High-Rise Residential Building Makeovers: Improving renovation quality in the United Kingdom and Canada through systemic analysis

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Highlights:

- Vague terminology and clauses in renovation policies permit non-compliance
- IEQ requirements are generally lacking in high-rise residential renovation policies
- Systemic barriers limiting renovation quality in the UK were identified
- Policy and process changes are recommended to improve renovation quality

Abstract

The need to renovate high-rise residential buildings to maintain or improve indoor environmental conditions and reduce energy use is becoming prevalent worldwide. Climate change concerns have driven the development of policies, regulations, and standards for building renovation; however, these standards are often narrowly focussed on energy use and fail to consider the complexities of high-rise residential building systems. To understand policy, process, and practice barriers to improving the high-rise residential building renovation process, we first examined high-rise residential building renovation policies, protocols, and guidelines in the UK and Canada – two countries which have significant stocks of aging high-rise residential buildings. This revealed several common limitations across jurisdictions, including a lack of consideration of non-energy and cost-related benefits, failure to adopt the 'building-as-a-system' approach and vague or inconsistent use of terminology surrounding the scope and feasibility of renovations which provide excessive latitude for non-compliance. Next, an example of an

existing high-rise residential building renovation processes is presented, in which a system dynamics approach is used to identify systemic barriers to improving renovation processes in the UK and Canada. Causal loop diagrams were developed to represent important variables and the causal interrelationships between variables using a combination of grounded theory analysis, validation interviews, and workshops involving stakeholders from both countries. Recommendations for improving renovation policies are presented including: mandatory standards for IEQ; incentivization of integrated design; improvements to practitioner education and training; implementation of feedback mechanisms to inform practitioners of successes and failures; and simplification of material and design certifications.

1. Introduction: The global landscape of high-rise residential building renovation

In many ways, the present state of housing stock in developed nations is a barometer of their success in achieving not only climate change mitigation targets, but also addressing numerous social equity issues, including where and how less socially advantaged citizens dwell. A growing wave of aging building stock has converged with emerging social, environmental, and economic imperatives, which necessitates the renovation of existing buildings. These renovations are often motivated by energy conservation goals or occupant comfort deficits (e.g., indoor air quality).

The buildings sector accounts for 30% of global energy consumption and, in combination with the building construction industry, produces almost 40% of global direct and indirect CO_2 emissions [1]. The global movement towards reducing energy use and greenhouse gas (GHG) emissions has prompted the development of policies, regulations, and standards for building renovation. These, however, are neither universally adopted nor comprehensive in treating high-rise residential buildings[i] as complex, multi-faceted systems.

Energy use is often a key driver of building renovations because of the potential to reduce operational costs, energy consumption, and GHG emissions. The energy impacts of renovating high-rise residential buildings have been studied widely and both envelope and mechanical system renovations have been shown to substantially reduce energy demand [2]–[10]. Still, energy modelling of different renovation strategies tends to over-estimate the energy savings of any implementation [11], [12], which results in uncertainty in terms of return on investment and, likely, reduces the rate at which renovations occur within the building stock.

Furthermore, energy renovations in high-rise residential buildings may introduce new or aggravate existing indoor environmental quality (IEQ) issues [8], [13]–[17], in particular when renovations only address the building envelope (and reduce infiltration across the envelope) and do not include mechanical ventilation. When IEQ is prioritized at the outset of project planning, potential IEQ issues may be identified and the building's renovation can be designed to improve the IEQ over the pre-renovation conditions. This can improve resident quality of life, reduce potential health impacts, and increase property values for building owners. Further integration of renovation performance information regarding energy use and IEQ into renovation policies, regulations, and guidelines is necessary to ensure they are successful tools in promoting renovations which reduce building energy use, while maintaining or improving IEQ.

Unfortunately, industry practice would suggest that this holistic integration of various performance factors including environmental, economic and social factors is uncommon. Experience from prior projects (“we’ve always done it this way”) [18], lack of training on and capacity for integrated design [19], [20], lack of established performance targets [21], siloed decision-making and even the way project meetings are run [18], all prevent consideration of the building as a system during the retrofit planning process.

Past research has shown that top-down policy approaches are generally insufficient to change renovation outcomes and that stakeholder engagement and procedural barriers must be also addressed [19], [22], however, the manner in which policy and industry processes interact to impact the extent and quality of high-rise residential building renovations has not been formally investigated. This paper uses a multi-method approach to investigate how the extent and quality of high-rise residential building renovations are impacted by both existing regulations and current industry practices and to identify ways to improve renovation frequency and quality through regulatory and process changes. The UK and Canada were chosen as the focus of this analysis as both countries have a large stock of aging high-rise residential buildings, but are governed by distinctly different regulations. As such, the differences in existing UK and Canadian renovation policies and processes provide the opportunity to better understand the extent to which they impact renovation outcomes. We chose to use the UK as the initial basis for an exploratory, causal study and to include the Canadian context to understand the extent to which similar issues are present in the Canadian context and how different regulations and processes may influence renovation quality.

In this article, first, the current state of the UK high-rise residential building stock and renovation drivers are characterized (Section 2). Note that only a brief summary of the Canadian context is included in Section 3 as the demographics and drivers of the Canadian high-rise residential building stock have been explored sufficiently in previous work [23] to incorporate into our analysis. Next, an overview of relevant regulations in the UK and Canada contexts is presented, along with a summary of related international protocols and guidelines for high-rise residential building renovation (Section 3). Sections 4 and 5 present the methods and results of a causal, exploration of the systemic risks in current high-rise residential building renovations, based on the extreme case of the Grenfell Tower disaster in the UK in 2017. This illustrative case uses a qualitative model-building approach inspired by grounded theory as well as participatory engagement with local stakeholders in both the UK and Canada through interviews and workshops for model validation. While the initial focus of the model-building was UK-based, the Canadian perspective is integrated into Section 5 to identify the contextual differences in another jurisdiction facing extensive building renewal challenges. This juxtaposition was used to identify common areas for renovation process improvement in order to highlight the degree of applicability of our findings to a broader audience, in Section 6.

2. High-rise residential buildings in the UK and Canada

It is important to understand the context of the building stock considered in this paper before examining the systemic issues surrounding renovation of this building stock. As such, this section provides a summary of the building stock characteristics as well as current renovation trends. Both the UK and Canada have a large number of aging high-rise residential buildings, which is why they are the focus of this paper. However, Canadian high-rise residential building demographics have previously been explored extensively in the “Tower Renewal Guidelines For the Comprehensive Retrofit of Multi-Unit

Residential Buildings in Cold Climates" [23] and, as such, we primarily focus on the UK building stock characteristics in this paper (Sections 2.1 and 2.2). A brief overview of the Canadian context is provided in Section 2.3 for the reader's reference.

2.1 High-rise residential building stock in the UK

The UK climate is classed as 'temperate maritime' and experiences an average annual temperature of 9°C [24]. This relatively mild climate has meant that building energy performance standards are not as stringent compared to colder European climates. Historically, building materials have varied across the UK, reflecting the local availability of clay, stone, and quarried rock, etc. leading to an overall diversity in older buildings from the pre-war period (i.e., buildings built before 1914) [25]. Over time, these regional building practices and use of materials have converged in general building archetypes and material usage. From the late 20th century onwards, these comprise standard clay cavity brick wall construction and modern reinforced concrete and steel structures and a growing use of glazed assemblies in high-rise buildings [25].

Nearly 90% of all high-rise residential buildings in the UK were constructed between 1959 and 1973, with approximately half of them in London [26]. Figure 1 shows the number of high-rise buildings by year of construction. Construction of buildings with five or more storeys accounted for just 9% of local authority housing[ii] between 1953 and 1959 but increased in the early 1960s to reach a peak of 26% in 1966 [25]. As of 2016, there are approximately 11,908 high-rise residential buildings in England, with six or more storeys, with between 2,000 and 3,000 of these buildings above 10 storeys [26].

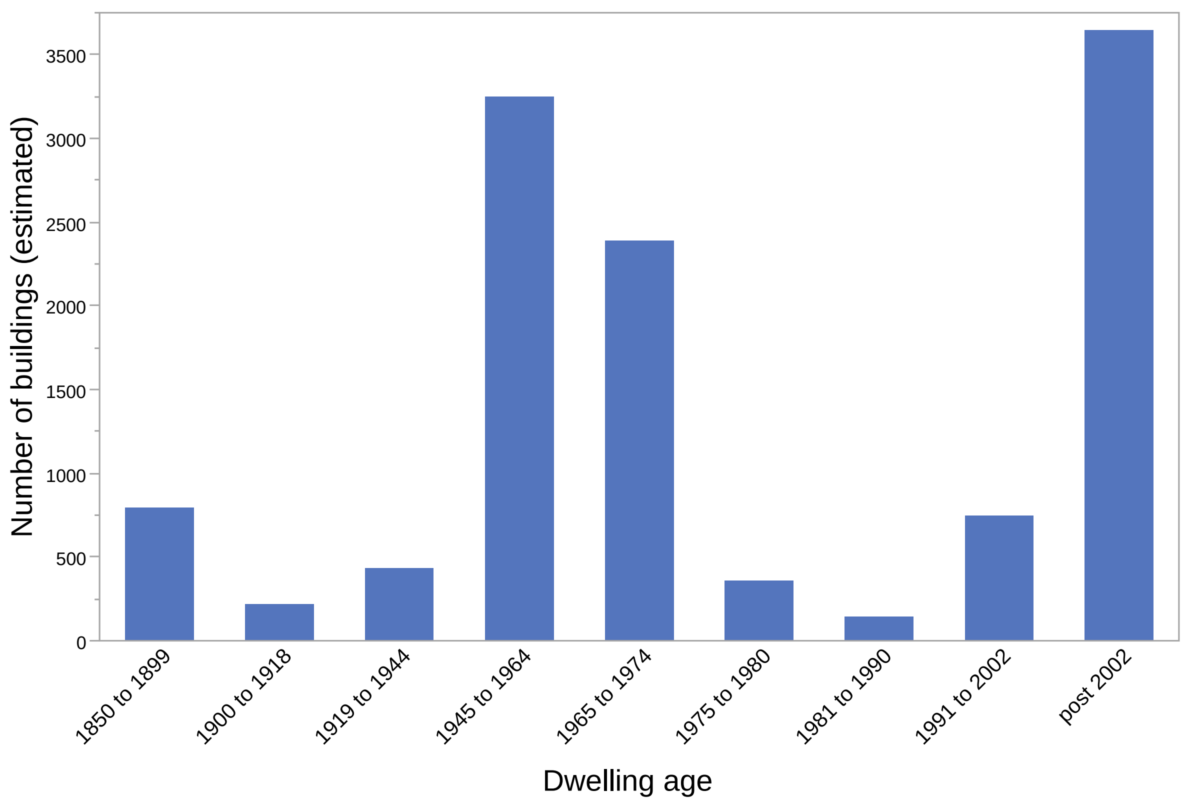

Figure 1: Number of purpose-built blocks of flats as classified by the English Housing Survey [26]. Note: the term "blocks of flats" has been used for consistency with the original source. Representation is equivalent to the number of high-rise residential buildings.

The bulk of the high-rise building housing stock is owned by Local Authorities (i.e. local government) with a small number owned by housing associations[iii]. However, since the 1980s, the 'right-to-buy' policy meant that many tenants have become owner-occupiers of formerly local authority housing (i.e. social housing), giving rise to a complicated ownership structure across the high-rise building housing stock. The quality of the high-rise building housing stock in the UK is reflective of the buildings' age and ownership structure, which complicates how owners can invest in the building pertaining to their legal rights, and commonly includes: degraded façades; poor acoustic separation; inadequate heating systems; unreliable elevators, poorly-maintained fire safety systems; as well as other building defects [27], [28].

2.2 Trends in UK high-rise residential renovation

The building renovation drivers in the UK have largely been studied from three perspectives: health and safety concerns; energy security and consumer protection; and climate change. Over time, these perspectives have been modified through various political lenses, including market- or government-directed approaches. While building renovation drivers are studied from multiple perspectives, policy formulation has often followed a single perspective in isolation from others (e.g. energy security alone or healthy and safety alone, etc.). This has led to contradictory and conflicting policy goals. For example, the 1965 Building Regulation, which included requirements for the thermal insulation of the building envelope, was largely a response to the need "that there should be Building Regulations common to the whole of England and Wales to replace a mass of byelaws" [29]. The 1973 oil crisis and the sudden shock to oil prices influenced the revisions in the late 1970s, while the free market approach promoted by the Thatcher government [30] influenced the shift from prescriptive standards (which specify how the requirements should be met) to functional standards (which specify what performance standards must be achieved by a chosen system). In the early 2000s, the call to address climate change began to influence energy efficiency policy in a direction that sought to reduce GHG emissions.

