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PERSPECTIVE

Towards an automated workflow for large-scale housing retrofit

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1. The retrofit challenge

Improving energy efficiency in buildings is essential to meet global climate targets as operation of the world's buildings accounted for 28% of energy-related greenhouse gas emissions in 2020 [1]. This proportion is even higher in particular regions. For instance, in Europe, where more than a third of buildings are over 50 years old and almost 75% of them are energy inefficient, buildings represent almost 36% of energy-related greenhouse gas emissions [2]. Although few newly constructed buildings are zero carbon, they are built to more energy-efficient standards. As such, implementation of large-scale housing retrofit programmes is critical to reduce emissions from the existing building stock, particularly given that approximately 80% of the buildings the world will use in 2050 have already been built [3].

A major challenge to delivering large-scale housing retrofit is in the slow rate of deployment [4]. To comply with the International Energy Agency (IEA) zero-carbon-ready building standards, around 2.5% of existing residential buildings in advanced economies will need to be retrofitted each year to 2050, increasing from currently less than 1% per year [5]. At a country level this means the UK, as an example, will need to improve all of its nearly 29 million existing homes with energy efficiency measures, at a rate of more than 1.8 homes every minute between now and 2050 to meet its net-zero targets [6]. Immediate and rapid improvements in building's energy efficiency are also needed in more than 30 million buildings in the Europe [7, 8], and across the North America [9, 10].

This perspective calls for an urgent step-change in scaling up retrofit deployment, as the longer we wait, the bigger the retrofit challenge will become and the less likely it is that emissions targets will be met. Retrofitting every home in the next decade is ambitious but is necessary to reduce energy demand and minimise fuel poverty. The purpose of this article is to provide a new perspective for future research to address the challenge of large-scale housing decarbonisation. The authors suggest that an end-to-end data-to-services framework is a means to develop automated data-driven retrofit workflows, addressing issues around the optimisation of retrofit identification and intervention.

2. Developing an automated retrofit workflow

In conventional retrofit workflows, technological inefficiencies in identifying retrofit opportunities, and the fragmentation of retrofit processes and information transfer across the supply chain, remain key barriers to widespread deployment of retrofit measures [11]. Miscommunications across the retrofit value chain may lead to poor decision making as the conventional workflows often comprise of a series of complicated procedural steps and manual building inspections that are inefficient and time consuming. This includes misinterpretations of the condition of the existing building and also the perceived retrofit needs of the existing building arising from the manual building inspection process. In general, procedures for analysing housing retrofit requirements involve manual surveys of physical stock and energy performance reports to examine the conditions of the building stock. These manual surveys are followed by an assessment of retrofit compatibility of the buildings to identify suitable solutions by a practitioner [12]. These assessments, including building's characteristics such as building envelope, thermal profile, and its rate of energy consumption, are often case-specific and are done in-person for each individual building or particular type of building. This may lead to fragmentation of information

