structured data exchange where selected renovation scenarios transfer from Planning and Design assessment into Retrofitting execution planning. The information model functions as persistent shared information backbone ensuring geometric and semantic consistency across the phase boundary, whilst JSON templates map TEA outputs to RRM inputs through explicitly defined schemas, ensuring compatibility across diverse tools (Pauwels and Terkaj, 2016). The feedback mechanisms connecting actual construction performance to assessment methodologies enable continuous improvement, progressively enhancing predictive capabilities as renovation programme experience accumulates (Doukari et al., 2023, 2024). This lifecycle integration represents a significant advance over fragmented approaches where design teams and construction teams operate with disconnected information systems.

However, the RINNO Suite's validation through demonstration projects, whilst establishing comprehensive building-level renovation management capability, simultaneously reveals what such platforms cannot address. A municipal authority managing thousands of buildings requiring renovation cannot employ the suite to determine which hundred buildings merit priority, nor can regional construction consortia use it to optimise equipment sharing across multiple concurrent sites. The platform optimises "how to renovate" individual buildings but provides no guidance on "which buildings to renovate when": precisely the strategic questions that urban-scale renovation programmes must address. This limitation reflects not platform inadequacy but rather the fundamentally different character of urban planning versus building execution, requiring different data types, analytical methods, and decision support frameworks. The platform's demonstrated capabilities and validated integration mechanisms position it as the essential building execution layer for urban programmes, yet this execution layer requires a complementary urban planning layer addressing prioritisation, sequencing, and circular economy coordination at city scale. The French demonstration case study, presented in the following section, provides empirical evidence of both the platform's building-level achievements and the necessity for urban-scale strategic frameworks.

3 French case study: validation and gap identification

3.1 Building context and BIM development

Figure 1. French case study: before (left) and after (right) renovation.

The French demonstration site comprises a four-storey residential building containing twenty-nine small apartments in Lille, managed by Lille Métropole Habitat (Figure 1). Constructed during the pre-1970s period, the building exhibits typical thermal performance deficiencies of its era with poor envelope insulation and natural gas boiler heating. The occupied building context imposed significant constraints on intervention strategies, requiring careful disruption management to maintain resident habitability throughout the renovation process. This real-world complexity provided a rigorous validation environment for assessing the RINNO Suite's capabilities under realistic conditions.

The demonstration project required comprehensive as-built information model creation to enable RINNO Suite application, employing contemporary 3D scanning technologies combining Leica BLK360 laser scanner for interior spaces with DJI Phantom 4 RTK drone for exterior facades. The scanning methodology achieved eighteen minutes per apartment average duration, proving acceptable to occupied residents whilst generating point cloud data sufficient for detailed information model development through Autodesk ReCap and Revit. The enrichment process assigned alphanumerical information based on construction period knowledge and visual inspection, creating the information-rich model necessary for TEA tool scenario simulation. This validation of 3D scanning as a viable approach for existing building documentation addresses a frequent objection that BIM adoption for renovation remains impractical due to modelling effort requirements.

3.2 Platform application: assessment and results

The TEA tool's application evaluated six renovation scenarios, with comparison between Scenario S1 (renovation from outside) and Scenario S3 (comprehensive deep renovation) revealing substantial performance trade-offs characteristic of renovation decision-making (Figure 2). S1 required 336 days duration employing 770 man-days at 229,000 euros total cost, addressing envelope thermal performance through external insulation and glazing replacement whilst minimising interior disruption. In contrast, S3 pursued transformational improvement through 12 renovation activities including heat pump installation, mechanical ventilation systems, and photovoltaic generation, requiring 814 days, 2,200 man-days, and 905,000 euros investment (approximately 619 euros per m^2). The simulation revealed strong positive correlations between duration and worker requirements, whilst disruption analysis showed S3 generating sustained impacts across all measured dimensions throughout the extended construction period, raising serious questions about maintaining building occupation during comprehensive interventions.