Challenges with the renovation process of high-rise residential buildings in the UK include: poor building management and maintenance, poor supervision of the renovation, poor oversight of fire safety, and poor communication between landlord and tenants, cost-cutting actions, and the delegation of responsibilities from Local Councils to weakened and opaque management organisations [28]. Renovating high-rise residential buildings for the purposes of energy efficiency requires that the upgraded systems meet the necessary building regulations Schedule 1; Part F: Ventilation, Part L: Heat and Power, and Part B: Fire [31]. Some extensive renovations, specifically renovations to buildings with a floor area greater than $1000m^2$ which include additions to building floor area, installation of new fixed building services, and/or an increase of capacity of existing fixed building services, can trigger 'consequential improvements', which are a mechanism for upgrading systems across the entire building [31]. The detailing and systems commonly used to meet regulatory requirements may result in risks and harms for occupants as a secondary effect, including: increasing moisture build-up and poor indoor air quality; façade deterioration; noise from newly installed mechanical systems; and, of course, the risk of fire.

In recent years, UK Government policy has changed and certain renovation programs have been removed – such as the Green Deal – which was the primary mechanism for encouraging owner- or tenant-led energy efficiency measures to be implemented in the residential stock. However, the UK is still currently committed (subject to the impact of Brexit) through the Energy Performance of Buildings Directive (EPBD) regulations to a single goal of all new buildings being nearly zero energy from 2021 through the UK's National Energy Efficiency Action Plan and Building Renovation Strategy [32]. Changes to Part L of the building regulations have set new energy standards in reference to EPBD regulations [33]. Despite regulation updates, they can still be seen as too rigid in a dynamic environment, where outcomes from research/on-site experience is not always fed back into policy/design, leading to a disconnect/delay between the current research and guidance [34]–[36]. In addition, many government departments appear to have a systematic and large turnover of experienced staff, such that it is difficult to maintain institutional knowledge, as is also the case within the construction industry [27]. Without long-term experienced staff, known issues are revisited afresh and possible progress or change can be curtailed or delayed.

For IEQ, renovation drivers have been related to pollution exposure reduction and occupant health protection. Research has shown that without proper controls on ventilation, there may be a trade-off between energy and IEQ as the drive for energy efficiency (Part L) can cause insufficient ventilation (Part F) [37]–[39]. An example of these conflicts is chronic overheating in highly-insulated and airtight new buildings [39]–[41]. Approved Document L of the building regulations only makes reference to maintaining air quality levels while improving building energy performance. Where specific additional mitigation measures are required when pollutant concentrations are at risk of exceeding target levels, such as from radon, significant improvements in health can occur in conjunction with energy savings [42].

As buildings, in terms of their designs, systems and service offerings have become larger and more complex, alongside the need to decarbonize the UK building stock to achieve the objectives of the Climate Act to reach net zero carbon by 2050 [43], practitioners and parts of the building regulations have failed to keep pace with these demands. The building industry working on energy efficiency retrofits has been required to respond to accelerate their own evolution of practice, while also accommodating a range of changes in design techniques and material systems. Sometimes the consequences of this quick pace are a failure to optimise the energy performance of refurbished buildings, in other instances, the impacts can be devastating, such as with Grenfell. In the following section, we explore the implications of these complex interaction by looking at an example of high-rise building retrofits using a qualitative system dynamics approach.

2.3 The Canadian context

Similar to the UK, Canada has a significant number of residential dwellings in high-rise residential buildings from the post-war period, which are characterized by their concrete structural forms [23]. In 2015, 9% of all Canadian dwellings were in high-rise residential buildings [44], with over 45% of these dwellings located in buildings constructed before 1980 [45]. This aging portion of Canada's high-rise residential building stock provides affordable housing for over 1.6 million households [23], [45], however, the quality of housing provided by these buildings is deteriorating due to aging components and makeshift repair and maintenance processes [23]. Renovation of these buildings is not generally required by Canadian regulations, however, renovation presents a significant opportunity to reduce energy use and improve indoor environmental quality when done correctly [23]. While the Canadian trends are not described in detail in this paper, further information can be found in the *Tower Renewal Guidelines for the Comprehensive Retrofit of Multi-Unit Residential Buildings in Cold Climates* [23].

3. Key regulations, protocols and guidelines for high-rise residential building renovation in the UK and Canada

The sections that follow provide an overview of the policy instruments that have guided high-rise residential building renovation in UK and Canada. This overview was developed through an expert-guided review of relevant policies in the two countries. Two experts with extensive knowledge of the history of renovations in the two jurisdictions as well as the guiding protocols, guidelines and standards were asked via email to provide these summaries. After the drafts were received, they were reviewed by the project team for completeness. Areas requiring further coverage or explanation were then identified for the experts to help them create a more complete picture of the evolution of the protocols, guidelines and standards in each jurisdiction. A series of phone calls were conducted during the review and clarification process.

Unlike policy instruments for new buildings, it should be noted that current policy instruments guiding renovations do not specify minimum acceptable levels of performance in terms of energy, indoor air quality, durability or health and safety. In different documents, different terminology is used to refer to the renovation of high-rise residential buildings. For simplicity, in this paper, the term "renovation" is used exclusively, however the terms 'comprehensive retrofit' and 'refurbishment' are commonly used in other works. Based on our review, the renovation of high-rise residential buildings is a relative late comer to the long list of initiatives in developed nations aimed at conserving energy and reducing GHG emissions (e.g. Energy Star, green building rating systems, Architecture 2030, Net-Zero/Near Net-Zero/Net-Zero ready targets). Further, our review observed that the regulations, protocols, and guidelines often narrowly focus on "cost effective" energy performance improvements, excluding larger social and economic factors associated with housing stock. It is worthwhile noting that the criteria for cost effectiveness are not clearly defined (e.g., rate of return, payback period, life cycle cost, etc.).

First, some helpful definitions of the terminology used in this paper are presented. Specifically, the terms regulations, protocols, guidelines, advocacy, and commentary are defined. Regulations, also referred to as policies, are mandatory requirements set out within a legal framework of governance and enforcement. For example, regulations may require that renovation projects must not compromise the fire safety of the building. Protocols are procedures that are established by government and professional bodies for carrying out regulations and policies, whose non-observance would constitute negligence. For example, the specification of a combustible cladding would be deemed professional negligence, and the approval of such a combustible over-cladding by a regulatory official would be viewed as a dereliction of duty. Guidelines are recommended practices that may or may not be observed on a discretionary basis. For example, increasing ventilation rates in refurbished buildings to compensate for reductions in air leakage through energy conservation measures may be recommended, but not mandatory. Advocacy and commentary generally contain reflections, critiques, or observations from practitioners on a process or its outcomes. Note that while regulations are considered on a country-specific basis, due to their limited applicability to specific jurisdictions, protocols, guidelines, and advocacy and commentary are considered in a jurisdiction-agnostic manner as they provide technical and contextual information on existing and best practices which can be applied in numerous jurisdictions.

3.1 UK regulatory developments in building energy performance

Building renovation in the UK has been guided by policies developed both nationally and through the European Union (EU). In this section, we first describe the development of relevant EU policies on building renovation, followed by nationally-developed policies in the UK.

3.1.1 European Union Regulations

Residential building renovation in Europe has been primarily driven by a legislative instrument known as the Energy Performance of Buildings Directive (EPBD) [46]. The EPBD aimed to promote the improvement of energy performance of buildings in general. Notably, energy renovations were not originally included in the EPBD when the EU committed itself to the Kyoto Protocol and binding GHG emission reduction targets. The building renovation process in Europe broadly follows the EPBD evolution described below, but individual countries may adapt aspects of the EPDB and implement additional energy efficiency measures, as detailed for the UK in Section 3.1.2.

Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings represents the first EU attempt for setting building energy efficiency standards [46] . Aimed primarily at new buildings, it contained provisions for buildings undergoing major renovations[iv]. In the case of major renovations, the energy performance of the building (or renovated portion) is required to be upgraded to meet minimum energy performance standards, provided conservation measures were technically, functionally, and economically feasible. The fact that the renovation standards must be met only when technically, functionally, and economically feasible opens the door for non-compliance with the directive due to a lack of specificity in defining what is considered technically, functionally, and economically feasible.

Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), subsequently addressed gaps and emerging issues related to the 2002 EPDB [47]. Specifically, for existing buildings, the 2010 version implemented provisions that required all buildings offered for sale or rent state their energy performance certification in advertisements. Member states were also required to set down minimum energy performance requirements for new buildings, for buildings subject to major renovation, as well as for the replacement or retrofit of building elements. They were also obligated to formulate national financial measures and instruments to improve the energy efficiency of buildings, new and existing. This recast EPBD had the effect of making the public aware of the energy performance of new and existing buildings, and spurred comprehensive retrofit programs.

Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency introduced a number of revisions and amendments to earlier directives [48]. In relation to existing buildings, this directive required member states to establish long-term strategies for mobilizing investment in the renovation of their national stock of residential and commercial buildings, in both the public and private sectors. An obligatory renovation quota of 3% of all public buildings owned and occupied by central governments was also prescribed.

Directive 2018/844/EU of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, is the most recent revised EPBD that was signed into law on 30 May 2018 and entered into force on 9 July 2018 [49]. This latest EPBD mostly responded to a previously adopted 'clean energy' package to help the EU meet its 2030 energy and climate goals, however, a great deal of related discussions among key players revealed a growing awareness of the importance of energy efficiency renovations for existing building stock. The 2018 amendments also added terminology and requirements surrounding the consideration and assessment of non-energy related performance factors, including indoor environmental quality and fire safety.

In summarizing the evolution of the European Union's Energy Performance of Buildings Directives, it reveals that some 15 years passed between the introduction of energy efficiency standards and the recognition that energy conservation measures for the renovation of existing buildings should not compromise health and safety. This suggests that, in addition to the traditional performance gap observed in building retrofits that did not deliver their promised energy savings, issues of indoor environmental quality have also ensued.

3.1.2 UK Regulations

In the UK, regulatory bodies for building control were first initiated for reasons of health and safety through the Public Health Act in 1875 (revised in 1936 and 1961) [50]. The first modern set of national building standards were enacted under The Building Regulations in 1965 and focused on health and safety [31]. The 1965 regulations also put in place thermal conductivity limits for walls, roofs and windows and set maximum fenestration ratios (maximum heat loss value for floors was introduced in 1990). A major change was introduced with the Building Regulations of 1985 and 1991 that set out functional performance standards and privatized building inspections (Approved Inspectors). Revisions to building envelope performance (Approved Document Part L) occurred in 1990 and 1995. Further major revisions of the Regulations occurred in 2000 and 2010, in line with energy efficiency policy changes. Those most impacting the energy performance gap and environmental quality were Part L – energy (revised 2010, 2013); Part F – ventilation (revised 2010); Part D – toxic substances (2010); and Part E – sound insulation of the building regulations.

The Sustainable Energy Act of 2003 set out further improvements for energy efficiency of residential buildings [51]. The Climate Change Act 2008 set legally binding targets for the UK to cut greenhouse gas emissions to 80% of 1990 levels by 2050 [52], which has since been superseded by targets of net-zero emissions by 2050 [43]. Sectoral carbon budgets, including those for buildings, were developed by the Committee on Climate Change (CCC) to meet this target. At arms-length from the UK Government, the UK's system of independent commissions has also acted as a catalyst for change and has provided the Government with a wider, sector-led approach to tackling major issues within the construction, operation and performance of buildings. Advisory documents such as the Latham Report [53], the Egan Report [54], and Construction 2025 [55] have all focused on improving construction, materials, and sustainability of the building sector.

The evolution of European legislation, such as the EPBD [49], has been a key driver in the development of Approved Document L related to building energy efficiency for England and Wales since 2002. The Energy Efficiency Directive has acted as a further pressure to improve energy performance standards and reporting of energy performance, for example, the requirement to display the energy performance certificate rating of any building purchased or sold [56]. An important development is that building energy requirements have gradually shifted from 'prescriptive' to more 'flexible' whole-building and performance-based frameworks since 2006. To a limited extent, this gave designers the flexibility to trade-off between different efficiency measures to achieve building energy efficiency targets e.g. building envelope vs. mechanical system efficiency.

3.2 Canadian regulatory developments in building energy performance

Regulations governing the minimum energy efficiency levels for building renovations across Canada, and North America as a whole, are in their relative infancy compared to the EU. Relatively low energy prices, social attitudes, cultural values, and/or building replacement habits may have slowed the development of energy efficiency standards and regulations for building renovation in the region.

In Canada, *Measures for Energy Conservation in New Buildings* was first published in 1978 and updated in 1983 by the National Research Council of Canada [57], [58]. It had no provisions for the renovation of existing buildings but was widely adopted within provincial building codes. Subsequently, a consortium of provinces, utilities, industry stakeholders, the National Research Council of Canada (NRC), and Natural Resources Canada developed the Model National Energy Code for Buildings (MNECB) in 1997, renamed the National Energy Code for Buildings (NECB) in 2011 [59]. The most recent version of the NECB (2017) outlines the minimum energy efficiency levels for all new buildings and offers more flexibility for achieving code compliance, however it still does not contain requirements for energy conservation measures in building renovations and alterations [59]. Some Canadian municipalities have also implemented city-wide building by-laws which contain requirements relating to the performance of renovations of existing buildings. For example, the City of Vancouver has implemented the *Vancouver Building By-Law* (VBBL), the current version of which requires specific energy and safety performance conditions to be met in existing building renovations, depending on the scale of renovation [60].

