Review

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Green Housing Retrofits as Complex Micro-Projects: Delivery Pathways and Whole-Life CO_2

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Abstract

Residential retrofitting is a cornerstone of national strategies for achieving net-zero emissions by 2050. Yet despite decades of policy incentives, adoption remains limited, delivery performance is uneven and realised carbon reductions often fall short of predictions. This paper conceptualises housing retrofit projects as complex micro-projects—small in scale but marked by technical, organisational, and social interdependencies that challenge conventional project delivery. Drawing on an integrative review of 56 studies, we synthesise evidence across the Owner, Supplier, and Delivery domains to identify the managerial, coordination, and communication barriers that shape whole-life CO_2 outcomes. By framing these challenges through concepts of static and dynamic complexity, the study demonstrates that performance shortfalls stem less from technological gaps than from fragmented project organisation and weak cross-domain coordination. The review contributes an evidence-based understanding of how complexity affects retrofit delivery, outlines implications for policy and practice, and proposes a research agenda for improving assurance, learning, and verification in housing retrofit management.

Keywords: housing retrofit; complex micro-projects; project delivery; whole-life carbon; construction management; sustainability transitions

1. Introduction

Global efforts to limit climate change under the Paris Agreement have intensified the urgency to decarbonise the built environment. The construction industry contributes over one-third of global CO_2 emissions [1], and existing buildings—particularly the residential stock—represent a major share of operational and embodied carbon. In countries such as the United Kingdom, around 28.5 million houses account for approximately 30 % of national energy use, with heating and hot water responsible for most of this consumption [2]. Because the majority of homes that will exist in 2050 already stand today, achieving net-zero housing depends primarily on upgrading existing dwellings rather than constructing new ones.

National policies have responded with various incentive programmes promoting improvements to building fabric, heating systems, and renewable technologies [3]. Nevertheless, progress remains slow. Despite decades of interventions—including grants, tax relief, and regulatory reforms—retrofit activity levels are far below what is required for 2050 targets. Previous research attributes this to barriers such as financial risk, disruption, information gaps, and lack of supply-side capacity [4,5]. Yet these explanations tend to treat retrofits as technical or economic problems rather than as a management challenge of organising complex micro-projects.

We argue that housing retrofit projects, though typically modest in size, are complex micro-projects. They exhibit the same characteristics of complexity found in major projects—uncertainty, interdependence, and emergent behaviour—but within the constraints of domestic settings, fragmented supply chains, and lay decision-makers. Treating retrofits as complex micro-projects reframes the challenge: rather than merely improving technology or subsidies, progress depends on

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how owners, suppliers, and delivery teams coordinate to manage uncertainty and integrate socio-technical systems effectively.

This paper pursues two main aims.

First, it provides an integrative review of housing retrofit research organised around the three domains of project organising [6,7]: the Owner Domain (homeowners, social landlords, private landlords), the Supplier Domain (manufacturers, merchants, installers), and the Delivery Domain (project execution and on-site integration).

Second, it examines how project complexity—both static and dynamic—affects the management and delivery of retrofit projects and, in turn, their contribution to whole-life CO_2 outcomes. By bridging project-management theory with housing retrofit practice, the review identifies how coordination, communication, and trust across domains influence project performance.

The remainder of the paper is structured as follows. Section 2 introduces the conceptual background and outlines the research gap. Section 3 explains the integrative review methodology. Section 4 synthesises the literature across the three domains and summarises common challenges. Section 5 discusses the interaction between project complexity and carbon outcomes. Section 6 presents the implications and future research agenda, followed by conclusions.

2. Conceptual Background: Housing Retrofits as Complex Micro-Projects

2.1. The Concept of Complexity

Complexity has become a defining feature of modern projects and organisations. Researchers across disciplines conceptualise it as the property of systems composed of numerous interrelated components whose behaviour cannot be fully predicted [8-10]. Complex systems were similarly viewed as hierarchies of interacting subsystems whose collective behaviour exhibits emergent properties not reducible to individual parts [11]. The Cynefin Framework [12] distinguishes complex situations—characterised by “unknown unknowns” and emergent patterns—from complicated ones, where cause-and-effect relationships are knowable through analysis. The terms are often conflated: complicatedness involves intricacy yet predictability, whereas complexity involves uncertainty and adaptation [7].

In project management, complexity has been defined as “consisting of many different interrelated components that can be viewed from a differentiated and interdependent perspective” [7] (p. 202). Building on this foundation, researchers identify recurring features of complex projects:

1. Unpredictability – outputs cannot be linearly derived from inputs.
2. Non-linearity – small changes can produce disproportionate effects.
3. Emergence – challenges and requirements shift over time [13].