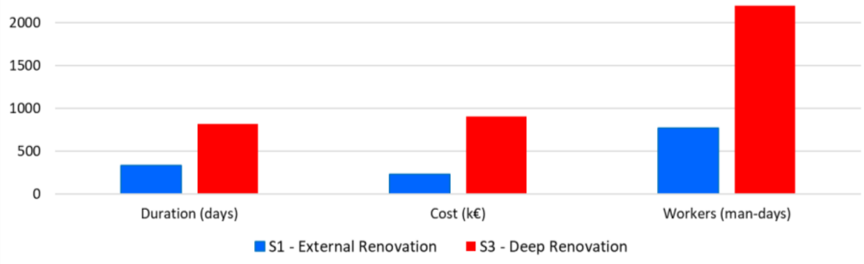


Figure 2. French case study renovation scenarios comparison).

The energy performance analysis following ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b) indicated substantial operational improvements from deep renovation, with the transition to electric heat pump heating powered partially by on-site photovoltaic generation substantially reducing primary energy demand and greenhouse gas emissions. However, the life-cycle cost analysis revealed challenging economics with capital investment requiring decades of operational savings to achieve financial break-even, highlighting that technical solutions alone prove insufficient without supportive policy and financing mechanisms.

The RRM platform deployment for Retrofitting phase coordination validated distributed workflow management capabilities across six integrated components. Technical testing confirmed error-free operation from authentication through multi-level schedule generation to BIM-based progress monitoring, with successful integration to remote Cockpit service generating comprehensive KPI visualisations overlaid on the French building information model. User evaluation engaging 29 construction industry representatives revealed positive reception regarding role-based access, three-level planning structure, and spatial progress visualisation, confirming that the platform addresses genuine industry coordination challenges. However, feedback also identified adoption barriers including learning curve requirements, information model prerequisites, and small enterprise resource constraints, indicating that technology deployment must be accompanied by training programmes and implementation support.

3.3 Critical insight: the strategic planning gap

The demonstration validated comprehensive building-level renovation management whilst revealing a fundamental limitation that motivates the MAUDIT framework introduction. The RINNO Suite optimised assessment and execution for Project Sarrazins, integrating Planning and Design scenarios generated through the TEA tool (Doukari et al., 2024) with Retrofitting phase coordination. The platform successfully managed complex workflows involving multiple stakeholders, maintained data consistency across phase transitions, and enabled informed decision-making through comprehensive scenario comparison. However, the platform provided no capability for addressing whether this particular building should be renovated now versus later within Lille Métropole Habitat's extensive portfolio of hundreds of similar buildings, nor how its renovation should coordinate with other buildings to enable material reuse or contractor resource sharing.

This gap between building execution optimisation and urban strategic planning extends beyond mere scope limitation to represent a fundamental difference in problem character. Building-level tools address operational questions about specific structures using detailed technical data and short-term timeframes. Urban-scale planning addresses strategic questions about entire portfolios using coarse-grained information and multi-year horizons. The housing association managing thousands of units needs to determine which buildings offer greatest carbon reduction potential per euro invested, which require urgent intervention due to deteriorating conditions, and how renovation sequencing can enable material reuse from buildings identified for demolition. These strategic questions precede individual building project initiation yet prove essential for systematic programme development capable of achieving required renovation rates. The MAUDIT framework, introduced in the following section, addresses precisely these urban-scale planning requirements whilst maintaining integration with the RINNO Suite's validated building execution capabilities.

4 MAUDIT: multi-agent framework for urban-scale renovation

4.1 From building optimisation to urban coordination

The French demonstration exemplifies both the achievement and limitation of building-level renovation tools. Whilst the RINNO Suite optimised assessment and execution for a single building, Lille Métropole Habitat manages thousands of residential units across hundreds of buildings, facing complex challenges in determining renovation priorities, intervention sequencing, and resource allocation to maximise environmental impact within constrained budgets. Current prioritisation approaches rely primarily on minimum Energy Performance Certificate (EPC) requirements, grant programme eligibility, and voluntary owner initiatives, lacking systematic assessment and strategic coordination. Buildings renovate when owners secure financing rather than when their renovation would contribute most effectively to urban decarbonisation or enable circular economy benefits through material reuse. This atomised approach generates systemic inefficiencies: contractors mobilising without visibility into adjacent projects, demolished building materials ending in landfill whilst new materials are manufactured for nearby renovations, and renovation activity concentrating in affluent areas whilst neglected neighbourhoods receive limited attention. These coordination failures fundamentally constrain achieving EU 2050 targets, necessitating frameworks operating at urban scale.