3.3 Protocols

Formal protocols have only recently emerged for energy renovations of existing residential buildings (e.g. [61]–[65]). In 2015, Zhivov et al. published Business and Technical Concepts for Deep Energy Retrofits of Public Buildings [61] through the International Energy Agency - Annex 61 Business and Technical Concepts for Deep Energy Retrofits of Public Buildings (https://iea-annex61.org). Annex 61 is a precursor to the various protocols that have since emerged. One of the most significant contributions of Annex 61 is its definition of a deep energy retrofit (DER) - a major building renovation project in which site energy use intensity, including plug loads, have been reduced by at least 50% from the pre-renovation baseline [61].

Stemming in part from the Annex 61 work, but mostly in response to the energy performance gaps that are witnessed across so many energy efficiency renovation projects, has been a protocol framework established by the Investor Confidence Project (ICP) (http://www.eeperformance.org) as a means of third party certification [62]–[65]. The ICP has developed four protocols related to multi-family housing energy efficiency renovations, the first being generic [62], and the other three pertaining to different types of multifamily housing projects [63]–[65]. The *Energy Performance Protocol, Project Development Specification* [62], was introduced in 2016 along with three protocols for apartment blocks that have since been revised in 2018 [63]–[65].

As the Investor Confidence Project suggests, energy efficiency renovations have not always delivered the promised financial return on investments in energy conservation measures. Research suggests that rigorous and standardized protocols are necessary to reduce the performance gap; however, protocols alone will not fully eliminate the gap. Resident behaviour and on-going commissioning and maintenance of HVAC systems are significant and ongoing factors which impact performance long after the energy-efficiency renovation has been completed [66]–[74]. Continuous resident engagement is a critical factor that currently falls outside of these protocols.

3.4 Voluntary guidelines, advocacy, and commentary

Outside of jurisdictions where mandatory regulations and policy instruments exist, a series of voluntary guidelines, advocacy and commentary are available to inform high-rise residential building renovation projects [7], [23], [75]–[84]. The significance and key contributions of selected documents from around the world are summarized in Table 1.

Table 1: Summary of selected voluntary guidelines and commentary on high-rise residential building renovation internationally.

Title	Year	Geographic Focus	Significance and Key Contribution
Overview of Retrofit Strategies - A Guide for Apartment Owners and Managers [85]	2002	United States	- earliest high-rise residential buildings renovation strategies uncovered in literature pertained to water conservation - little mention of energy conservation – except to note that conserving hot water would reduce water heating costs.
Energy Efficiency in the North American Existing Building Stock [77]	2007	United States	- established a framework for policy and program effectiveness indicators that are still useful today
Tower Renewal Guidelines for the Comprehensive Retrofit of Multi-Unit Residential Buildings in Cold Climates [23]	2008	Toronto, Canada	- first voluntary guideline specifically for high-rise residential building retrofits. - deals mostly with the technical and logistical challenges of comprehensive tower apartment building retrofits - also contains energy modelling and financial analysis methodologies - most significantly, it advanced the “building-as-a-system" approach to comprehensive renovation projects
Fire Safety in Purpose-Built Blocks of Flats [78]	2012	United Kingdom	- focuses on the common areas in blocks of flats that were brought within the scope of the mainstream fire safety legislation in 2006 - highlights that, if life safety is not always on the public radar, it is understandable why energy conservation remains an even more elusive concern
Boosting Building Renovation. An Overview of Good Practices [79]	2013	Europe	- high-level overview of international practices and clearly identifies the critical barriers to the achievement of the EU’s larger climate and energy goals by 2050 - acceleration of building renovation is not viewed optimistically, due low rates of renovation and long payback periods - highlights the relative scarcity of exemplary deep energy retrofit projects
Short-Term Test Results: Multifamily Home Energy Efficiency Retrofit [7]	2013	United States	- contrary to [43] above, this report concludes that deep energy retrofits (DERs) are feasible and economically viable - the large percentage reductions in energy consumption found in this work may be due to the fact that baseline buildings were extremely energy inefficient (minor interventions yielded significant improvements - this reinforces the need to conduct and maintain inventories of existing building stock so that energy conservation programs can better target the lowest hanging fruit that yield the highest savings to investment ratios.
Strategy for energy renovation of buildings. The route to energy-efficient buildings in tomorrow’s Denmark [80]	2014	Denmark	- holistic framework for energy renovations of the existing building stock - highlights the challenges of skills training needed to carry out energy conservation measures properly, but also the employment benefits associated long-term investments in building renovation
Demolition or Refurbishment of Social Housing? A review of the evidence [81]	2014	United Kingdom	- among the first references that conceives of social housing as a social and cultural resources, rather than a real estate commodity - strictly pecuniary parameters are contrasted with the social, cultural and environmental factors at play in decisions affecting the lifecycle of social housing
Estate Regeneration Sourcebook [82]	2015	United Kingdom	- provides tips for successful regeneration projects through considering case studies of renovation projects - focus is on fully engaging with the inhabitants from start to finish of the project so that they take ownership of the regeneration scheme rather than viewing it as an external imposition
Renovating Germany’s Building Stock - An Economic Appraisal from the Investor’s Perspective [83]	2015	Germany	- presents a comprehensive picture of building renovation potentials in Germany based on policy conditions and measures that do not currently exist - the German building stock is found to present limited opportunities for cost effective comprehensive renovations
Boosting Building Renovation: What Potential and Value for Europe? [84]	2016	Europe	- report considers highly integrated policies that support a gradually escalating rate of renovations and finds this is a highly feasibly approach
National Policy Recommendations for Sweden - Recommendations for local and national policy on retrofitting multi-occupancy, mixed tenure buildings [75]	2016	Sweden	- addresses a complex building typology - multi-occupancy, mixed tenure buildings - contains a long list of best practice examples for handling unusual situations (e.g., historical buildings) and offers a list of specific recommendations for local and national policies in Sweden
The Energy Improvement of the Existing Urban Building Stock: A Proposal for Action Arising from Best Practice Examples [76]	2016	United States	- presents recommendations for how to deal with the legal aspects of implementing and enforcing energy efficiency measures for existing building renovation - one of few papers in the literature which focus on implications for legal practitioners - conclusions provide helpful guidelines for the development of effective policies

3.5 Key findings related to policies, protocols and guidelines for building renovation

Overall, UK policies for energy renovations of existing buildings are advanced compared to those in Canada, mainly because deep renovations have been implemented earlier and on a broader scale, likely due to the relative age of the building stock. On average, the Canadian building stock is much younger, compared to the UK [26], [86]. With a younger building stock, the Canadian industry has historically viewed building renovations as optional, or as a poor investment with potential financial benefits not matching the required capital investment. A handful of Canadian jurisdictions have developed local regulations governing energy renovations of existing buildings, suggesting that attitudes in North American industry and policy are changing; however, currently these jurisdictions are primarily municipal and are still in the minority.

Several observations resulted from the overview of policies, protocols and guidelines presented in Sections 3.1 to 3.4, which are later used to inform the exploration of systemic issues associated with UK and Canadian high-rise residential building renovation.

- Under the present economic framework for investment returns, energy prices, carbon taxes, real estate values, household housing expenditures and healthcare costs, renovations of existing buildings are not feasible when only the energy savings are considered in the short term. Whole building life cycle economics that factor energy, water, environmental degradation, GHG emissions, health and wellbeing, cultural cohesion, and social stability need to be integrated within a suite of policy instruments (not just fiscal policies) that comprehensively support sustainable housing resources.
- For the proper integration and coordination of energy conservation measures, it is critical to adopt the *building-as-a-system* concept so issues related to IEQ, health and safety are not adversely compromised to the detriment of residents when renovations are undertaken.
- Protocols and guidelines for achieving energy performance targets are now available (Sections 3.3 and 3.4), but they continue to operate without or outside of a larger framework of protocols to ensure harmonized *building-as-a-system* performance and healthy housing resource stewardship. Standardization and harmonization of protocols is needed and comprehensive guidelines for practitioners should be crafted.
- Since only a fraction of the high-rise residential building stock across most developed nations is conducive to cost-effective comprehensive renovations, a situation where there is a flood of simultaneous energy efficiency renovations is unlikely to materialize. A positive aspect of this situation is that there is the possibility to develop the human, technical, and financial infrastructure needed to address renovation of the building stock in a systematic manner.
- There continues to be a range of unclear and/or inconsistent terminology (renovation, rehabilitation, refurbishment, retrofit, restoration, regeneration, renewal, etc.) that is used in policies protocols and guidelines. It would be helpful if more specific and precise terminology was developed to describe the programs and performance improvement measures for existing buildings. Further, while some flexibility in terms of renovation performance requirements is necessary for policies directed at existing buildings, using vague terms related to “feasibility” leaves opportunity for abuse of these provisions and limits the number of renovations which ultimately conform to policy standards. A more specific definition of what it means for a renovation to meet performance criteria in a manner that is “technically, functionally, and economically feasible” should be provided to reduce instances of non-compliance.

The coming decade will likely witness a critical turning point in the policies, protocols and guidelines for the renovation of existing buildings. Certainly, disastrous events like the Grenfell Tower tragedy call into question the status quo and the need to forge an improved trajectory. A more promising trajectory would provide the opportunity to transform the building renovation industry into a network of stakeholders that together provide life cycle stewardship over affordable housing resources. However, to realize this, policy instruments and process guidelines must be further refined and the intended outcome of the current study is to provide recommendations to facilitate this (Section 6).

4. Methodology for identifying systemic issues in high-rise residential building renovation

The overview of existing regulations, protocols, and guidelines governing the renovation of high-rise residential buildings identified a range of drivers, trends, and opportunities associated with building renovation, but assessment of their combined impact on building renovation requires further investigation. Both the UK and Canadian building stocks experience low levels of replacement and investment in renovation is a key driver for changes in the building stock. The UK's stock specifically is among the oldest and least energy efficient in Europe [87]. Due to these factors, and in light of the events which precipitated the Grenfell fire, the UK was chosen as the focus of this investigation. The Grenfell fire occurred on 14 June 2017, which resulted in the tragic loss of 72 lives. The fire spread and severity was the result of the improper use of insulating cladding that was applied to the high-rise building during an energy efficiency retrofit as a result of a product substitution. The Phase 1 Report of the Grenfell Tower Inquiry highlighted the importance of oversight and information sharing of building design and materials with fire services, but to also ensure application of materials is appropriate to the building design [88]. This extreme case provides the basis for a causal, exploration of systemic failures in tower block refurbishment [89], [90]. Through its focus on causal relationships, it provides a critical realistic perspective of systemic failures and potential improvements [89], [91]. It also elicits the underlying structure of current dynamics and interrelated trends beyond those identified in the previous section [92]

2To identify where and how changes to existing renovation policies, processes, and practices need to occur, we analyzed the UK high-rise residential building renovation process from a systems perspective using a qualitative system dynamics approach. Visual models were developed to provide an overview of the systemic context of tower refurbishment, highlight lock-ins (e.g. "we have always done it this way") or barriers and potential unintended consequences. The models were used as tools to structure discussions between industry stakeholders and help generate shared meaning amongst these stakeholder participants. In the following sub-sections, we describe the system dynamics approach, our participatory modelling process, and the resulting causal diagrams and their insights.

4.1 System dynamics modelling methods

System dynamics originated from control engineering and was developed by Jay Forrester [92]. It is an approach for policy analysis and design and addresses complex and dynamic problems in socio-technical, socio-material, socio-economic or socio-ecological areas. It is particularly useful to understand the complex system structures, i.e. the interaction of balancing and reinforcing feedback loops, that generate observed dynamics and trends [93]. The system dynamics process starts with the definition of an issue or problem followed by mapping and/or modelling of the issue. Traditionally, this involved formal simulation models, but in recent decades it has also become common to use qualitative models. Causal loop diagrams (CLDs) are used to represent important variables related to the issue under investigation together with the causal interrelationships between variables in feedback loops.

Our system dynamics process began with an assessment of *dynamic trends* in the UK, followed by the generation of what is called *dynamic hypotheses*. Dynamic hypotheses explain, in the form of CLDs, how these Dynamics and trends are consequences of causal relationships between key variables related to the theme [94] .Thus, they are well suited for theory-building-oriented and causally-oriented research [90]. Our CLD building process involved five stages: 1) a CLD modelling stage based on reports and literature; 2) validation interviews with stakeholders from the UK building industry; 3) a validation workshop with the project team and Canadian stakeholders; 4) more modelling and amendments; and 5) a final validation workshop with community-based UK stakeholders, as shown in Table 2 in the context of the *dynamic trends* assessment and generation of *dynamic hypotheses*, as described.