Complicatedness, by contrast, concerns projects with many elements but stable relationships among them [7,12]. It was described as intricacy rather than indeterminacy [14]. Such projects are difficult yet ultimately analysable through detailed planning, modelling, and expert knowledge. In the housing context, constructing a new dwelling is complicated—it demands coordination of many trades but follows well-established methods. A community-wide retrofit programme, however, is complex—it involves evolving technologies, occupant behaviours, and policy conditions that interact unpredictably.

2.2. Static and Dynamic Complexity

Static and dynamic complexity were distinguished from each other [10,15]. Static (or structural) complexity refers to the number of elements and interfaces within a project—its visible architecture [10]—which we here align with the concept of “complicated” [12]. Dynamic complexity concerns the unpredictable interactions and feedback loops among those elements over time [16,17], thereby linking dynamic complexity to emergent change and learning within systems, which we here align with the concept of “complexity” [12]. Table 1 (below) summarises their distinctions.

Table 1. Features of complicatedness (static complexity) and complexity (dynamic complexity).

Complicatedness (Static Complexity)	Complexity (Dynamic Complexity)
Tangible, countable, predictable elements of a project	Unpredictable, nonlinear, interdependent relationships
Challenges known; outcomes generally predictable with expertise	Uncertain interactions lead to unforeseen outcomes
Managed by detailed planning and control	Managed by adaptability, learning, and communication
Example: constructing a standard house	Example: retrofitting occupied dwellings with variable needs

Understanding this distinction is vital for housing retrofit. Complicatedness arises from numerous components—walls, roofs, heating systems, insulation layers—each requiring technical coordination. Complexity emerges from how these elements interact with human, social, and regulatory systems: owners' decisions, tenant behaviours, funding schemes, and supply-chain dependencies.

2.3. Complexity in Housing Retrofit Projects

Retrofit projects appear deceptively small yet embody substantial complexity. Even modest dwellings can involve unpredictable structural conditions, bespoke designs, and evolving regulations. Heterogeneity of the existing stock, emerging energy technologies, and multi-actor arrangements were identified as key sources of complexity [18]. Recognising complexity aids managers by clarifying coordination needs, guiding organisational form, and shaping success criteria [19].

Technological complexity stems from the integration of new systems into old structures. Retrofitting may require specialised construction methods to preserve integrity, avoid thermal bridging, and meet airtightness or ventilation standards. Older homes conceal unknowns—degraded materials, outdated wiring, hidden dampness—that are only discovered during project execution [20]. Introducing modern heating and control systems into such contexts often triggers unforeseen compatibility problems [21].

Organisational complexity arises from fragmented governance and multiple small stakeholders. Retrofit projects involve diverse actors—homeowners, tenants, installers, architects, merchants, and regulators—whose objectives may conflict [22,23]. Managing these interdependencies requires continual negotiation, learning, and trust-building.

Social complexity reflects occupants' daily lives and emotional attachments to their homes. Unlike new construction, retrofits often occur in inhabited spaces where disruption and aesthetics strongly influence acceptance [24,25]. Owners' risk perceptions, trust in suppliers, and cultural meanings of "home" all shape project outcomes.

Technological, organisational, and social complexities interact to produce dynamic uncertainty: small changes in design or occupant preference can cascade into cost overruns, performance gaps, or dissatisfaction. These micro-level challenges mirror those of large-scale infrastructure projects but unfold within the personal domain of households. As a result, project success in retrofit depends less on rigid planning and more on adaptive management—iterative coordination, flexible learning, and transparent communication among participants.

2.4. Complexity, Delivery, and CO_2 Outcomes

Complexity also affects environmental performance. Variability in workmanship, sequencing, and user behaviour contributes to the well-documented energy performance gap—the discrepancy between modelled and realised savings [26]. Dynamic complexity means that even well-specified technologies can underperform when installed under real-world constraints or used differently than anticipated. Addressing this requires not only better technical standards but also improved project delivery processes that integrate feedback, monitoring, and verification.

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Recognising housing retrofit as a complex micro-project, therefore reframes its contribution to sustainability transitions. It underscores that achieving reliable CO_2 reductions is not simply a matter of scaling technologies, but of managing socio-technical complexity effectively. The following sections operationalise this insight by reviewing how the Owner, Supplier, and Delivery domains interact to influence project outcomes.

2.5. Research Gap and Contribution

While several reviews have addressed housing retrofit from policy or technical perspectives, most concentrate on incentive schemes, governance, or engineering solutions rather than on the management and delivery of retrofit projects.