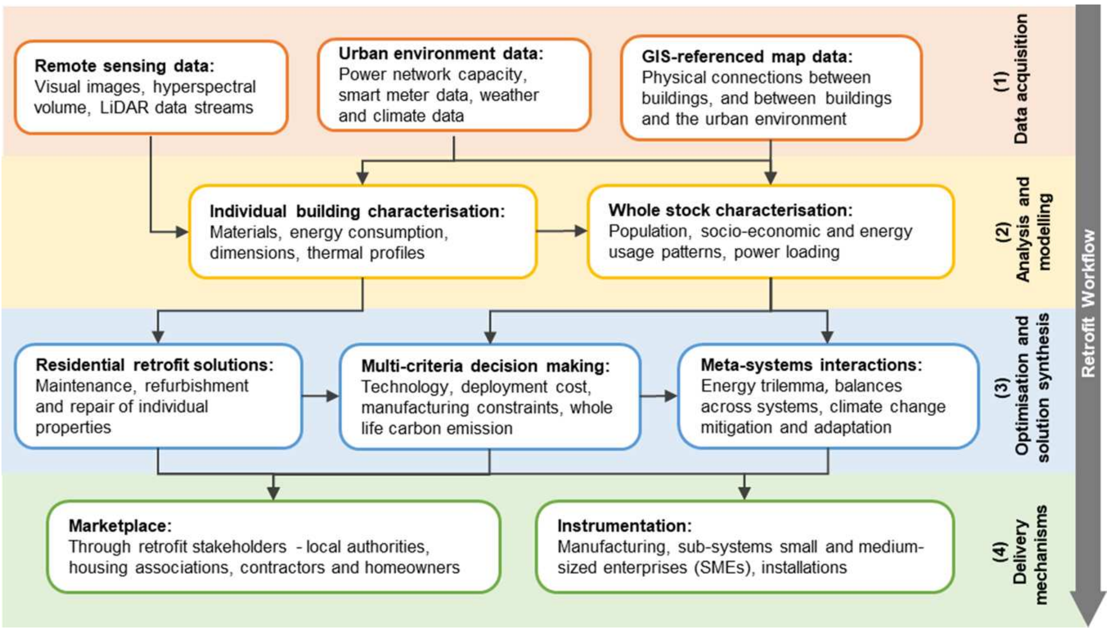

Figure 1. A schematic diagram to demonstrate the scopes of the proposed retrofit workflow, with itemised examples, from the processes of data acquisition and analysis, to perform solution synthesis, and finally to enable delivery of the retrofit for greater impact on long-term sustainability.

across stakeholders of domestic retrofit processes, including building designers, homeowners, manufacturers, and installers, which could hinder productivity of the delivery mechanisms, causing setbacks in the mass rollout of building retrofit and energy efficiency measures.

Thus, the methods by which we examine and characterise building stocks would need to be more efficient at a building level and become more cost-effective in tackling larger workloads through a scalable approach [13]. Scalability represents a system's capacity to adapt under an increased workload demand and benefit from economies of scale [14]. For a retrofit workflow to be scalable and more economically viable, it must be extendable with increasing workloads while remaining optimally cost-effective. The overall time and resources required for a large-scale roll out of housing retrofit should increase at a slower rate compared to the workload size due to the cost advantage gained from economies of scale.

Considering the highlighted benefits that come from increased scalability, an automated workflow is needed to upscale the current retrofit programmes from largely ad hoc and fragmented pieces of building repair and maintenance work into a seamless scalable delivery of retrofit strategy. Development of such a workflow will require a suitably large-scale data acquisition and building stock characterisation component for whole housing stock retrofit modelling. In this regard, automation of building characterisation processes, by making use of mobile sensing and machine learning methods, can provide a quick and effective tool for identifying retrofit priorities of buildings at property-level. Figure 1 illustrates a holistic framework for integrating data capturing and decision-making in a scalable workflow to automate the identification of retrofit requirements and delivery mechanisms.

The scope of this workflow can be summarised in four main components:

(1) The first step is to set up a scalable platform for **data acquisition**. The data component deals with the development of data streams, which consist of three sub-components of raw data collection. Firstly, information on building geometry can be acquired from remote-sensing models and data products, providing wide-scale approximations of building shape and roof geometry. Data generated in the urban environment, with geo-referenced information, can be acquired from either first or third-party sources to allow socio-spatial understanding of current building energy use in the existing built environment and infrastructure system. Whilst there is increasing use of data and models to understand retrofit needs, they are rarely utilised at the city or national scale to prioritise retrofit interventions.

(2) The subsequent **modelling and analysing** processes should combine and translate multiple data streams into an interpretable representation of the building stock for assessing the stock conditions at individual building level, and at wider scales for a whole urban system or at a regional scale. The whole stock characterisation

component allows for the identification of the retrofit requirements in the built environment across spatial levels.

(3) **Multi-objective optimisation** needs to be integrated into **solution synthesis** to quantify trade-offs and provide transparency to the constraints and benefits for each intervention. Bespoke technical solutions that are optimised across multiple criteria and constraints should be developed to meet specific retrofit requirements, as well as the collective objectives considering their whole-life impacts and interactions with the wider meta-systems of the whole housing stock and the environment.

(4) Integrated **delivery mechanisms** ensure stakeholders and individual users can benefit from the retrofit solutions, encouraging societies towards carbon reduction goals and climate commitment targets. This requires establishment of marketing platforms to enable delivery and instrumentation of a portfolio of retrofit interventions and financing options at a variety of scales and ownership models [15].