Table 2: System dynamics process

(A) *Dynamics and trends* in the UK	(B) Generation of *dynamic hypotheses* (CLD building and validating)					(C) Elicitation of *insights* from the CLD structure on how the causal relationships may influence desired outcomes	(D) Exploration of theme-specific *interventions*
	(1) CLD modelling based on reports and literature	(2) Validation interviews with UK stakeholders	(3) Validation workshop with project team and Canadian stakeholders	(4) Further modelling	(5) Final validation workshop with community-based UK stakeholders		

The process of CLD building and validation started with an investigation using the actions that precipitated the Grenfell fire as a basis for this analysis (Stage 1) [95]. We followed best practice on how to use a grounded theory approach [96] for building system dynamics models [97], [98]. This included the identification of concepts/variables from textual data, identification of interrelationships and a process of linking these variables in feedback loops in a system dynamics model. Thorneycroft generated draft CLDs from construction industry reports and investigative journalism by the BBC and Inside Housing magazine (e.g. [27], [99]). The CLDs were validated through five semi-structured interviews with industry experts (Stage 2). In these interviews, the CLDs were presented to interviewees who were asked whether the draft structures presented the issues as they see them, or whether the CLDs needed modifications. This process resulted in five individual CLDs, each based on an important theme that emerged from the analysis [95], as well as an overarching CLD that showed the interconnections between the five individual CLDs (developed after the workshops based on the final CLDs). Further details on the CLD development process in Stages 1 and 2 is available in [95].

To improve the CLDs and investigate to what extent they also fit a Canadian context, we discussed these CLDs in a 5.5-hour workshop among the six academic project team members from the University of Toronto and University College London and two further Canadian stakeholders (Stage 3). As the participants were distributed between Canada and the UK, we hosted this confirmatory/disconfirmatory workshop online. The facilitator and three project team members were online in London (UK) and Toronto (Canada) and two team members and the three external stakeholders (two from local government and one from a local social housing provider) were in a meeting room in Toronto. The facilitator explained the CLDs variable by variable and invited questions and comments. When participants suggested amendments, the facilitator drew these amendments, new variables and causal links into the CLDs live. Most structures were confirmed and changes primarily involved the addition of variable and links. Due to time constraints, the CLD that we already had the highest confidence in (Renovation) was not discussed in the workshop.

The CLDs were then further modified based on a review of policy and precedent literature and then simplified for comprehensibility (Stage 4). A further and final process of model validation then took place; this time with a group of five community-based UK stakeholders from a neighbourhood association, a resident-managed housing association, and the community group Just Space (Stage 5). This workshop took the same form as the workshop in Stage 3. Again, as this workshop was constrained to three hours, participants could only be shown four of the five CLDs; the CLD that we already had the highest confidence in (Renovation) was left out. Similar to the online workshop with the Canadian stakeholders, participants confirmed the structures shown in the CLDs and added in policy variables that were relevant for their communities. After the workshop, the CLDs were reviewed to identify recommendations that emerged from the modelled system and final updates were made to the diagrams.

The information added to the CLDs presented in the following subsections is highlighted in different colours to show what was added at each stage of development. Information added during Stages 1 and 2 is highlighted with blue arrows and black text; information added in Stage 3 is highlighted in red; information added in Stage 5 is highlighted in green; and information added after the workshops during the CLD analysis is highlighted in grey.

Once CLDs were built and validated, the system dynamics process proceeded with an elicitation of *insights* from the CLD structure on how the causal relationships may influence desired renovation outcomes. This involved an analysis of the CLD structure by the researchers, i.e. of balancing and reinforcing feedback mechanisms and critical variables that can serve as leverage points because they affect multiple feedback loops or can generate vicious and virtuous cycles. The process ended with an exploration of theme-specific *interventions*, i.e., an analysis of where regulations, protocols and guidelines affect this system structure.

5. Results of the system dynamics analysis

Although the initial development of the diagrams was completed through an investigation of the factors that enabled the Grenfell fire to occur, the validation process showed that the resulting CLDs are representative of the processes involved in the renovation of high-rise residential buildings in general, in both the UK and, to some extent, Canada as well (discussed for each CLD in the following sections). This is an important finding because it means that the Grenfell disaster was not necessarily a result of an abnormal renovation process but rather, the circumstances and context that lead to this event were generally representative of 'normal' renovation processes. The CLDs cover the five most prominent themes which emerged from the reviews and stakeholder consultation processes on renovation quality and regulatory compliance: renovation, product compliance, oversight, procurement, and supply chain fragmentation, which are summarized below in Sector Diagram in Figure 2.

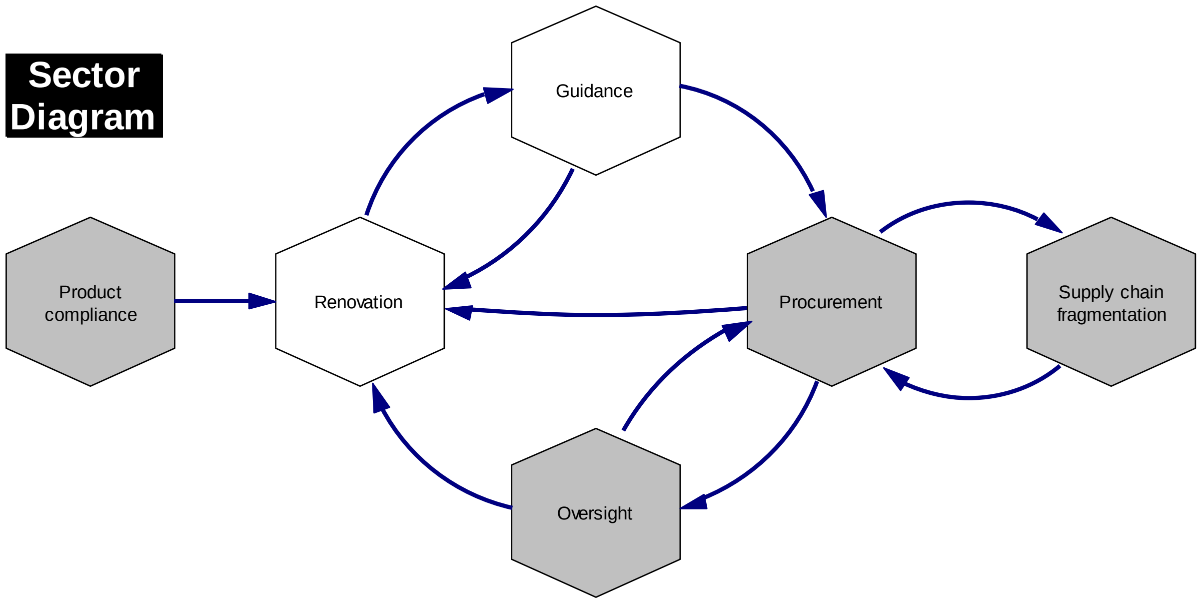

Figure 2: Sector diagram showing the most apparent relationships between the five emerging themes/CLDs. The four selected CLDs we discussed with participants at the last workshop are highlighted in grey.

CLDs contain feedback loops, which consist of variables and arrows that represent their causal interrelationships. Table 3 outlines symbols and representations used in the CLDs. Additionally, the core variable of "building quality and compliance with regulation" is highlighted by black shading and policy parameters are represented by circles. In the main text, variable names are italicized.

Table 3: Description of CLD symbols and representations.

Symbols/Representation	Interpretation
+	a change in the independent variable results in a change in the dependent variable in the same direction
-	a change in the independent variable results in a change in the dependent variable in the opposite direction
B	interrelationship forms a balancing feedback loop
R	interrelationship forms a reinforcing feedback loop
?	interrelationship is undetermined/unknown
< variable >	variable is a duplicate, which shows up at other places in the CLD

In the following sections, each of the five CLDs are described. In line with the system dynamics approach, descriptions begin with identifying UK *dynamics and trends* related to the CLD's theme. *Insights* on how the causal relationships influence desired outcomes and theme-specific *interventions* are explored. We then explore how the findings of the causal analysis may apply in the Canadian context. We start the analysis with a focus on the renovation theme, which represents the core of high-rise residential building renovation. Subsequently, the themes of product compliance, oversight, supply chain fragmentation, and procurement are analysed followed by the interactions between the five themes.

5.1 Renovation

In the UK, the process of undertaking energy efficient renovations is subject to the scale and type of renovation being undertaken. If they pertain to systems that are governed by the Building Regulations, such as major renovations that would trigger Part L or Part F through consequential improvements, or heating systems, then these would need to be done in accordance with the regulations for existing buildings (i.e. the B series) [100]. Recently, in May 2019, government funded schemes are required to use the *PAS 2035:2019 Retrofitting dwellings for improved energy efficiency* standard is required [101], [102], which provides guidance on installation best practice (though still refers to the Building Regulations).

Dynamics and trends in the UK: Despite an increasingly urgent need to act on climate change, the rate of occurrence of high-rise residential building renovation and the perceived value of renovation remains low. Furthermore, IEQ issues, in particular those related to overheating and indoor air quality (IAQ), are a common concern in buildings post-renovation.

Dynamic hypothesis: While building renovations can improve the energy performance and reduce the GHG emissions of buildings, a lack of focus on the 'building-as-a-system' concept causes overheating and poor IAQ and limits realized energy savings, providing little incentive for future renovation projects. Figure 3 shows a causal loop diagram of the renovation processes and inputs.

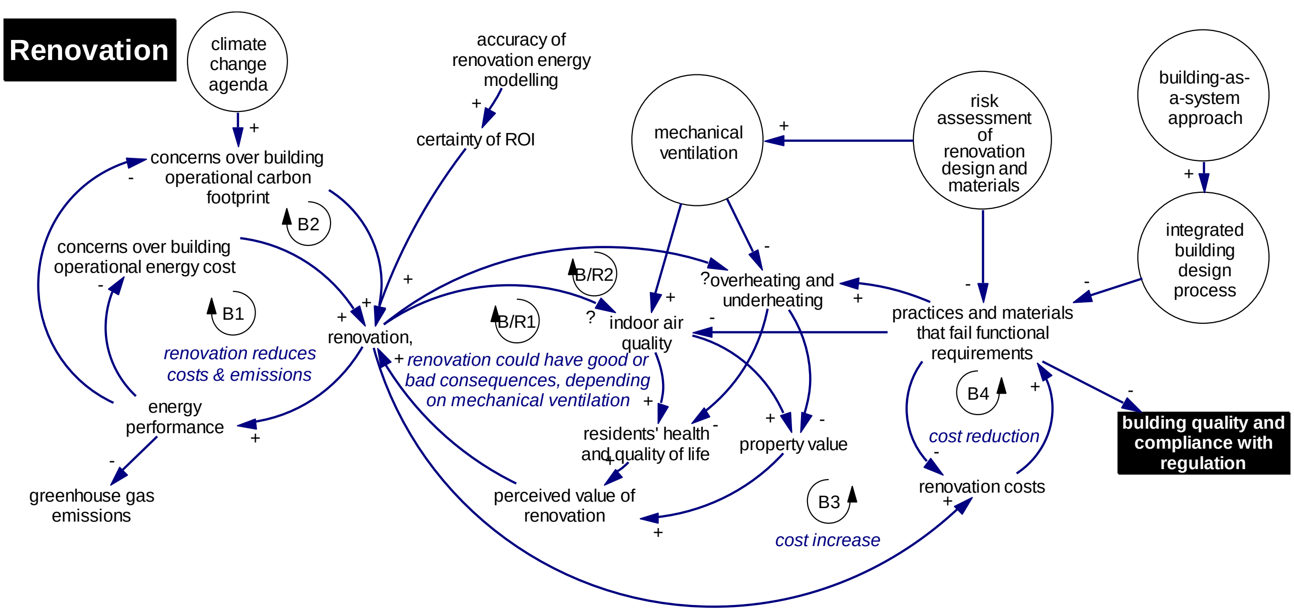

Figure 3: Causal loop diagram for the renovation theme.

As shown in Figure 3, the *climate change agenda* drives *concerns over the building operational carbon footprin*t. Through *renovations*, the building *energy performance* improves, *GHG emissions* are reduced, and *concerns about both the carbon footprint and operational energy costs* are reduced (B1 and B2). However, the extent to which *renovations* occur depends on the *certainty of the return of investment* of such measures and the *accuracy of renovation energy modelling*. The energy, *IAQ*, and *over-heating/under-heating* impacts of renovations are frequently uncertain, which can negatively affect *property value* and *residents' health and quality of life*, and reduce the *perceived value of renovation* (B/R1). When *mechanical ventilation* requirements are included in renovation policies and guidance, the *IAQ* situation is improved, which can help increase the *perceived value of renovation*. Value engineering[v] efforts to reduce the *renovation costs* encourage the use of *practices and materials that may fail functional requirements* (e.g., the cladding system used in the Grenfell Tower [27]), despite reducing *renovation costs* (B4). The use of inappropriate materials and practices may further aggravate the occurrence of *over- and under-heating* in renovated buildings (B3), reduce *building quality and compliance with regulation*. Implementing policies requiring proper *risk assessment of renovation design and materials* can reduce bad practices and associated negative IEQ or safety impacts from energy renovations, yet, while not shown here, they may also increase renovation cost in the short term.

Insights: The renovation of high-rise residential buildings can reduce energy use and GHG emissions and improve IEQ, but it needs to be done correctly. If done poorly, initial renovation momentum in the industry will slow because building quality is not significantly improved and the value of renovation is low. However, if renovation is done correctly, the perceived value of building renovations can be improved and a positive-feedback mechanism is created in which the perceived value of renovation increases and renovations become more widespread.