- An interdisciplinary lens was adopted to link engineering and social theory to assess sustainable thermal retrofit policy [27]. They highlight neglected issues such as health, affordability, and heritage.
- A systematic review of “green retrofitting” was conducted to identify critical success factors (CSFs) and barriers, including unreliable technologies and material shortages [28].
- Chinese policies promoting building green retrofit were examined, and they identified barriers related to finance, awareness, and technical capacity [29].

Policy frameworks and technologies vary widely by country and context, limiting the generalisability of these studies and leaving the practical problem of project organisation largely unexplored. Yet housing retrofits are, at their core, projects whose outcomes depend on how owners, suppliers, and delivery actors coordinate resources and manage complexity. This paper, therefore, contributes an integrative review that consolidates fragmented knowledge on retrofit management across these domains, identifies recurring barriers, and highlights gaps where project-management research can strengthen future retrofit practice.

3. Methods: Integrative Review with PRISMA-Style Transparency

3.1. Rationale for the Integrative Review

We conducted an integrative literature review methodology because research on housing retrofit management is fragmented across disciplines, sectors, and geographical contexts. Unlike a systematic review, which requires a large volume of empirical studies for meta-analysis, an integrative review allows for the inclusion of diverse forms of evidence—including conceptual, qualitative, quantitative, and grey literature—while maintaining transparency and rigour [30,31]. This approach is particularly suitable for synthesising an emerging field that bridges technology, policy, and project management [32].

Integrative reviews go beyond descriptive stock-taking: they aim to generate conceptual insights by critiquing and recombining existing knowledge [33]. In this study, we used the integrative approach to identify how different strands of research conceptualise and address the challenges of managing housing retrofit projects, focusing on the interrelationships between owners, suppliers, and delivery processes.

3.2. Review Protocol

Following established guidance for integrative reviews in management research [30,34,35], we structured our review around three phases: scoping, searching/screening, and synthesis. This approach is widely adopted in management and organisation studies and ensures transparency while accommodating diverse forms of evidence.

We operationalised this structure into a transparent, reproducible protocol aligned with PRISMA-style reporting principles. The review question guiding our search was:

How have housing retrofit projects been studied and managed across owner, supplier, and delivery domains, and what factors influence their success in achieving sustainability and CO_2 reduction?

3.3. Search Strategy

To ensure comprehensive coverage, we searched four major academic databases—Google Scholar, Web of Science, ScienceDirect, and Scopus—along with selected government and professional reports. We used Boolean combinations of keywords related to housing retrofit and project management (Table 2).

Table 2. Search parameters.

Database	Fields searched	Core Keywords and Boolean Strings	Time Horizon	Language
Google Scholar, Web of Science, ScienceDirect, Scopus	Title and Abstract	"housing retrofit" OR "energy renovation" OR "building refurbishment" OR "residential retrofit") AND ("project management" OR "construction management" OR "delivery" OR "supply chain" OR "stakeholder")	2005–2022	English

The starting year (2005) corresponds to the entry into force of the Kyoto Protocol, marking the beginning of coordinated global greenhouse gas reduction commitments. Although the Paris Agreement (2015) represents a later milestone, including the earlier period captures important foundational research in retrofit practice and policy.

A snowballing process (Ghafoor et al., 2023) was also applied, using citation tracking and reference lists from key papers to identify additional studies. After duplicates and non-relevant records were removed, 56 articles met the inclusion criteria. The flow of selection is summarised in Figure 1.

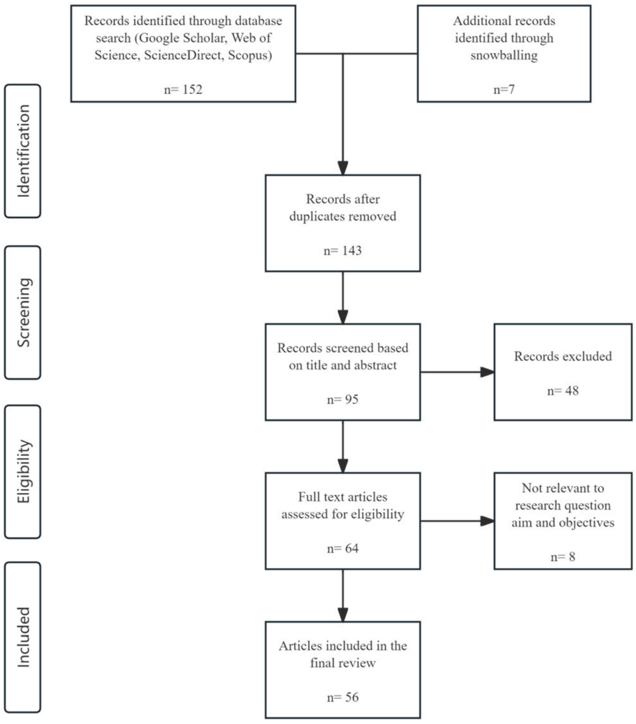

Figure 1. PRISMA-style flow diagram of literature identification, screening, and inclusion.