4.2 Multi-agent architecture and innovations

The MAUDIT framework addresses urban-scale challenges through multi-agent architecture distributing assessment, analysis, and communication functions across specialised components with clearly defined interfaces and data exchange protocols (Figure 3). The framework builds upon 3D virtual city models, such as Virtual NewcastleGateshead (VNG) spanning 100 square kilometres developed through stereo aerial photogrammetry and terrestrial laser scanning (Northumbria University, 2023). MAUDIT extends such geometric models through systematic integration of property records, EPC databases, demographic data, and utility consumption patterns, transforming spatial representations into information-rich DT supporting strategic renovation planning. The Data Acquisition Agent establishes the DT synchronization loop through drone-based infrared imaging at urban scale. Object recognition algorithms automatically identify building pathologies including heat losses, faulty insulation, facade deterioration, and structural defects. The agent enables convergence between physical and digital building states at synchronization rates appropriate to programme needs, quarterly for strategic planning or more frequently for active monitoring (ISO/IEC, 2023). This automated approach substantially reduces costs and timeframes relative to traditional surveys whilst confronting limitations including weather dependency and automated recognition requiring validation. The Social Agent manages data storage, transmission, and access control within cloud-based infrastructure whilst implementing adaptive learning capabilities. Connectivity with diverse urban information systems through open Application Programming Interface (API) technologies ensures building condition data integrates with EPC, ownership records, and infrastructure networks. Learning capabilities enable continuous improvement as renovation programmes generate performance data. The Cognitive Agent performs analytical reasoning transforming building condition data into strategic renovation priorities, evaluating pathologies across structural, environmental, and functional dimensions. The