Interventions: An increased focus on healthy buildings and the building-as-a-system approach to renovations, in addition to the climate change agenda, is necessary to ensure improved building quality, regulatory compliance and reductions in GHG emissions. Introducing requirements for risk assessments of renovation design and execution, materials, and building operation may help to address performance gaps in renovations. Additionally, a focus on adding mechanical ventilation requirements to policy and guidelines for renovations should help to reduce unintended negative IAQ impacts resulting from energy renovations. Utilizing an integrated project delivery (IPD) process[vi] during all phases of building renovation may improve renovation results.

Canadian and Broader Applicability: Renovation in the Canadian context is driven by similar factors as those identified in the UK where high-rise residential building renovation is primarily driven by climate change and energy use concerns, with significant uncertainty surrounding projected energy savings, IAQ, and overheating impacts of individual renovations. The Canadian system similarly has issues with renovations' failure to meet functional requirements due to value engineering, however, the specific manifestations of functional issues may be different than in the UK context, given the differing code development pathways and integration (or lack thereof) of different codes and standards. Based on the similarity of the two contexts, the interventions proposed should also be applicable in the Canadian context. It is worth noting that, based on our overview of international protocols and guidelines, global renovation drivers predominately appear to be consistent with the UK and Canadian contexts which indicates that the interventions proposed in this section are likely to be applicable more broadly.

5.2 Product compliance

To date and up to the end of 2020, all products and materials for use in construction in the UK has been subject to the European Union by Regulation (EU) No 305/2011 [103], which sets out the laws and regulations for construction products and quality controls, to ensure harmonised standards across the economic zone. The Regulation covers a system of harmonised technical specifications, an agreed system of attestation of conformity for each product family, a framework of notified bodies, and the CE marking of products.

Dynamics and trends in the UK: There has been an increase in the number of innovative building materials and designs available for use. The number of large-scale tests and desk studies[vii] has grown since their introduction into product compliance testing, but so has the number of inadequate materials and methods approved and used.

Dynamic hypothesis: Flaws in the product testing regime legitimize the use of component assemblies that fail to meet functional requirements. Figure 4 shows a causal loop diagram of the product compliance processes and inputs.

Innovations in building materials and assemblies potentially create a number of *untested materials and designs* which may be brought into the market (see Figure 4). *Large-scale tests* generate new information regarding material and assembly performance and reduce the number of *untested designs* (B1). *Large-scale tests* also provide *data*, which is a basis for the *use of desk studies* of new combinations of materials used in building assemblies (B2). Both large-scale tests and desk studies are used to determine whether materials and assemblies are suitable for use in building renovations. Limited *practitioner liability*, poor *training and competence* have allowed for an unreasonable *degree of extrapolation* along with infrequent or insufficient *quality assurance* requirements for desk study protocols that have made the desk study testing configurations unrealistic. In some cases, this may have resulted in *inadequate materials and methods being approved*. As a result, *building quality* suffers and completed renovations may not comply with regulations. Lack of adequate *inspectors and staff* for inspection during and after building renovations and limited *enforcement* of regulations have aggravated the situation along with value engineering practices.

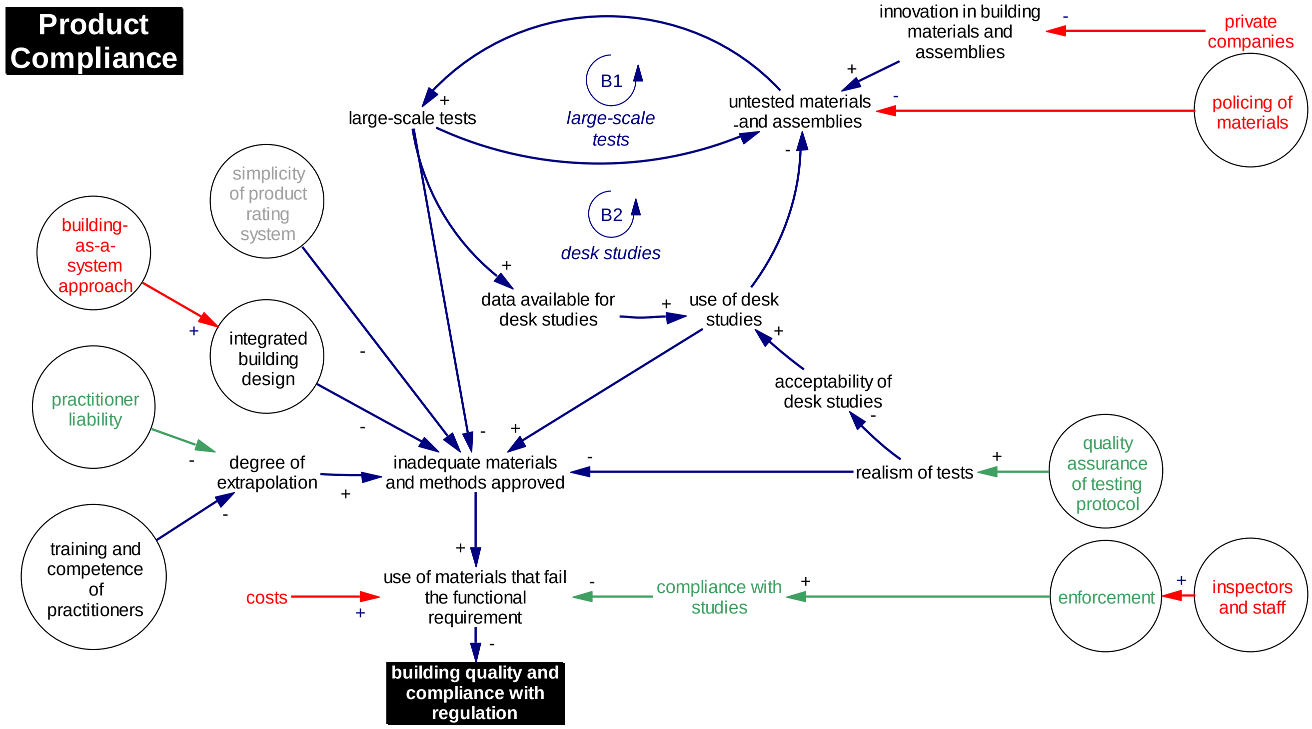

Figure 4: CLD for the product compliance theme.

Innovations in building materials and assemblies potentially create a number of *untested materials and designs* which may be brought into the market (see Figure 4). *Large-scale tests* generate new information regarding material and assembly performance and reduce the number of *untested designs* (B1). *Large-scale tests* also provide *data*, which is a basis for the *use of desk studies* to examine new combinations of materials used in building assemblies (B2). Both large-scale tests and desk studies are used to determine whether materials and assemblies are suitable for use in building renovations. Limited *practitioner liability*, poor *training and competence* have allowed for an unreasonable *degree of extrapolation* along with infrequent or insufficient *quality assurance* requirements for desk study protocols that have made the desk study testing configurations unrealistic. In some cases, this may have resulted in *inadequate materials and methods being approved*. As a result, *building quality* suffers and completed renovations may not comply with regulations. Lack of adequate *inspectors and staff* for inspection during and after building renovations and limited *enforcement* of regulations have aggravated the situation along with value engineering practices.

Insights: While desk studies are one potential way to test novel materials, they are prone to extrapolation and realism issues. Further, large-scale testing may be prone to realism issues, depending on the test procedures used. Faulty data obtained from unrealistic large-scale tests may aggravate extrapolation and realism issues in desk studies.

Interventions: Due to extrapolation and realism issues with desk studies, large-scale tests should be used instead. For both large-scale tests and desk studies, the liability of practitioners, along with training and competence requirements should be increased. Additional guidelines to improve the realism of large-scale tests should be introduced. Increasing the occurrence of inspections and enforcement of regulation during the renovation design and construction phases as well as implementing quality assurance requirements for testing protocols would also be beneficial. Additionally, a building-as-a-system approach (e.g. IPD) has the potential to reduce the likelihood of unforeseen, indirect impacts of product choice on building systems. More broadly, in light of the product substitution which occurred in the Grenfell Tower renovation, simplifying any product rating schemes to more clearly reflect the substantial meaning of the rating may reduce the number of inappropriate product substitutions that occur between the design and material procurement phases of a renovation project.

Canadian and Broader Applicability: While the use of desk studies (i.e. "engineering reviews") is a compliance pathway in Canadian building codes [104], the same widespread failure to meet functional requirements using materials and assemblies approved through desk studies observed in the UK has not yet been observed in the Canadian context. Similar risks may exist within the Canadian context, however, further investigation into the processes and industry culture surrounding product compliance specifically in the Canadian setting are needed to understand how approval pathways and associated risks differ. Globally, it is likely desk studies are used in many countries for material and assembly approval processes, however, it is unclear what other systemic similarities and differences exist without further investigation.

5.3 Oversight

The UK's building regulations requires that a construction project compliance with building regulations is independently assessed through building control bodies (BCB), who can be either local council building control departments or independent Approved Inspectors (AIs) [105]. The choice of using local council or an approved inspector is up to those carrying out the work. The role of the BCBs are to advise the client on the building regulations and design submission, check compliance, inspect the work on site, and issue a final certificate of compliance. Inspectors, regardless of whether they are public or privately employed have minimum qualifications requirements and are governed by the Competent person schemes [106].

Dynamics and trends in the UK: Since the semi-privatization of building control in 1985, the number of private AIs has grown from one organization to around 90. Today, these private AIs account for approximately 30% to 35% of the market share for building control services [79]. The number of formal enforcement[viii] cases has fallen by 75% over the last decade [27].

Dynamic hypothesis: The structure of the semi-privatized inspection and enforcement system incentivizes a reduction in the number and rigor of building inspections, gradually undermining the efficacy of the oversight regime over time. Figure 5 shows the oversight system central to building control.

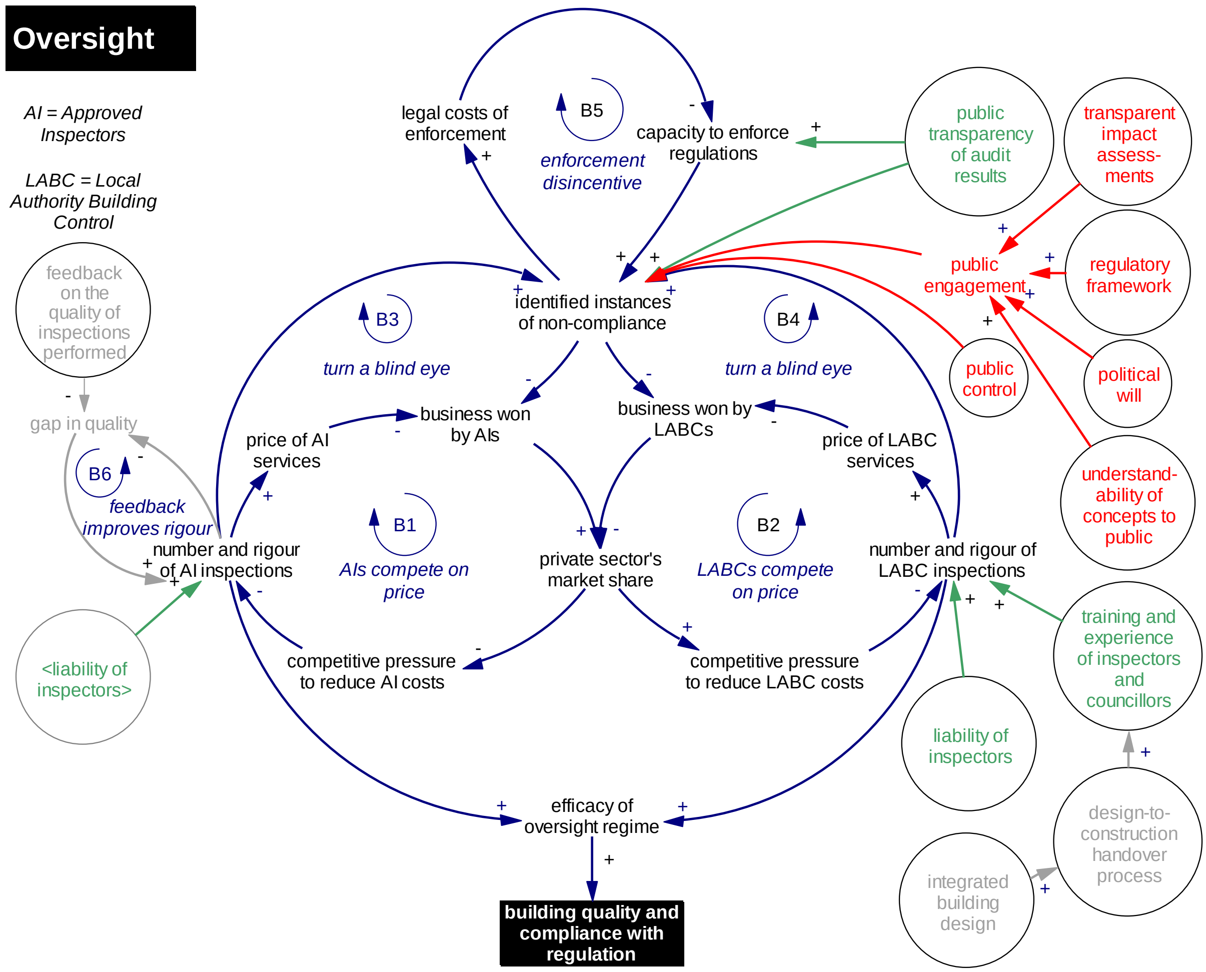

Figure 5: CLD for the Oversight theme.