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3.4. Inclusion and Exclusion Criteria

We included studies that:

- addressed housing retrofit projects with explicit discussion of management, organisation, or delivery.
- provided empirical or conceptual insights relevant to the Owner, Supplier, or Delivery domains.
- were published in peer-reviewed journals or as authoritative reports between 2005 and 2022.
- were written in English and focused on housing (not commercial or industrial buildings).
- We excluded studies that:
- focused solely on technical or engineering aspects without organisational or management analysis.
- addressed new-build projects rather than retrofit.
- were purely policy commentaries without methodological transparency.

Because few empirical studies report quantified CO_2 outcomes, we broadened inclusion to encompass research on energy efficiency, retrofit quality, and performance gaps, as these factors are directly related to CO_2 outcomes.

3.5. Data Extraction and Synthesis

For each paper, we recorded:

- bibliographic information (title, author, year, journal, DOI).
- research focus and methods.
- housing type and country context.
- key findings on barriers, drivers, and delivery processes.
- We then classified the literature using the three domains of project organising [6,7]:

1. Owner Domain – including owner-occupiers, social landlords, and private landlords.
2. Supplier Domain – covering manufacturers, merchants, contractors, and installers.
3. Delivery Domain – focusing on project execution and integration.

We used this conceptual framing because it provides a holistic perspective on project organising, encompassing both the temporary and permanent organisations involved, and the interfaces between them. This is in contrast to much of the project management literature (Lundin & Söderholm, 1995), which focuses merely on the temporary project organisation in the delivery domain.

3.6. Iterative Thematic Synthesis

Data analysis followed an iterative thematic synthesis approach [37]. Each article was read multiple times to identify recurring themes—for example, trust, financing, split incentives, training, communication, and performance gaps. Themes were compared, grouped, and refined through successive coding cycles until stable clusters emerged both within and across the three domains. This iterative process enabled us to trace interdependencies—for instance, how supplier capability influences owner confidence and delivery quality—and to interpret their broader implications for sustainability.

3.7. Synthesis and Interpretation

Finally, we synthesised the coded material thematically to highlight three dimensions:

1. recurring barriers and drivers across domains.
2. cross-domain interdependencies shaping project outcomes.
3. implications for energy and potential CO2 performance.

While the majority of reviewed studies assessed energy efficiency or organisational performance rather than direct carbon metrics, we interpret these findings as proxies for whole-life CO_2

performance. We also note the absence of consistent carbon reporting as an important evidence gap for future research.

The following section presents the results of this synthesis, organised around the Owner, Supplier, and Delivery domains.

4. Results: Evidence Across the Three Domains

4.1. Overview of the Evidence Base

Of the 56 reviewed papers, 25 focused on owner-occupiers, eight on social landlords, and seven on private landlords. Thirteen studies centred on suppliers, while nine analysed project delivery (Table 3). The evidence was geographically concentrated in north-western Europe—particularly the UK, the Netherlands, Germany, and the Nordic countries—reflecting shared reliance on gas heating, similar tenure mixes, and mature housing stocks.

Table 3. Categorisation of reviewed literature by domain and ownership type.