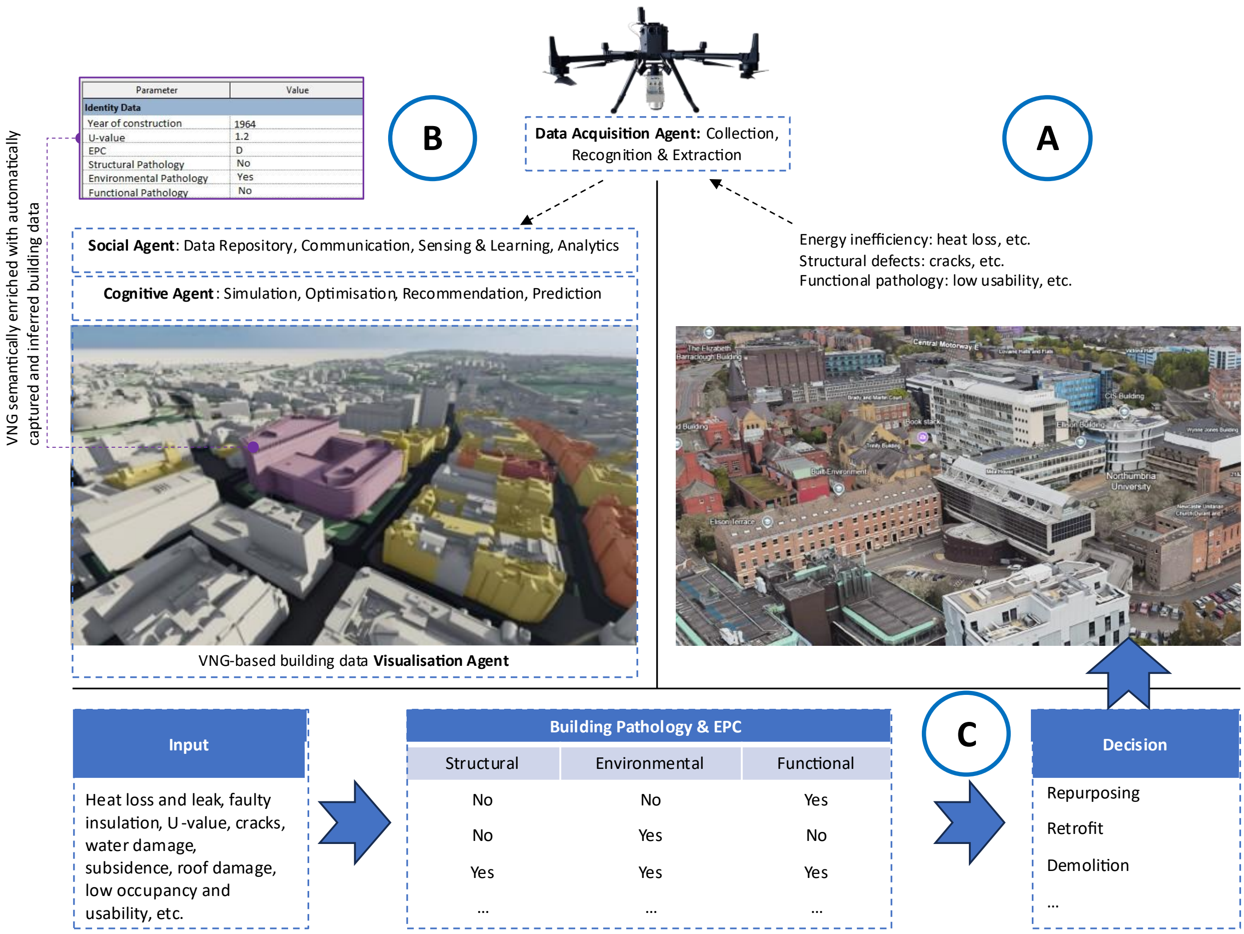


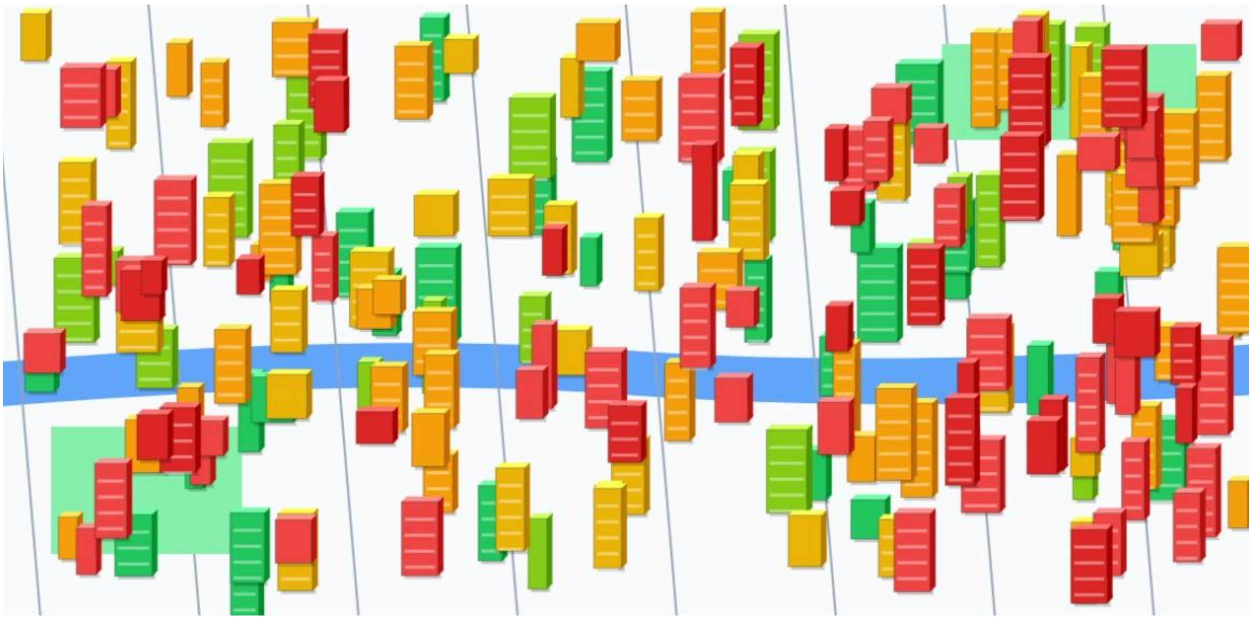
Figure 3. MAUDIT – multi-agent urban digital twin framework for building pathology assessment and massive retrofit planning and delivery. (A) Physical. (B) Digital. (C) Automated Decision-making process.

agent's innovation comprises 4D city simulations incorporating temporal information alongside spatial geometry, introducing pathology-specific age variants reflecting how different characteristics deteriorate at different rates. These multiple temporal dimensions enable scenario exploration projecting how alternative strategies affect building stock evolution, supporting evidence-based municipal strategy development. The Visualisation Agent presents complex urban building stock information through intuitive 3D representations accessible to diverse stakeholders. Building upon platforms such as VNG, the agent overlays real-time pathology data onto virtual city models through colour-coded visualisations (Figure 4). The interactive interface supports exploration from city-wide overviews through neighbourhood detail to individual building inspection, facilitating strategic programme development and stakeholder engagement.