Historically, local authority building control (LABC) inspectors carried out this task, but with the semi-privatization of inspection in 1985, clients could also choose private Approved Inspectors (AIs). This triggered an escalation mechanism between local authority and private inspectors for lower prices to win business (B1 and B2). The competitive pressure to reduce the LABC costs reduced both the *number and rigor of LABC inspections per renovation project*. The loss of rigor also reduced the *identified instances of non-compliance* on both the public and private side, which incentivizes both public and private inspectors to “turn a blind eye” to compliance issues to *win business* from clients (B3 and B4). B5 shows a further balancing mechanism by which *identified instances of non-compliance* cause *legal costs* and bring the system to the limits of its *capacity to enforce regulations*, limiting the identification of non-compliance instances.

Multiple policy levers affect this system. The rigour of inspections is influenced by degree of *liability of inspectors* on both the public and private sides, and the level of *training and experience of inspectors and councillors* on the public side. In addition, the use of *feedback on the quality of inspections* *performed* can trigger a valuable reduction in the *gap in quality* and *rigor of inspections* (B6), shown for AIs in Figure 5, which also applies to LABC inspectors in equal manner.

The identification of non-compliance instances depends on the *public transparency of audit results* and the degree of public *control* and *engagement.* In themselves, the public control and engagement aspects depend on the existence of *transparent impact assessments*, *regulatory frameworks*, *political will*, and the *understandability of concepts to the public*.

Insights: The oversight system has a sensitive race-to-the-bottom structure that easily causes a lack of rigor and enforcement. This lack of rigor and enforcement is influenced both by the system's capacity to deal with identified instances of non-compliance and the number and rigor of inspectors. Inspectors have a conflict of interest in their responsibility for identifying non-compliance due to the fact that they win more business if they turn a blind eye. Inspectors are often seen as consultants to help find ways of meeting regulatory guidance, rather than independent arbiters [95].

Interventions: AI contractual obligations likely reduces the efficacy of inspections. AIs are contracted by the project owner, which may present a conflict of interest at times (e.g. push to complete project faster/cheaper/etc. at the expense of being thorough). Changing the contracting flow to have private inspection agencies contracted through public entities, as opposed to the building owners, may reduce this conflict of interest and improve oversight, however this has the potential to introduce different motivations for AIs to do work quickly and cheaply (e.g. to be rehired by the municipality). Eliminating private inspection options (e.g. full municipalization or nationalization of the oversight regime) would eliminate contractual conflicts of interest and reduce the race-to-the-bottom structure observed in this theme and, as a result, would likely improve the rigor of oversight.

The lack of feedback on the quality of inspections performed and mistakes in oversight reduce inspector learning and inspection efficacy. It is necessary to close this feedback loop by providing more information to individual inspectors on issues that arose on their projects post-inspection or providing aggregated research on which issues are commonly missed during inspections (e.g. through the analysis of common insurance claims). This along with the associated potential impacts on building performance should improve the quality of oversight and also provide guidance on where further training of inspectors may be needed. One example of the use of aggregate insurance claims analysis for education of practitioners can be found in the *Claims Experience Workbook* compiled for Prodemnity Insurance Company and the Ontario Association of Architects [107]. Alternatively, mandatory no-blame reporting schemes may be used to incentivise a culture of learning from errors. Additionally, the long timeline associated with the discovery of building-systems defects makes enforcement difficult. When issues arise decades after project completion, investigating and identifying liable parties (including inspectors) is difficult, resource intensive, and rarely pursued by building owners. While inspectors are required to gain on-site experience through a mandatory apprenticeship program in the UK, this is frequently accelerated through book training, which often deals with idealized situations and should not be a substitute for on-site experience. The ability to reduce on-site training requirements through accelerated book training routes should be limited.

Lack of continuity of inspection personnel and companies throughout the design and execution of a renovation project is also a prevalent issue in providing effective oversight. Project inspection is often handled by different companies during the design and execution stages. Renovations would benefit from greater consistency throughout the entire project lifecycle: retaining people who understand what was designed, what was specified and what was built would facilitate the identification of shortcomings in the project by inspectors. This can be accomplished through the adoption of regulations that incentivize an integrated design process.

Canadian and Broader Applicability: Unlike the UK, Canada's building inspection process is a fully public. As such, the challenges associated with semi-privatization and contracting flows as outlined above do not exist in the Canadian context. While statistics on formal enforcement case trends within Canada are not available, the general sentiment of Canadian workshop participants was that Canadian building inspectors are viewed as independent arbiters (as opposed to consultants to assist with finding pathways to compliance as observed in the UK perspective [95]). Globally, it is difficult to gauge how broadly applicable the UK findings may be, as implementations of semi- or fully-privatized building control will differ between countries and regions in ways that greatly impact the quality of oversight in these jurisdictions. However, there is a trend in European countries towards greater privatization of building control [108], which indicates that investigation of how differing private or semi-private building control schemes impact oversight quality would be beneficial.

5.4 Fragmentation

The challenge the UK construction industry faces in terms of building renovation work is related to the complex nature of construction development and management. Fragmentation challenges include everything from communication, client and design teams, materials and supply chains, and focus on risks and profits [109]. The UK's Industrial Strategy for Construction 2025 cited the high degree of fragmentation in the UK's construction industry and impacts collaboration and innovation [55]. In the wake of the Grenfell Tower fire in 2017, an independent review of the building regulations 'Building a Safer Future' was undertaken that provided more than 50 recommendations for how to improve the application and regulatory systems of building control. These included steps to simplify and unify the building control legislation, a new competence framework of individuals working in building control, a code of conduct, and a new regulator [27].

Dynamics and trends in the UK: The number of building materials used in construction and the number and complexity of building components have increased. The number of subcontracting tiers on any given project has increased and the number of staff directly employed by the tier-one contractor on a given site has decreased.

Dynamic hypothesis: Increasing innovation and specialization has created an incentive to transfer risk down the supply chain, leading to an ever-increasing number of subcontracting tiers. Figure 6 shows the supply chain fragmentation CLD.

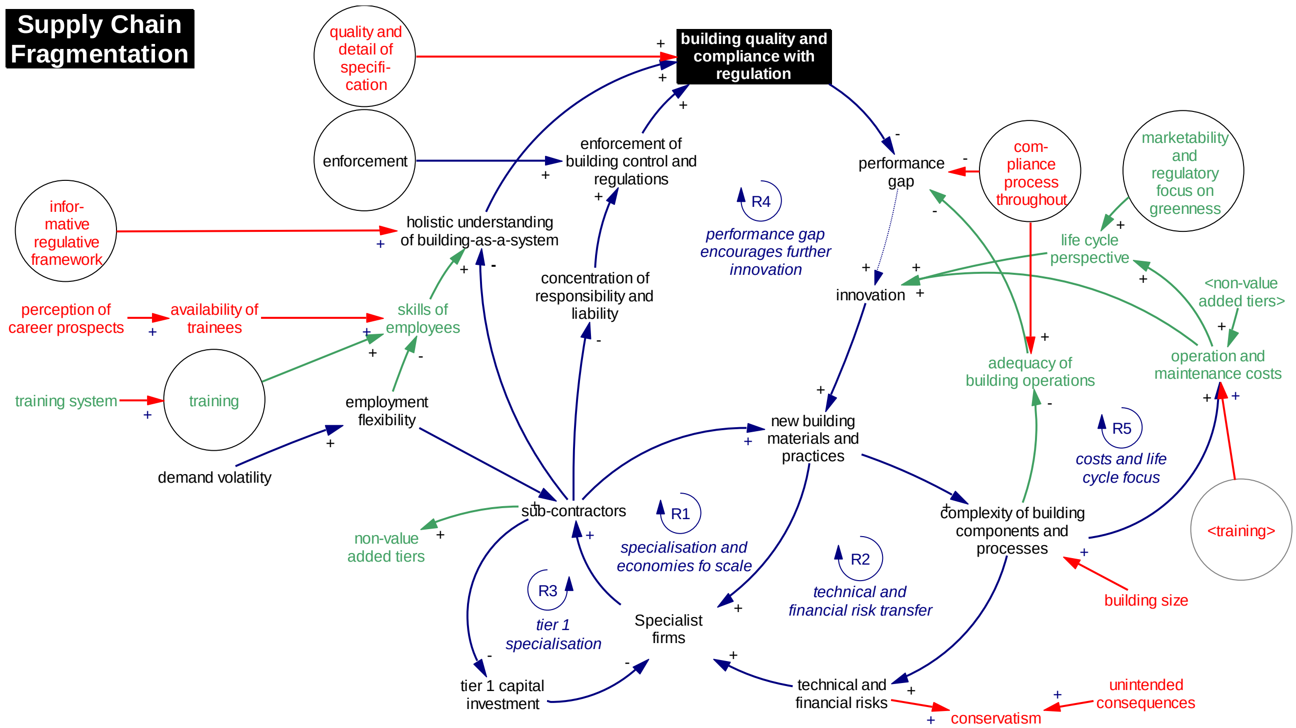

Figure 6: CLD for the Fragmentation theme.

Often, dozens of sub-contractors are involved in a renovation project. As the application of *new building materials and practices* increases (see center of Figure 6), there is an even greater reliance on *specialist firms* and *sub-contracting* (R1). New materials and practices imply a higher *technical and financial risk*, which may lead to *conservatism* and an even higher reliance on *specialist firms* and *sub-contracting* (R2). Consequently, tier-one contractors reduce their *capital investment*, increasing the reliance on *sub-contracting* (R3). This distributes the *responsibility and liability* across multiple parties and limits the ability of regulatory bodies to *enforce building controls and regulations*. It also reduces the *holistic understanding of building-as-a-system*, resulting in an overall reduction in *building quality and compliance with regulations*. As a consequence, the *gap* between estimated and actual building performance is not reduced, which may drive further *innovation* and use of *new building materials and practices* (R4). In turn, the use of *new building materials and practices* may increase *complexity*, which is likely to increase *operation and maintenance costs*, shifting focus towards a building *life cycle perspective* and further increasing *innovation* (R5).

The policy levers affecting the operational aspects of the system include *training*; the *compliance process throughout* the building design; construction and operation phases; and the *marketability and regulatory focus on 'greenness'* in the building industry. *Building quality* is enhanced when construction workers are highly-skilled. *Skills* are likely to be higher when workers are motivated by stable *career prospects* and when sufficient employee *training* is provided. An *informative regulatory framework* improves the *holistic understanding of the building-as-as-system* mindset and *enforcement* of the quality and detail of specifications enhance *building quality*.

Insights: There exists a vicious cycle of increased reliance on specialist firms and sub-contracting. Unless counteracted by requirements and regulation, it is likely to reduce the holistic understanding of a building-as-a-system, quality and compliance.

Interventions: As in the oversight case, a lack of experience cannot be met solely through book training and on-site training plays a necessary role in developing sufficient worker competence. One option would be a mandatory apprenticeship for inspectors, contractors and sub-contractors and others which is not replaceable by school-based book training. Post-training evaluation of worker competence must also occur and revisions to the training system must be considered regularly to meet changing industry requirements.

Frequently, nobody fully 'dissects' what went wrong at the design and construction stage when defects are realized – or at least not openly and publicly. Similar to how greater feedback would improve the oversight system (section 5.3), it can also help reduce quality and compliance problems resulting from supply chain fragmentation. Due to liability concerns, it may be difficult to facilitate open discussion of individual project shortcomings, however, an aggregate review of common issues or the implementation of mandatory no-blame reporting schemes may resolve some of these concerns (see section 6.4).

Implementing cross-training programs, in which pathways are established for trades to learn from one another (e.g. as discussed in [19]), can provide other opportunities to further develop contractor's holistic understanding of the building-as-a-system concept and understanding of how, individually, their work impacts renovation quality. Finally, ensuring construction specifications are of high quality and sufficient detail and tighter enforcement of existing building controls and regulations are key.

Canadian and Broader Applicability: The same drivers explored in the UK context are also at play within the Canadian supply chain. Increased building system complexity has driven an increase in the number of sub-contractors involved in projects and, generally, reduced individual contractors' and trades' holistic understanding of the building-as-a-system. Internationally, the same trend can be seen as renovation project complexities increase. As such, the interventions proposed are generally broadly applicable, however, jurisdiction-specific factors, such as any pre-existing regulations guiding sub-contractor integration must be considered.

5.5 Procurement

In the UK, a range of approaches are used for procurement of buildings and building works, including traditional contracting, single- or two-stage design and build, management contracting, and private finance initiative (PFI), with numerous variations of these. The choice of the procurement route can have significant impacts on those involved in the building works, the roles and responsibilities over the procurement process. However, regardless of the procurement of the works, they are still subject to the building regulations.