Domains		Reference	Number of Articles
Owner Domain	Owner-occupier	Tjørring and Gausset(2019) [24]; Ambrose & McCarthy(2019) [25]; Sunikka-Blank & Galvin(2012) [26]; Liu et al. (2020) [29]; Risholt and Berker(2013) [38]; Galvin(2014) [39]; Kuusk & Kalamees (2015) [40]; Wilkinson et al.(2015) [41]; Buser & Carlsson(2017) [42]; Collins & Curtis (2017) [43]; Cauvain & Karvonen(2018) [44]; Hope et al.(2018) [45]; Matosović & Tomšić (2018) [46]; Trotta (2018) [47]; Wilson et al.(2018) [48]; Bravo et al.(2019) [49]; Liang et al.(2019) [50]; Broers et al.(2019) [51]; Zheng et al.(2019) [52]; Butt et al.(2020) [53]; Jia et al.(2021) [54]; Azcarate-Aguerre et al.(2022) [55]; D'Angelo et al.(2022) [56]; Jowkar et al.(2022) [57]; de Wilde(2019) [58];	25
	Social landlord	Cauvain & Karvonen (2018) [44]; Trotta (2018) [47]; Swan et al. (2013) [59]; Meehan & Bryde (2015) [60]; Grandclément et al. (2015) [61]; Monteiro et al. (2017) [62]; Weber & Wolff (2018) [63]; Lambrechts et al. (2021) [64].	8
	Private landlord	Trotta (2018) [47]; Weber & Wolff (2018) [63]; Ástmarsson et al. (2013) [65]; Lee et al. (2015) [66]; März (2018) [67]; Miu & Hawkes (2020) [68]; Malinowski et al. (2020) [69].	7
Supplier Domain		Killip et al. (2020) [5]; Owen et al. (2014) [21]; Berghorn & Syal (2016) [70]; Wade et al. (2016) [71]; Clarke et al. (2017) [72]; Hrovatin & Zorić (2018) [73]; Wade et al. (2018) [74]; Pallesen and Jacobsen (2018) [75]; Murto et al. (2019) [76]; Simpson et al. (2020) [77]; Murtagh et al. (2021) [78]; Simpson et al. (2021) [79]; Zaunbrecher et al. (2021) [80].	13
Delivery Domain		Killip (2013) [20]; Owen et al. (2014) [21]; Bryde and Schulmeister (2012) [81]; Rovers (2014) [82]; Alam et al. (2019) [83]; Lowe and Chiu (2020) [84]; Brocklehurst et al. (2021) [85]; Sandberg et al. (2021) [86]; Dauda & Ajayi (2022) [87].	9

4.2. Owner Domain

4.2.1. Owner-Occupiers

Owner-occupiers remain central to national retrofit targets because they represent the majority of the housing stock. However, evidence shows that their decisions are rarely motivated purely by energy efficiency. Rather, homeowners prioritise aesthetic and comfort improvements—visible changes such as kitchens and bathrooms—over invisible thermal upgrades [24,25,58]. The distinction between house and home is crucial: energy-related investments compete with personal and emotional attachments to domestic spaces [48].

Participation is strongly shaped by life-cycle factors: new homeowners, often younger and more educated, are more willing to undertake disruptive retrofits [49]. In contrast, long-term residents tend to avoid interventions that disturb familiar routines. These behavioural patterns align with studies showing that homeowners with higher environmental awareness and social capital networks are more likely to act [51,57].

Knowledge gaps are another persistent barrier. Limited publicity and inconsistent advice from consultants leave homeowners dependent on peer networks for information. Trust, both interpersonal and professional, plays a decisive role [88]. Finally, financial considerations constrain adoption: retrofit costs are high, returns take a long time, and predicted energy savings are often not realised due to rebound and prebound effects [26,39].

Overall, homeowners’ engagement in retrofitting remains low because they face a combination of technical uncertainty, emotional reluctance, and limited confidence in the supply side.

4.2.2. Social Landlords

Social landlords—public or non-profit entities providing affordable housing—are better positioned to manage retrofits because they operate at scale and employ professional asset managers. Their social purpose aligns with reducing fuel poverty and carbon emissions [44,59]. Uniform building typologies allow economies of scale and replication of solutions [61].

However, even here, complexity arises. Upgrades must accommodate tenants’ needs and prevent political backlash when rent increases exceed energy savings [63]. Social landlords must balance technical and social objectives, manage expectations and coordinate multiple stakeholders. Effective communication with tenants is essential for adoption and sustained performance [61].

4.2.3. Private Landlords

Private landlords, especially small private landlords (SPLs), are typically risk-averse and poorly informed about retrofit opportunities [67,68]. Being older and less financially leveraged, SPLs prioritise property maintenance and stable rent income over energy performance. The classic split-incentive problem—where landlords pay for retrofits, but tenants benefit from lower bills—undermines investment motivation [65]. Bureaucratic funding schemes further discourage participation [67]. Even when policies permit rent increases to recoup investments, as in Germany, tenants often pay more in rent increases than they save in energy costs [63].

Overall, across owner types, the evidence highlights limited demand for retrofit, low trust in supply chains, and insufficient integration between financial, technical, and behavioural interventions.

4.3. Supplier Domain

Suppliers—manufacturers, merchants, and installers—form the intermediary infrastructure of retrofit delivery. The literature consistently portrays this sector as fragmented, under-capacitated, and dominated by micro-enterprises employing fewer than ten people [5,79].