3. Automating stock characterisation and digitising building data

Acquisition of building-level information at the required quality and resolution in a scalable manner is of vital importance for running large-scale building energy simulations. To provide a comprehensive analysis of the built environment, the authors advocate for an automated workflow to adopt a bottom-up approach to building stock characterisation, which collects data of individual buildings to identify their respective retrofit needs and the best solutions for each unit [16]. Such approach can provide high resolution, disaggregated spatial distribution to simulate energy performance of individual dwellings, but one major limitation to such approach is the intensive requirements for collecting and processing large amounts of building attribute data to model an entire building stock at scale. Machine learning methods can offer a viable and affordable solution, in terms of time and cost, by automating the feature detection and stock characterisation processes for identifying building's retrofit needs.

To mobilise data-driven retrofit at scale, digitisation of building data, for example, the introduction and utilisation of building stock and material passports for individual properties, is a key enabler for the workflow to be scalable to handle higher workload effectively. A digital approach can also benefit from increased confidence due to the use of more high-quality data in building stock modelling and retrofit analysis. Considering meta-system interactions, the workflow could be coupled with a power network optimisation module to ensure stable operations within the limit of network loading capacity, while maximising energy efficiencies and whole life carbon savings through optimal retrofit improvements.

Automation of data acquisition processes can be performed with an integration of mobile sensing and computer vision approaches to detect building features and characterise stock conditions in the built environment through machine learning methods [13]. The four media integrated in the building data capturing system are: visible light photography, infrared thermography, hyperspectral imaging, and distance measurements using LiDAR sensors, examples of which are summarised in figure 2. Such sensing approaches would enable reconstruction of a three-dimensional model of the buildings, which also lay the groundwork for creating a digital twin of the built environment using real-world measurements.

4. The way forward

The automated framework would integrate data acquisition and modelling modules into decision-making processes and delivery mechanisms to ensure streamlined information transfer across different stages of the workflow, providing transparency and connecting all the stakeholders and contractors involved within the same pipeline. Furthermore, the manual identification of potential challenges relating to planning and access for construction would be improved through the use of automated data driven processes.

Future work in this space would need to be structured in a modular way such that the various components of the workflow, including those highlighted in figure 1, can interact interchangeably with work across different research areas. There has been extensive research on reviewing the applications of data-centric methods in monitoring and modelling energy performance to inform decision making [17, 18], including studies on optimisation of retrofit analysis in mixed-use energy systems [19, 20]. To facilitate a systematic approach to identifying, designing, and implementing the most suitable retrofit measures, these components need to be digitally integrated into a collaborative manufacturing system, enabling a digital transformation in business models for delivering housing retrofits [21].

Development and utilisation of digital tools plays a key role in enabling scalability in data acquisition steps, in which figure 2 outlines one potential route to achieve scalability through remote and mobile sensing techniques. For an automated approach, remote sensing techniques are capable of detecting physical features and identifying retrofit needs for buildings across a city by means of drive-by imaging; and have the potential to save costs and time compared to the resources needed to inspect the same number of buildings via physical survey [12]. Strategically, development of automation modules would allow