Dynamics and trends in the UK: Both construction quality and profitability in the construction industry has been low for decades [95].

Dynamic hypothesis: Limited budgets and the housing crisis together with an adversarial procurement process structure undermine the incentive for contractors to compete based on quality. Instead, contractors compete on the basis of cost by compromising materials, time, and labour. Figure 7 shows the CLD for the Procurement theme.

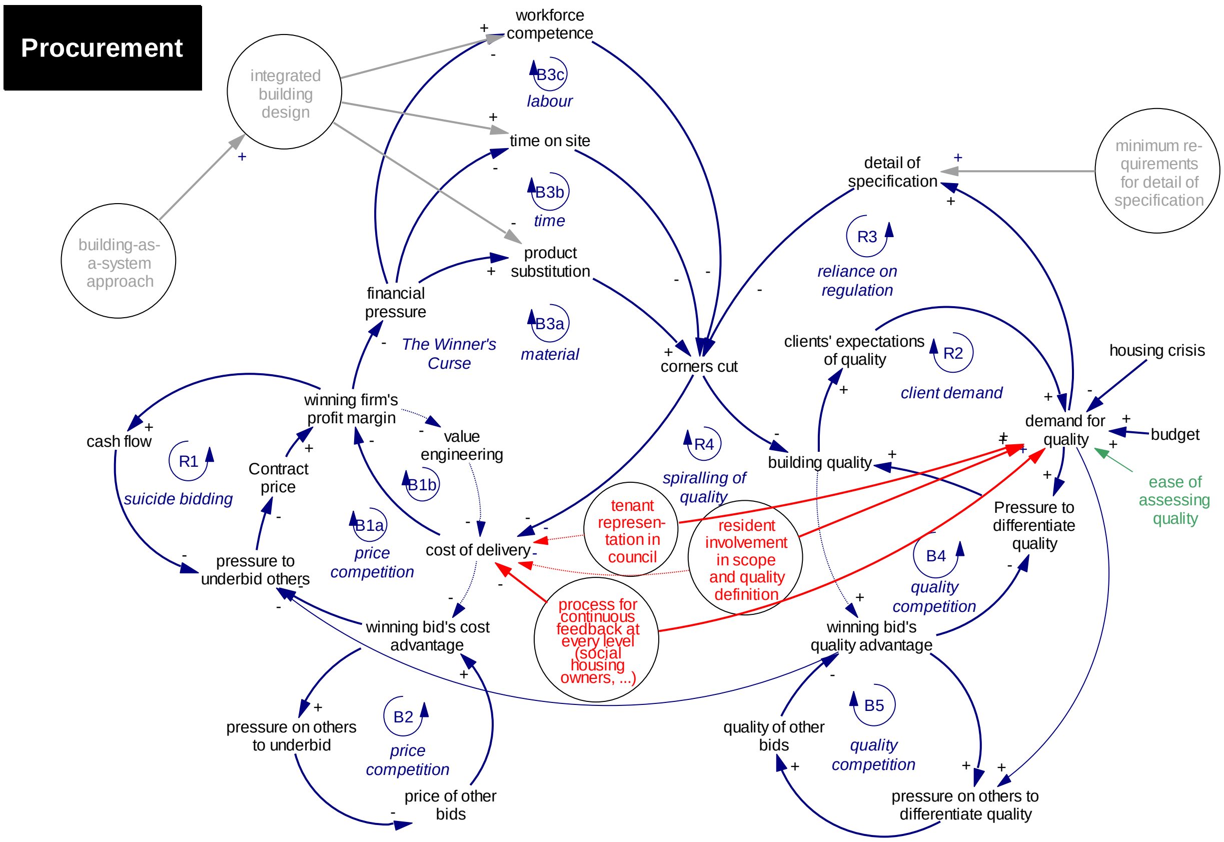

Figure 7: CLD for the Procurement theme.

Firms gain a competitive advantage via lower *costs of delivery* or higher *building quality* than their counterparts. A higher *winning bid's cost advantage* creates *pressure to underbid others* and companies counteract this pressure by lowering the *contract price*, which they make possible through *value engineering* (B1a and B1b). This creates *pressure on others* to do the same (B2), creating an escalation mechanism between B1 and B2. The resulting small *profit margin* means that companies lack *cash flow*, which they try to counterbalance again by *underbidding others* (R1). This *financial pressure* leads to *corner cutting* via material, time, and labour, which all reduce the *cost of delivery* (B3a-c). However, this *corner cutting* also reduces *building quality*. As a result, the *winning bid's quality advantage* is reduced, which may theoretically add *pressure to differentiate via quality* and to increase *building quality* again (B4). However, this is not necessarily needed because other bids also adapt to the existing level of quality (B5) and experiencing low building quality over time strengthens clients' low expectations and *demand for quality* (R2). *Demand for quality* affects the *details of the specifications* and, if low, allows for *corner cutting* because details are not specified (R3). Thus, the entire structure describes a reinforcing downward spiral of quality (R4).

Policy levers include *minimum requirements for the detail of specifications* and the previously raised importance of using integrated design processes and a building-as-a-system approach. Workshop participants put special emphasis on the usefulness of residents through their *representation in building management and oversight*, *involvement in scope and quality definitions* and a *process for continuous feedback at every level*.

Insights: Residents can be a lever for triggering demand for quality. Resident involvement in the planning and design processes has the potential to reduce costs, however, the inverse effect on cost may also occur. Cost is commonly the primary or sole metric used to compare bids, which increases the use of value engineering and reduces renovation quality.

Interventions: Restrictions to product substitutions, minimum workforce competency requirements, and improved oversight efficacy limit the ability to cut corners. Higher minimum requirements for the detail included in design specifications should be used to counteract construction and design phase fragmentation as well as the common practice of specifying detail design 'by others'. Particularly, requirements to include detailed interface design specifications are needed as interfaces are a common location of design and construction defects. Adopting a building-as-a-system approach and using an integrated design process can also reduce fragmentation of construction and design work.

Increased resident involvement in the planning and design processed may or may not improve the process. Residents are motivated to improve the buildings and they will generally work towards achieving this without rental increases, i.e. without increasing renovation or operation costs. Other research has found that resident involvement may also cause process delays [110]. Additionally, fears of rental cost increases amongst residents in certain regions and building types, along with misunderstanding of building systems, energy, and IEQ benefits may reduce the benefits of their involvement in the renovation process. Consideration of the political environment in which the renovation is taking place, along with the design and implementation of a situationally-appropriate resident involvement process will help to bolster the benefits associated with resident involvement.

Consideration of cost as the sole or primary basis for bid comparison reduces overall renovation quality. Quality of bids' proposed renovation methods should be part of the basis for comparison, however, building owners are likely to have difficulty assessing and comparing the quality of different bids. Providing education and guidance to building owners on how to assess bid quality, or recommending the use of an independent consultant to help compare bids, may help to improve renovation quality.

Canadian and Broader Applicability: The renovation procurement process within the Canadian context is primarily driven by cost and renovation quality and appears to be hindered by the same factors observed in the UK context (e.g. value engineering, difficulties interpreting non-financial benefits between bids). While the extent of these issues may vary somewhat in other jurisdictions due to cultural differences in industry (e.g. a greater awareness of the impact of renovation quality) or differing regulations (e.g. higher minimum standards for renovated building performance), a myopic fixation on cost is likely to reduce realized renovation quality in most jurisdictions. Based on this, the interventions suggested in the previous section are likely to be broadly applicable to high-rise residential renovation systems global.

5.6 Between-sector interactions

The between-sector interactions CLD explores the manner in which aspects of the five themes (renovation, product compliance, oversight, supply chain fragmentation, and procurement) interact to create additional reinforcing or balancing effects.

Dynamics and trends in the UK: Large-scale sub-contracting and corner cutting are established practices. There is a chronic under-capacity to enforce regulations.

Dynamic hypothesis: The mechanisms discussed above for the five themes interact to fuel a normalization process of practices and materials that fail functional requirements. Figure 8 shows the interaction dynamics between the five themes.

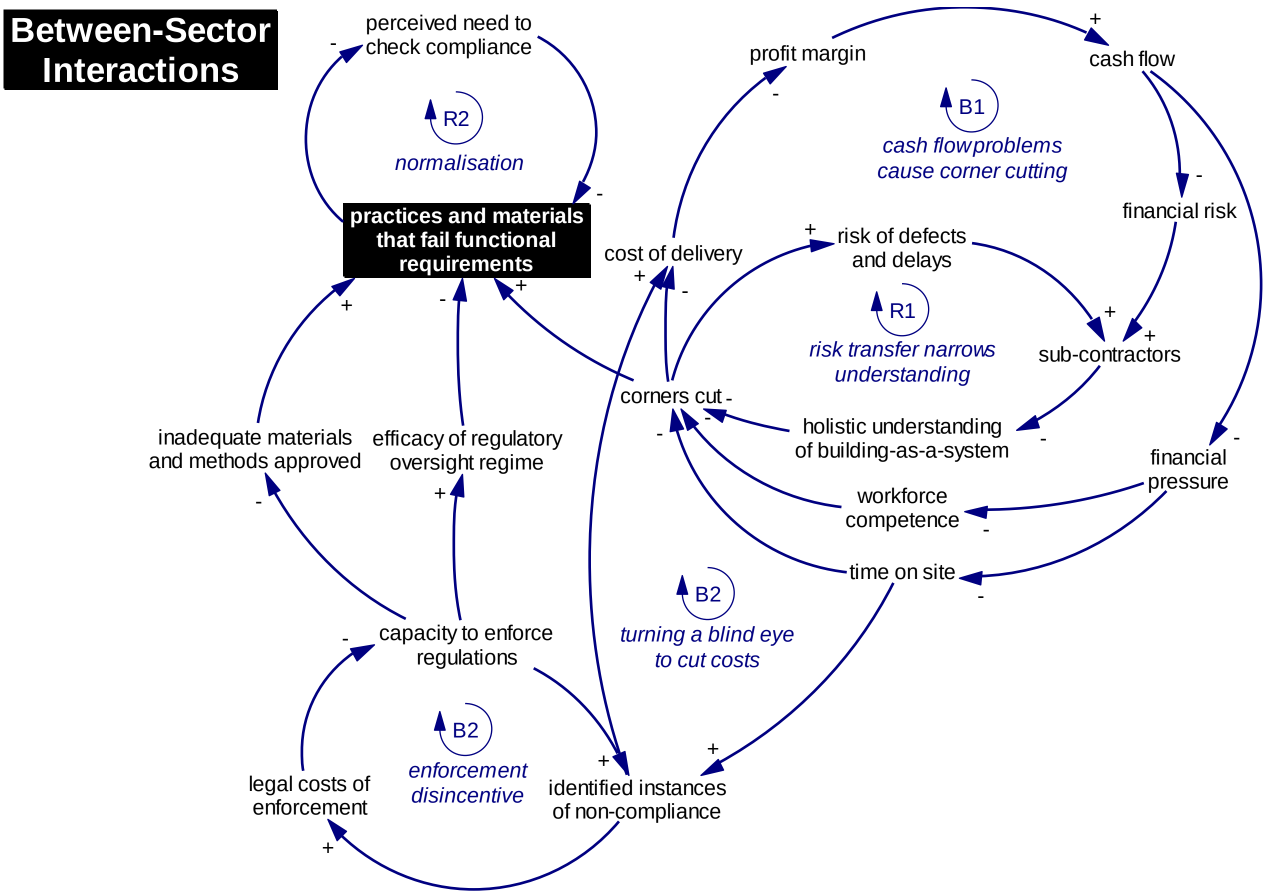

Figure 8: CLD of the between-sector interactions.

Procurement's focus on cost-cutting (see procurement section 5.5) supports the use of *sub-contractors* (see fragmentation section 5.4), which further encourages *cutting corners* (B1 and R1). Reduced *time on site* of each individual contractor through an accelerated construction process also reduces the *identified instances of non-compliance*, which affects *inadequate materials and methods approved* (see product compliance section 5.2) and the *efficacy of the regulatory oversight regime* (see oversight section 5.3). Using *practices and materials that fail functional requirements* becomes reinforced in a normalization cycle that also affects the *perceived need to check compliance* (R2).

Insights: Leverage points exist in the system at the interaction of feedback loops that policy levers in the form of regulatory actions and requirements need to focus on. Regulatory actions should reduce corner cutting, improve the holistic understanding of the building-as-as-system concept, improve the identification of instances of non-compliances, improve the capacity of the regulatory system to enforce requirements, and reduce opportunities for the approval of inappropriate materials and design methods.

Interventions: Leverage points should be managed through incentivizing integrated design processes, regulatory enforcement that ensures that residential towers are built as they were approved and by putting in place a monitoring system that identifies instances of non-compliance for all involved parties. This ensures a level playing field for stakeholders, not disadvantaging those who opt for best practices and high building quality.

Canadian and Broader Applicability: The between-sector interactions identified in the CLD are high-level and broadly applicable to most jurisdictions. The relative magnitude of influence of between-sector interactions, however, will depend on individual jurisdictions' sector dynamics, as discussed in previous sections. Therefore, jurisdictional contexts must be considered to identify which interventions are likely to be most effective in individual jurisdictions.