4.3.1. Intermediary Role and Market Maturity

Suppliers act as intermediaries linking homeowners◎ needs to technologies. Yet they are primarily demand-led: since most renovation work targets aesthetics, retrofit products are marginal to their business [78]. Manufacturers provide limited training, often more promotional than educational [5]. Merchants play an under-recognised role by shaping what materials and technologies are available locally [89].

4.3.2. Knowledge and Capability Gaps

Micro-enterprises lack resources for innovation and rely on “learning by doing.” Training systems remain technology-specific rather than system-based [72]. As domestic energy systems become smarter, the installers◎advisory role grows, yet professional jurisdictions remain fragmented [74]. These structural weaknesses contribute to inconsistent quality and reinforce homeowners◎ mistrust.

4.3.3. Conservatism and Resistance

The retrofit supply chain exhibits conservatism akin to “hard-wired inertia” [5]. Installers prefer familiar products, merchants stock proven items, and manufacturers depend on established distribution relationships. The result is limited uptake of innovative technologies and slow diffusion of best practices.

4.3.4. Supplier–Owner Relationship

Poor communication between suppliers and clients amplifies risk. Owners unfamiliar with technical language misinterpret advice, leading to mismatched expectations. Negative experiences propagate through social networks, deterring others [80]. Effective communication—clear, jargon-free, and trust-based—is therefore central to improving retrofit outcomes.

4.4. Delivery Domain

Retrofit delivery involves executing works within occupied buildings under uncertainty. Compared to new-build projects, retrofits exhibit discovery during execution—hidden defects, unforeseen materials, or occupant interventions [20,90]—all contribute to dynamic complexity and therefore emergence during project execution.

4.4.1. Uncertainty and Risk

Execution uncertainty complicates scheduling and budgeting [91]. Each dwelling presents unique physical conditions requiring bespoke solutions. For example, the Kerkrade West project in the Netherlands achieved remarkable energy performance through standardised prefabrication (“renovation trains”), but only after extensive trial-and-error learning and at high cost [82]. Conversely, the UK FLASH project revealed severe incompatibilities among retrofit systems, showing how technical interdependence and site variability can undermine performance [84]. Even properties that were built to a standardised template many years or decades previously will have become differentiated as they “learn” in response to occupants◎diverse requirements [92].

4.4.2. Occupant Interactions

Delivery complexity also stems from ongoing interaction with occupants. In owner-occupied housing, families usually remain in situ during renovations, making disruption management a key success factor. Schedules must accommodate daily routines and negotiate aesthetic choices [82]. In social housing, landlords often act as mediators between tenants and contractors, improving coordination [84].

4.4.3. Performance Verification

Unlike new-build projects, retrofit success cannot be judged at handover; performance unfolds over time. Continuous monitoring and post-occupancy evaluation are rarely implemented, leaving limited feedback to improve future projects. The energy performance gap—the divergence between predicted and actual savings—illustrates how inadequate commissioning and verification erode long-term CO_2 benefits [39].

4.4.4. Managerial Capabilities

Retrofit project managers must integrate technical, social, and organisational complexity. The need for a new professional role is highlighted [93]—the retrofit coordinator—who bridges design, installation, and quality assurance. Adaptive management, strong communication, and iterative learning are critical competencies.

4.5. Key insights Across Domains

Owner Domain

Across contexts, owners◎decisions have significant carbon implications. Projects initiated for aesthetic reasons often ignore optimal insulation or heating upgrades, resulting in minimal CO_2 benefits. Conversely, projects with high environmental awareness achieve deeper energy savings but face financial constraints. Policies focusing solely on subsidies fail to address these behavioural and social determinants.

Supplier Domain

Supplier capability directly affects performance outcomes. Poor installation quality, lack of system integration, and inadequate commissioning are major sources of the performance gap. CO_2 savings depend not only on materials but also on workmanship and sequencing—factors seldom captured in policy modelling.

Delivery Domain

Delivery determines whether technical potential becomes actual CO_2 reduction. Poor coordination among trades, insufficient monitoring, and user mismanagement reduce effectiveness. Few studies report post-retrofit evaluation, and those that do [94] find lower-than-expected savings due to behavioural rebound—a phenomenon where occupants, after improving energy efficiency, increase their energy use (for example, by heating rooms to higher temperatures or using appliances more often), thereby offsetting some of the expected savings. In addition, incomplete commissioning processes and inadequate post-occupancy support further limit the actual achievement of carbon emission reductions.