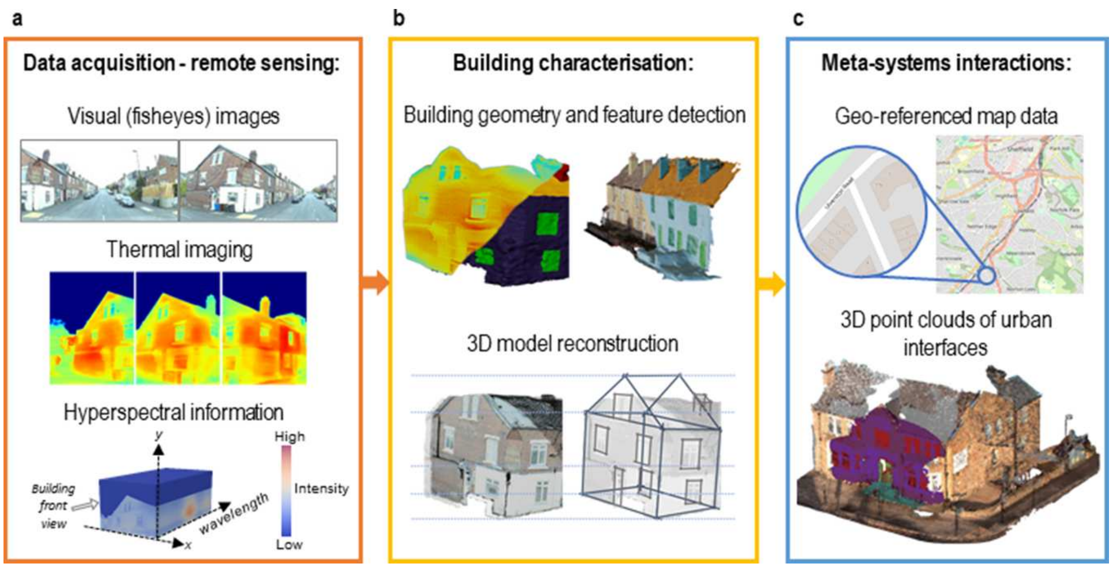

Figure 2. An automated workflow for (a) data acquisition through remote sensing methods and (b) building characterisation for reconstruction of a 3D model, integrated with an analysis of the urban environment to understand the (c) meta-systems interactions with urban interfaces. Reproduced from [13].

prioritisation of the houses with urgent retrofit needs in order to leverage the limited resources available by targeting the properties that need a physical survey for in-depth retrofit analysis. Physical survey of building internal features for a representative sample of buildings could also be used to cross-check with the remote sensing data for validation purposes [22].

Furthermore, whole building stock characterisation, as illustrated in figure 1, can provide useful market insights such as where are the hotspots, and the level of upcoming retrofit demand over a wider area from a whole supply chain perspective. This would give an indication of material supply requirements and the potential manufacturing capacity needed to meet the demand. In moving the market forward, plans and incentives to prepare the building and retrofit industries with well-rounded delivery mechanisms and a marketplace are needed to support delivery of new solutions, fostering opportunities to boost new skills and drive investment in low-carbon initiatives.

Climate models can also be integrated into the workflow for developing regionally defined retrofit solutions. Applications of the framework could be adjusted to include adaptive energy loads in regions with varying heating and cooling needs [23]. Such adjustments may also increase the granularity of building characteristics to improve the confidence and reliability of building stock models, offering tailored retrofit measure suggestions at the individual building level [24]. Other factors to consider are the marketplace and policies in place to support large-scale deployment.

For future challenges, advancing automated methods in retrofit identification and optimisation processes requires input of high-quality data at high spatial resolution, i.e. at individual building level. This is necessary for a better understanding of the relationship between stock conditions and energy usage in buildings, considering the built forms, insulation materials, and household composition. In addition, each element of the proposed workflow has different requirements for validation. For example, validating building energy simulation models is essential to produce a trustworthy benchmark for the development of data driven modelling and obtain high quality training data for fitting in the machine learning models. Integration of third-party data, such as smart meter data, which give measurements of electricity and gas usage and demand for individual houses, would augment predictive and data driven solutions. However, such data is often considered personal data, and thus access is restricted on an individual basis and hosted securely with commercial organisations. To bypass this, the accessibility of a ground truth, gold standard data source, that can be relied on to a significant degree of confidence, is crucial. Identifying or creating such a gold standard with existing or new data is a key driver to producing robust, reliable data-driven models.

In conclusion, the retrofit workflow presented in this perspective piece offers a route to improve uptake of digital approaches and provide capability for identification of retrofit requirements at mass scale by utilising emerging and cutting-edge methods and solutions. If nations are to meet their commitments under the Paris Agreement, the pace of retrofit must be accelerated to unprecedented levels. This requires a step change in approach, away from manual methods to identify retrofit needs, to those that exploit digital technologies at every step of retrofit identification and deployment. The problems addressed in this paper present significant research challenges to tackle, and real opportunities for partnerships between research institutions, regional leadership, and the construction supply chains who will deliver retrofit on the ground. Given the scale of the climate emergency, there is a pressing need for these actors to work together to deliver the step change in retrofit approach and deployment that is so urgently required.

Data availability statement

No new data were created or analysed in this study.

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Author contributions

L M T, H A, M M and A K have designed the study. L M T undertook the study and wrote the manuscript. H A, W W, X L and D D T contributed to the discussion of workflow development and preparation of the manuscript. All authors have given approval to the final version of the manuscript.

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