5.7 Overview of findings from the system dynamics analysis

Findings from the system dynamics workshops confirm the findings of the Hackitt Review of Building Regulations, which was undertaken in light of the Grenfell Tower fire [27]. The Hackitt Review found that there are currently "significant issues in the production, maintenance and handover of building information by those responsible for the design, construction and renovation of the building to the duty-holder in the occupation phase" [27]. The review identified several key issues underpinning the system failure in the UK, including: ignorance or misinterpretation of regulations and guidance; indifference regarding the delivery of quality residential buildings (with the primary motivation in the industry being to complete work as quickly and cheaply as possible, at times at the expense of safety); lack of clarity on roles and responsibilities; and inadequate regulatory oversight and enforcement tools.

In addition, the systems dynamics analysis identified concerns with regard to lack of practitioner experience requirements and feedback mechanisms across all aspects of the building renovation process; a negative influence of the existing semi-private inspection structure on the rigor of inspections; a lack of quality assurance and practitioner liability and competence in materials and methods testing, particularly in the case of desk studies; inadequate transparency and public engagement/control of inspection results; and a lack of perceived value of building renovations due to the lack of quality in completed projects, which limits the rate of occurrence of renovation projects.

The key avenues of intervention identified through the CLD analysis presented in Section 5 are summarized in Table 4.

Table 4: Key avenues of intervention identified through the system dynamics approach.

	Intervention	Relevant CLDs
1	Incentivize the use of the building-as-a-system approach.	Renovation, Product Compliance, Fragmentation, Between-Sector Interactions
2	Introduce requirements for risk assessment for design, construction, materials selection/substitution, and building operation phases of projects to reduce performance gaps.	Renovation, Product Compliance, Fragmentation,
3	Implement feedback mechanisms that allow practitioners to learn from the identified renovation quality resulting from their work.	Product Compliance, Oversight, Fragmentation
4	Introduce guidance to help building owners compare renovation bids based on quality as well as cost.	Procurement
5	Introduce requirements for the addition of mechanical ventilation systems in renovated buildings.	Renovation
6	Increase the required level of detail in construction specifications, particularly for interface design.	Fragmentation
7	Increase building resident involvement in IPD planning, design, and decision-making processes.	Procurement
8	Increase the liability of practitioners across the building renovation industry, combined with mandatory no-blame reporting schemes to incentivise a culture of learning from errors. (This can be accomplished through schemes which have limited timeframes for no-blame reporting and issue identification, after which the responsible party will be held liable.)	Product Compliance, Oversight, Fragmentation
9	Increase experience and training requirements for practitioners across the building renovation industry.	Product Compliance, Oversight, Fragmentation
10	Increase requirements surrounding test protocols to improve the realism of large-scale material and design tests.	Product Compliance
11	Simplify product rating systems to more clearly reflect the substantial meaning of the rating.	Product Compliance
12	Implement quality assurance requirements for material and method testing and desk study protocols.	Product Compliance
13	Change the contracting flow for private inspection agencies to reduce conflicts of interest and improve inspection rigor.	Oversight
14	Reduce or eliminate the use of desk studies for material and design testing for the purpose of approvals.	Product Compliance

6. Conclusions and Recommendations

Using the findings from the overview of UK and Canadian building renovation regulations, protocols, and guidelines (Section 3.5) and the modes of intervention identified in the system dynamics analysis (Table 4), five key conclusions and recommendations for improving the regulatory framework of high-rise residential building renovations were developed. These recommendations do not address all of the identified policy gaps or modes of intervention identified in the system dynamics approach, instead, they are targeted to primarily address interventions and policy gaps which are likely to be broadly applicable across multiple jurisdictions. These recommendations include the development of mandatory standards for IEQ post-renovation; incentivization of integrated project delivery (IPD) processes; improvements to practitioner education and on-site training; implementation of feedback mechanisms to inform practitioners on successes and failures; and the simplification of material and design certifications. While these recommendations were developed through an example of building renovation in the UK context, many are applicable more broadly in other building renovation contexts. In the subsections that follow, each recommendation is outlined in more detail.

6.1 Develop mandatory standards for indoor environmental quality post-renovation

Addresses: Interventions 1, 2, 4, and 5 from Table 4; Minimum IEQ standards policy gap identified in Section 3

Energy renovations may create, aggravate or fail to improve IEQ and safety issues within high-rise residential buildings [8], [13]–[17], which often pose health, productivity and quality of life concerns for residents. As the number of energy renovations in high-rise residential buildings continues to grow, it is important to ensure that minimum IEQ standards are met, post-renovation. While the global focus on climate change has enabled significant progress in energy efficiency regulations in both newly constructed buildings and building renovations, similar requirements for IEQ in these buildings are lacking, based on our overview of building renovation policies in the UK and Canada. The 2018 amendment to the EU's EPBD directive added terminology surrounding the need to include IEQ considerations in building renovations, however, the directive does not specify how this should be achieved or what metrics member states should use to assess IEQ performance [49]. Furthermore, the system dynamics approach identified a lack of focus on the building-as-a-system approach and the influence of design decisions on indoor environmental quality considerations due to a singular focus on energy performance and renovation costs. Developing IEQ regulations can improve building performance and resident health and safety, in a diverse industry where renovation decision makers have competing priorities (e.g. cost, timelines, etc.) that can eclipse IEQ concerns. Additionally, developing best-practice guidelines for practitioners to help them achieve desired IEQ performance and guidance for building owners which describes how to compare the IEQ performance of various renovation bids would be beneficial to ensure regulatory requirements are met and/or exceeded.

6.2 Incentivize integrated renovation design and execution

Addresses: Interventions 1, 2, 6, and 7 from Table 4; Need for building-as-a-system approach identified in Section 3

Case studies of renovations completed using IPD processes have shown great promise for improving building performance (e.g., [110]–[113]); however upfront costs (design, procurement, construction) are typically higher than using traditional renovation processes, even if lifecycle costs are reduced through this process. Using IPD can address many of the process issues identified in both the policy overview and system dynamics approach completed in this project, including reducing the gap between predicted (modelled) energy use reductions and those actualized post renovation; harmonization of stakeholder goals (energy use, operational cost, IEQ); improving continuity throughout the design, product specification, construction and inspection processes; better integration of work across sub-contractor groups; and more straightforward risk and liability allocation. As IPD is typically associated with higher upfront costs, it needs to be incentivized through either regulatory requirements or education of renovation decision makers on the potential for operational cost reductions. One potential incentivization method could be a requirement for major changes in project staff between the design and construction phases to be subject to handover processes which are so onerous that they are only employed in extenuating circumstances.

6.3 Improve educational and on-site training requirements for workers

Addresses: Intervention 9 from Table 4

As innovation in the buildings industry continues to increase the complexity of high-rise residential buildings and spur the development of new materials and designs, renovation processes require a more diverse range of designers, specialists, trades, and workers. In general, the number of sub-contractors involved in a renovation process has also increased, with each sub-contractor being responsible for a smaller portion of the total project work. Additionally, an aging workforce within parts of the industry and a boom in building construction and renovation projects has created a skills gap within the sector as the proportion of inexperienced workers in the industry grows. Classroom education ("book-learning") is a popular method for getting workers up to speed within the industry, however, on-site learning through apprenticeships, for example, is also key to ensure knowledge transfer and to build competence in inexperienced workers. While some trades (e.g. electricians, pipe fitters) already have long mandatory apprenticeship periods, expanding this requirement to other areas within the sector may improve the quality of building renovations. Also, establishing pathways for trades to learn from one another and develop cross-skills in related tasks (e.g. Ecoartisan program in France) [19], can provide other hands-on educational opportunities. Furthermore, incorporating general principles of high-performance building design into training curricula can provide all trades with broader perspective on how their work must interface with others in order to achieve energy and IEQ performance targets [20].

6.4 Regulate and facilitate information sharing on renovation design, execution, and oversight shortcomings

Addresses: Intervention 3 from Table 4

A lack of feedback to inspectors on their quality of work was identified in the system dynamics approach as a shortcoming which reduced opportunities to improve the quality of oversight for building renovations. This lack of feedback is likely prevalent across professionals in the industry due to the long timelines associated with the discovery of building defects, lack of continuity between the design, construction and operations phases of a building's lifecycle, and limited reporting requirements on post-completion renovation performance of high-rise residential buildings. Regulating what information needs to be collected on building performance pre- and post-renovation, including both energy and IEQ metrics, is the groundwork for developing a system to close the feedback loop with practitioners. Where liability concerns exist, this is likely best accomplished through the implementation of a mandatory, no-blame reporting scheme to collect and share information which may otherwise not be reported. This information can then be analyzed in aggregate and integrated into continuing education requirements by professional organizations to build competencies within their respective industries. The Ontario Association of Architects and Prodemnity Insurance Company has executed a review of professional liability claims with an aim to educate their members [107] which can be a reference for developing a similar feedback mechanism for inspectors and designers.

6.5 Simplify and clarify product and design certifications and standards

Addresses: Intervention 11 from Table 4

Existing product certifications are often confusing to less experienced practitioners and pose concern during the material procurement phase, where an inappropriate material may be inadvertently substituted for what was specified in the design due to perceived equivalency. Product certifications often use alphanumeric codes to classify materials and different classifications of materials may have similar codes. Additionally, due to the length and complexity of certification documents, they may not be fully read or comprehended by practitioners prior to substituting materials. Improving classification mechanisms to more directly indicate the substantial meaning of the classification along with IPD and improved practitioner education may reduce the number of inappropriate material or designs substituted during the procurement process.

7. Summary and Future Work

This paper presents a method to identify barriers to achieving high-performing renovations in high-rise residential buildings using qualitative system dynamics. With its focus on the systems feedback structure via the system dynamics approach, it provided an innovative and visual representation of systemic failure but also of potential improvement. The current state of key building renovation policies, protocols, and guidelines was reviewed, followed by an example of high-rise residential building renovation in the UK. Causal loop diagrams (CLDs) were developed for five key themes (renovation, product compliance, oversight, supply chain fragmentation, and procurement) through an analysis of literature and reports as well as interviews and workshops with stakeholders in Canada and the UK. Based on the findings of the policy review and system dynamics modelling, several recommendations to improve policy surrounding high-rise residential building renovations in the UK and abroad and next steps to extend the work were identified (see Section 6).

Several areas for further investigation became evident during this research both from a system dynamics and technical engineering perspective. Application of the system dynamics approaches in the following areas would help to confirm the recommendations made in the previous section and to identify further interventions available to improve renovation quality:

- Additional investigation into the existing renovation design and construction process in the UK, Canada, and other countries would help identify interventions which can be used to improve renovation performance. Specifically, this should include detailed investigation of multi-disciplinary building systems integration processes and hand-off processes between design and construction teams;

- Further investigation of approaches to education, training, and the provision of feedback on quality of work in building renovation in different countries and/or industries would provide valuable information on which approaches are most effective in improving renovation quality;
- Investigation of the renovation process in other jurisdictions would generate information on how to improve the process in these jurisdictions as well as provide further examples for how the process in the UK can be improved.

In addition to the above suggested future system dynamics work, a systematic, comprehensive review of the literature regarding IEQ in buildings, including IEQ impacts on health and productivity and best-practices in concurrent design for IEQ and energy efficiency, should be undertaken to identify best practices for integration into regulations. This review should be summarized in an easily digestible form for use by policy makers. Through this review, key indicators of renovation performance may also be identified, which can be used to develop feedback mechanisms on work quality for practitioners by their respective organizations.

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[i] The definition of the term “high-rise residential building” varies between protocols and guidelines and between geographic regions. In the context of this work, we use the term to refer to residential buildings with multiple dwelling units and generally greater than six storeys, excluding those in semi-detached or single-family homes. For example, City of Toronto defines low-rise as up to three storeys, mid-rise as four to 11 storeys, and high-rise as 12 storeys or greater. But it depends on context – in New York City, 12 storeys is not considered high-rise.

[ii] Local authority or council housing is a form of social housing in the UK.

[iii] In the UK, local authorities also known as unitary authorities are local governments who have responsibility over all local and municipal services, including housing. An exception is in London, where local councils have responsibility over housing. Housing associations are not-for-profit housing charities that provide public non-government owned housing.

[iv] Major renovations are defined as (a) renovations where the total cost of the renovation exceeds 25% of the value of the building (excluding the value of the land) or (b) renovations in which over 25% of the surface of the building envelope undergoes renovation [46]. Member countries may choose to apply either definition.

[v] Value engineering is an approach to optimizing value (i.e. the relationship between function and cost). This may be done through many means, including material substitution, scope reduction etc.

[vi] Integrated project delivery is a construction project delivery method in which each party involved in the design and construction of a building (or building renovation) work as a team and accept and manage risks jointly. Frequently, this is accomplished through procuring new construction or renovation projects through single, multi-party contracts [114].

[vii] The terms “desk study” or “desktop study” refer to a study or assessment of materials or designs carried out purely through research, without full-scale testing.

[viii] Formal enforcement measures are undertaken by the Local Authority and may include fines or notice of enforcement requiring the owner to do the work. AIs are not permitted to pursue formal enforcement measures directly.