4.6. Summary of Common Challenges

Across domains, four overarching themes emerge:

1. Fragmented project management – retrofits lack integrated delivery models linking design, installation, and verification.
2. Trust and communication deficits – low confidence between owners and suppliers undermines uptake and satisfaction.
3. Performance uncertainty – the energy performance gap remains pervasive due to dynamic complexity.
4. Socio-technical misalignment – technical measures often conflict with occupant preferences or use patterns.

4.7. Implications for Carbon Outcomes and Delivery Practice

The review confirms that management processes are as critical to CO_2 outcomes as technological specifications. Delivery failures, rather than technology limitations, explain much of the deviation between modelled and realised CO_2 reductions. Addressing this requires a process-anchored approach linking complexity management with measurement and verification.

5. Framework and Discussion: Mapping Complexity, Delivery, and Whole-Life CO_2

5.1. Linking Project Complexity to CO_2 Performance

The preceding review revealed that retrofit outcomes depend less on technological innovation and more on how complexity is managed during delivery. Technical potential alone cannot guarantee CO_2 outcomes; rather, project organisation—coordination, sequencing, and quality assurance—determines whether predicted energy savings are realised.

Drawing on the concepts of static and dynamic complexity [15,95] and our three-domain analysis, we propose a conceptual framework that maps project-management complexity to whole-life CO_2 outcomes as Figure 2.

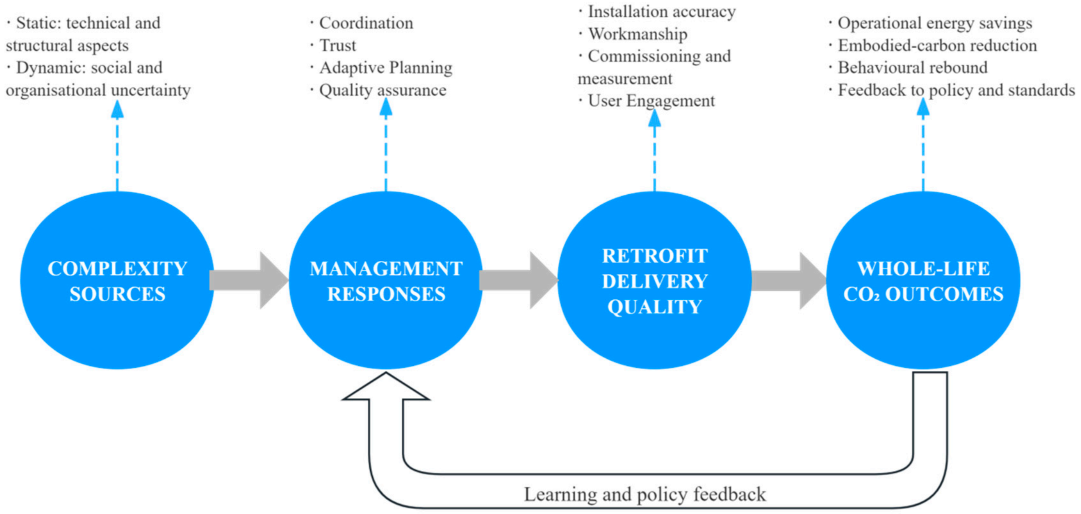

Figure 2. Framework linking project complexity and CO_2 outcomes in housing retrofit projects.

Figure 2 conceptualises how the management of project complexity shapes CO_2 outcomes in housing retrofit projects. Static complexity arises from the technical configuration of multiple systems and trades, while dynamic complexity stems from social, organisational, and regulatory uncertainty. Effective management responses—such as coordination across the Owner, Supplier, and Delivery domains, transparent communication, adaptive planning, and rigorous quality assurance—translate these complexities into controlled delivery processes. High-quality installation, commissioning, and user engagement then determine whether the technical potential of retrofit measures is realised as verifiable reductions in operational and embodied CO_2. Where complexity is out of control, fragmented decision-making and poor workmanship generate performance gaps. The feedback loop indicates that learning from measured carbon outcomes should continuously inform policy, standards, and professional practice, closing the gap between predicted and achieved sustainability benefits.

Static complexity corresponds to the number of physical components, trades, and interfaces involved in a retrofit (e.g., insulation systems, glazing, HVAC upgrades). Managing static complexity requires detailed planning, sequencing, and technical coordination—activities typically handled by contractors and site managers.

Dynamic complexity arises from unpredictable interactions between social, organisational, and technical subsystems—homeowners◎ decisions, installer behaviour, policy changes, or tenant adaptation. Managing dynamic complexity demands adaptive coordination, learning, and trust building across project boundaries.