4.3 Strategic prioritisation and circular economy coordination

The framework's prioritisation capabilities depend on comprehensive energy performance characterisation. EPC provide standardised assessment generating ratings from A (excellent) through G (very poor), yet significant coverage gaps persist. MAUDIT addresses this through predictive modelling estimating ratings for uncertificated buildings based on construction year, building type, and location, with machine learning trained on certificated buildings. Urban-scale performance mapping reveals spatial patterns with strategic planning implications, such as poor-performing building concentrations indicating opportunities for area-based programmes achieving economies of scale.

Beyond energy prioritisation, the framework's transformative potential emerges through material flow coordination enabling circular economy approaches. MAUDIT addresses coordination failures through systematic matching of material supply from buildings recommended for demolition against renovation project demand. When the Cognitive Agent identifies buildings requiring demolition, these enter a material source database cataloguing available resources. The framework cross-references renovation requirements generated by RINNO Suite's RRM platform against available supplies, identifying matches enabling reuse rather than new procurement, generating embodied carbon reductions and waste diversion from landfill. Furthermore, material flow coordination introduces strategic programme sequencing considerations beyond individual building optimisation. A building yielding modest energy improvements might merit early demolition if its material recovery could supply multiple renovations, generating greater aggregate benefits. This portfolio-level optimisation represents a fundamentally different paradigm than evaluating each building independently.



Energy Performance Certificate (EPC) Rating Legend

A-C: Good Performance	**D-E: Moderate Performance**	**F-G: Poor Performance**
• Modern construction (post-2000)	• 1980s-1990 construction	• Pre-1970s construction
• Recent renovation	• Some insulation present	• Minimal/no insulation
• Low energy construction	• Medium energy consumption	• High energy consumption
• Priority: Maintain performance	• Priority: Cost-effective upgrades	• Priority: Deep renovation/deconstruction
~25% of stock	**~37% of stock**	**~38% of stock**

Figure 4. VNG visualisation concept showing 3D city model with colour-coded building energy performance overlay (red = poor EPC F-G, yellow = moderate EPC D-E, green = good EPC A-C) across Newcastle-Gateshead urban area

4.4 Multiscale integration: from urban strategy to building execution

The integrated architecture positions MAUDIT as urban planning layer and RINNO Suite as building execution layer within a comprehensive multiscale system (Figure 5). This hierarchical structure maintains clear separation between municipal planning responsibilities and project execution activities whilst ensuring seamless information flow through standardised data exchange protocols. The workflow commences at urban planning where MAUDIT performs building stock assessment through drone-based scanning and automated pathology identification. The Cognitive Agent analyses these assessments alongside EPC data to generate building-specific recommendations regarding renovation suitability and urgency. Prioritisation algorithms balance multiple objectives including carbon reductions, cost efficiency, social equity, and material flow optimisation, producing ranked building lists validated through stakeholder engagement facilitated by the Visualisation Agent. Once buildings receive priority status, the workflow transitions to building execution where RINNO Suite performs detailed assessment and coordination. The TEA tool receives building information from MAUDIT including geometric data, pathology assessments, and material availability, initialising assessment whilst providing context regarding reuse opportunities. Following scenario simulation and selection, the RRM platform coordinates Retrofitting phase execution with its Planning Component receiving schedules from TEA whilst accessing material delivery schedules from MAUDIT's circular economy coordination. The Monitoring Component's performance data feeds back to both TEA databases and MAUDIT prioritisation algorithms, enabling continuous improvement. This bidirectional information flow proves essential for adaptive programme management. When renovations achieve energy savings differing from predictions, this updates performance models informing future prioritisation.