When static and dynamic complexities are both high—as in most housing retrofits—the risk of performance gaps and rework increases. Mismanaged complexity translates directly into CO_2 inefficiency: poor sequencing causes thermal bridging; communication failures lead to incorrect operation of heating systems; fragmented responsibility delays fault detection.

5.2. The three-Domain Interaction Model

The integrative synthesis shows that the Owner, Supplier, and Delivery domains interact through feedback loops that influence both energy and carbon outcomes (Table 4).

Table 4. Interactions between Owner, Supplier, and Delivery domains and their influence on CO_2 performance.

Domain	Core Complexity Drivers	Mechanisms Affecting CO_2 Performance
Owner	Decision uncertainty; aesthetic vs. energy priorities; limited knowledge; trust deficits	Determines project scope and retrofit depth; behavioural rebound reduces realised savings
Supplier	Predominantly small and micro-enterprises with limited integration across the supply chain; weak training systems; conservative, risk-averse practices	Affects installation quality, commissioning accuracy, and the durability of CO_2 benefits
Delivery	On-site uncertainty, occupant interaction, and poor project management practices	Shapes actual energy savings through workmanship, sequencing, and verification

Although few studies provide quantitative data on firm size distribution, the literature consistently characterises the retrofit supply chain as dominated by small and micro-enterprises, with limited capacity for coordination and innovation [5,79].

These three domains are mutually interdependent. For instance, supplier professionalism affects owner confidence, which in turn determines retrofit ambition and budget. Delivery performance then feeds back into public trust and future policy uptake. The framework, therefore, emphasises that achieving whole-life CO_2 reduction requires systemic coordination across all three domains rather than isolated technological optimisation.

The synthesis above shows that effective coordination among owners, suppliers, and delivery actors is central to improving whole-life carbon performance. The following section discusses the practical, theoretical, and research implications arising from these findings.

6. Implications and Future Research

6.1. Managerial and Policy Implications

1. Adopt complexity-aware management practices.

Policymakers and industry bodies should recognise retrofit projects as complex micro-projects and train coordinators accordingly. The emerging retrofit-coordinator role exemplifies this shift from technical to integrative capability [93].

2. Strengthen quality assurance and verification.

National programmes should require commissioning and post-occupancy monitoring to ensure predicted CO_2 reductions are achieved.

3. Professionalise the micro-enterprise supply chain.

Developing shared training standards and collaborative networks can mitigate capability fragmentation and ensure consistent workmanship.

4. Encourage owner engagement and trust.

Transparent communication, user-centred design, and clear demonstration of comfort and financial benefits increase willingness to invest.

5. Integrate retrofit policy with carbon accounting.

Linking grants and tax incentives to verified CO_2 outcomes, rather than merely energy-efficiency ratings, would improve accountability.

6.2. Theoretical Implications

This review extends project management theory by demonstrating that complexity dynamics observed in major projects also apply at the micro-project scale of housing retrofits. It also advances sustainability-transition research by linking managerial practices to environmental outcomes, bridging socio-technical and project-organising perspectives. Finally, it shows how integrative review methods can synthesise interdisciplinary evidence to generate conceptual clarity in emerging research areas.

6.3. Research Agenda

1. Quantification of management-carbon linkages.

There remains limited empirical evidence linking delivery practices directly to carbon outcomes. Mixed-method studies combining monitoring data with qualitative process evaluation would address this gap.

2. Comparative analysis across regions.

Most existing research focuses on north-western Europe. Expanding analysis to other climatic and regulatory contexts would test the framework's generalisability.

3. Integration with digital technologies.

Building Information Modelling (BIM), digital twins, and data analytics offer tools for managing complexity and verifying CO_2 outcomes in real time.

7. Conclusions

This study conceptualises housing retrofit projects as complex micro-projects whose success depends on managing technological, organisational, and social interdependencies. Through an integrative review of 56 studies, we mapped challenges across the Owner, Supplier, and Delivery domains and developed a framework linking project complexity to whole-life CO_2 performance.

Our findings reveal that the barriers to decarbonising the existing housing stock are primarily managerial rather than purely technical. Fragmented supply chains, limited owner engagement, and inadequate verification processes undermine the potential of retrofit technologies. Recognising and managing these forms of complexity can transform retrofit delivery from a series of isolated interventions into a coordinated, learning-based system capable of delivering verified carbon reductions.

By reframing retrofits through the lens of complexity-informed project management, this paper contributes to both theory and practice. It invites researchers and practitioners to view small housing projects not as routine construction tasks but as dynamic socio-technical systems whose management determines their true climate impact.

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