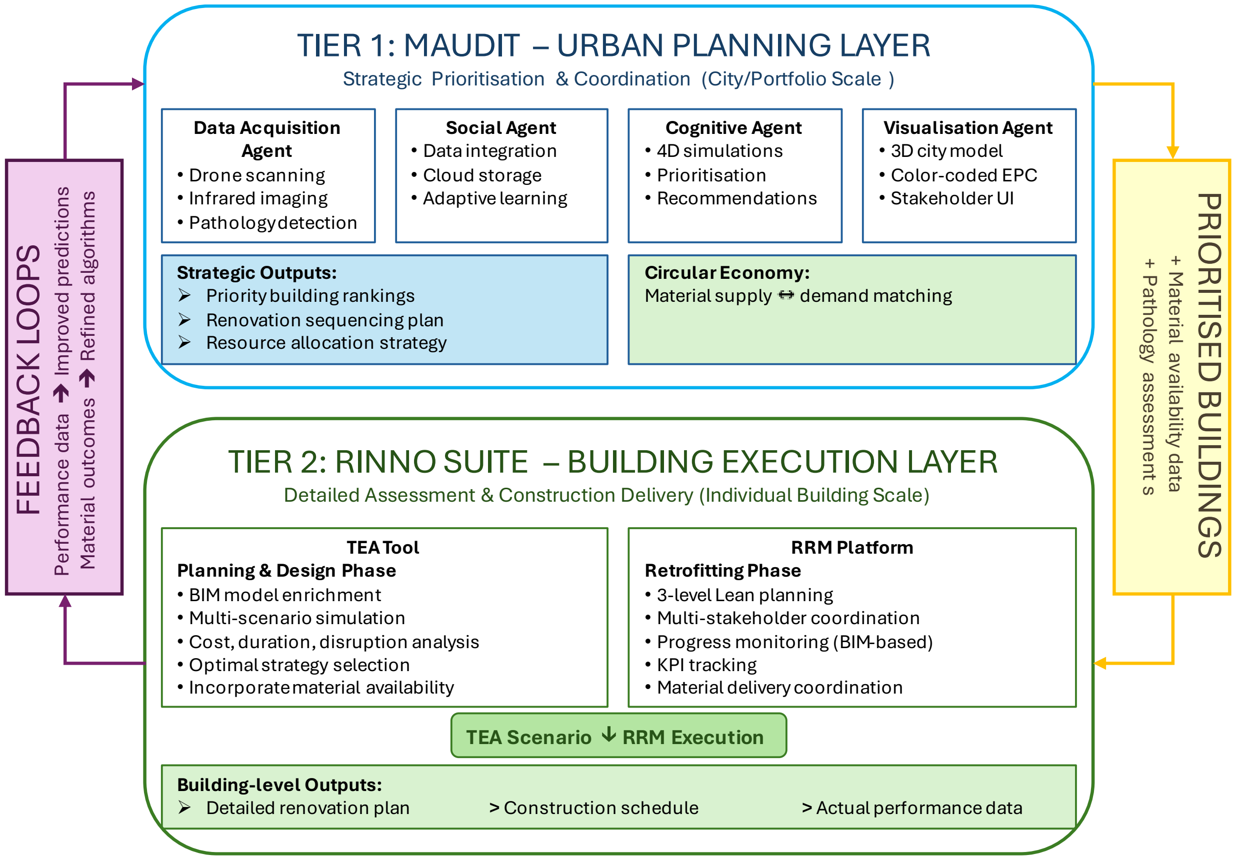


Figure 5. Multiscale integration architecture showing MAUDIT urban planning layer and RINNO Suite building execution layer with bidirectional feedback loops and circular economy coordination

The learning mechanisms transform renovation programmes from static implementation into dynamic systems progressively enhancing effectiveness through accumulated experience, whilst multiscale architecture ensures strategic improvements inform tactical decisions and vice versa.

5 Discussion: integration and implementation

5.1 Framework contributions and critical success factors

The integrated framework demonstrates that systematic urban-scale renovation requires capabilities spanning two complementary scales, with neither sufficient independently. The French demonstration validated that RINNO Suite provides comprehensive building-level lifecycle integration from Planning and Design through Retrofitting phases, addressing known renovation challenges through BIM-based automated assessment enabling systematic multi-scenario exploration and coordinated workflow management implementing Lean construction principles.

MAUDIT addresses the strategic layer that building-level tools cannot encompass, enabling rapid building stock assessment through drone-based infrared imaging, strategic prioritisation through 4D modelling projecting building stock evolution under alternative scenarios, and circular economy coordination through material flow matching. The multi-agent architecture's distribution of functions enables flexible deployment whilst integration with RINNO Suite maintains appropriate separation between municipal planning and project execution.

Critical success factors span technical, organisational, and data dimensions. Comprehensive building information models constitute essential prerequisites, yet substantial documentation effort represents a capacity constraint requiring selective deployment strategies. At urban scale, 3D virtual city models provide geometric foundation whilst EPC databases enable performance characterisation. Organisational agreements regarding data sharing across institutional boundaries prove essential for coordinated operation, as do progressive circular economy barrier reductions regarding quality assurance and logistics coordination.

5.2 Implications for EU 2050 targets and research directions

The European Commission's Renovation Wave strategy recognises that achieving climate targets requires massive renovation acceleration, proposing to at least double annual rates. However, even perfectly optimised individual renovations occurring at current ad-hoc rates prove insufficient. The fundamental challenge concerns dramatically increasing how many renovations occur annually through systematic urban-scale deployment, which the integrated framework enables through strategic prioritisation supporting evidence-based programme development pursuing maximum environmental impact within constrained resources.

Yet achieving required acceleration depends critically on addressing fundamental economic challenges exemplified by the French case study, where deep renovation capital requirements generate extended payback periods challenging viability without policy interventions including grants, subsidised financing, or regulatory mandates. The pathway toward 2050 targets involves progressive evolution as frameworks demonstrate value, industries adapt practices, policies develop supportive environments, and financing mechanisms mature. Future research requires MAUDIT pilot implementations at meaningful scale to validate assessment accuracy, prioritisation effectiveness, and circular economy facilitation. Additional priorities include investigating governance structures for multi-entity coordination, evaluating alternative policy instruments, and ensuring distributional equity alongside environmental goals.

6 Conclusions

This paper addressed scaling building renovation from isolated projects to systematic urban programmes capable of meeting EU carbon neutrality targets through integration of two complementary frameworks operating at different scales yet designed for coordinated deployment. The RINNO Suite, validated through the French demonstration in Lille, provides comprehensive building-level capabilities spanning Planning and Design phase assessment (TEA tool) through Retrofitting phase execution (RRM platform), demonstrating seamless workflow integration using BIM as shared repository and generating substantial improvements in renovation project planning, stakeholder coordination, and construction delivery.

However, building-level optimisation cannot address strategic questions of which buildings merit priority within extensive portfolios, optimal intervention sequencing, and material flow coordination enabling circular economy approaches. The MAUDIT framework provides this urban planning layer through multi-agent architecture encompassing automated building condition assessment via drone-based infrared imaging, strategic prioritisation incorporating 4D modelling of building stock evolution, and material flow coordination enabling systematic reuse through matching demolition material supply with renovation demand. The integrated multiscale system enables MAUDIT to identify renovation priorities and coordinate material flows whilst RINNO Suite optimises individual building execution, with bidirectional feedback loops enabling continuous improvement as programmes generate empirical performance data.

The research contributes technically through demonstration of seamless Planning and Design to Retrofitting phase integration, methodologically through articulation of how building-level tools scale to urban deployment via appropriate planning layer integration, and practically through frameworks supporting both construction industry stakeholders and municipal programme developers. The circular economy coordination capability addresses fundamental unsustainability of linear construction models through systematic material flow matching at urban scale, though realising this potential requires progressive barrier reduction regarding quality assurance, logistics coordination, and industry practice transformation.

The fundamental challenge confronting European societies concerns not whether existing building stock requires deep renovation but rather whether frameworks can be deployed sufficiently rapidly within timeframes that climate science demands. The integrated frameworks demonstrate that technical foundations for systematic urban-scale renovation exist, validated through real-world demonstration and grounded in established technologies. The remaining barriers are predominantly organisational, financial, and political rather than technical, suggesting that achieving 2050 targets depends critically on sustained commitment to renovation acceleration. The frameworks provide the tools; societal will must supply the determination to deploy them at the scale and pace required to address the climate emergency.

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