Simulation and data-driven tools for buildings energy optimisation

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The Insights Series has been developed to highlight key findings arising from Energy Systems Integration Partnership Programme (ESIPP) research in decarbonised energy systems. These publications share new insights into various aspects of energy decarbonisation that have been gained from a multidisciplinary team of researchers in ESIPP from institutions across Ireland.

This Insights paper highlights recent findings of ESIPP research on the use and development of simulation, optimisation, and artificial intelligence-based data-driven techniques for modelling building and energy systems at different scales. The methodologies presented in this Insights paper can facilitate building energy refurbishment decision-making and accelerate technical solutions for different building energy retrofit scenarios. This will aid the development of future energy policy scenarios, support decreasing the carbon footprint of the building sector, and facilitate renewable energy integration and demand response implementation of the housing stock by 2050.

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Energy Systems Integration Partnership Programme

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Context

The Energy Systems Integration Partnership Programme (ESIPP), a major Science Foundation Ireland-funded research programme, is coordinated by the University College Dublin (UCD) Energy Institute and delivered in partnership with industry and a multidisciplinary team of researchers from UCD, Trinity College Dublin, NUI Galway, the Economic and Social Research Institute (ESRI) and Dublin City University. The research programme has three strands: (i) addressing operational and technical aspects of the network, (ii) identifying energy solutions for people in their homes and businesses, and (iii) informing energy policy and infrastructure investment to enable energy decarbonisation.

The Insights series highlights the main findings of ESIPP research and provides insights into topics that are relevant for academics, industry, and policymakers. This series enables us to bring together different research findings to provide unique perspectives gained through a multidisciplinary research approach. The focus of this paper in the Insights series is on the simulation and data-driven tools used for building energy optimisation in line with EU and Irish policy.

In spring 2020, EU Member States adopted the Directive (EU) 2018/844 (**European Union, 2018**), which focuses on the energy efficiency and performance of existing buildings. This directive establishes new obligations to retrofit the existing building stock, innovative solutions to improve building energy performance and overall efficiency which requires robust and reliable procedures for building energy modelling and simulation **(Ascione *et al,.* 2020).**

For carbon emissions reduction targets to be met, extensive refurbishment of existing homes will be required. Both within literature and in practice, there is limited understanding of the interaction between housing energy efficiency refurbishment and occupant behaviour **(Walker *et al,.* 2014)**. On the other hand, large-scale modelling using current well-known simulation tools which integrate physical models for simulation, can be time-consuming when a wide range of design solutions need to be evaluated.

Moreover, building automation, demand response schedules, and heating, ventilation and air conditioning (HVAC) control systems should be well designed and programmed for optimum functionality to maximise energy efficiency and minimise carbon emissions and thermal discomfort in buildings. This goal requires simulation-based optimisation techniques.

Advancement in big data analytics creates unique opportunities and possibilities to deeply analyse building energy retrofitting optimisation scenarios and, from a wider perspective, citizen behaviour and energy use patterns in urban areas. Data-driven building and energy system models can be used to perceive macro-climate and community-level energy use and behavioural patterns which are not presented in current versions of dynamic building modelling tools, or are not advanced enough yet **(Salim *et al,.* 2020)**. **Salim *et al.* (2020)** highlight that little research has been done into the use of urban data for large-scale occupant behaviour and energy use modelling at multiple scales, from buildings to neighbourhood to city.

Research Description

Over the duration of the ESIPP project, researchers have published several papers on the optimised simulation and control techniques for buildings, as well as data-analytics approaches for large-scale building modelling. Shifting from traditional simulation and sensitivity analysis to numerical optimisation and data-driven models is important for improved energy efficiency and for accelerated design and assessment of different building refurbishment scenarios at large-scale. This Insights paper highlights the findings of four ESIPP research papers on the use of simulation and data-driven tools in building energy and demand response optimisation. We begin with a summary description of each of the papers in this section.

Energy modelling is an essential and preliminary step to efficiently design buildings and integrated energy systems to evaluate their performance and sustainability, and compatibility with energy codes. Advancements in building energy performance modelling tools have led to an increase in user inputs and parameters utilised to define energy models. There are numerous sources of uncertainty in model parameters which exhibit varied characteristics. For this, **Shamsi *et al,.* (2020)** uses an integrated uncertainty approach to address the correlations and classify different types of uncertainties. This method can identify and quantify different types of uncertainties associated with reduced-order grey-box [1] energy models used in heat demand predictions of the building stock.

Ali *et al.* (2019) propose a multi-scale building archetype development methodology using different data-driven techniques. Building archetypes utilise geometric (e. g. building shape) and non-geometric (e. g. building occupancy, thermostat setpoints) parameters to classify the building stock. All buildings possessing similar parameters are grouped together and are termed as archetypes. These archetypes are developed by using Irish national survey data, which provides sufficient information about the national housing stock. This technique includes five steps: 1) data collection, 2) segmentation, 3) characterization, 4) quantification, and 5) modelling results. A test case based on the available building stock data of Ireland was developed, using previously created archetype geometries **(Ali *et al,.* 2020)** coupled with the parameters determined by the characterization process to calculate annual energy use of buildings at medium to large scale. The resulting archetypes at national, city, county and district scale are analysed and compared against one another. These studies highlight that significant differences occur in terms of energy simulation results when national scale archetypes are used to simulate the building energy performance at the local scale. This is a generic methodology to optimize urban-scale energy retrofit decisions for residential buildings using data-driven approaches.

Ali *et al.* (2020b) developed a generalizable bottom-up data-driven approach for multi-scale GIS (Geographical Information System)-based mapping of residential building energy performance, which could be applied to existing available building stock data for building energy performance prediction. Also, a comparative study is carried out where different supervised machine learning algorithms are compared to determine the optimal data-driven building energy model for large scale implementation. In addition, it could be used for building energy flexibility analysis where different energy systems are integrated.

Buildings can play an important role in future smart electricity grid for the decarbonisation of the building sector. Heat pumps are considered as a promising solution for energy decarbonisation in buildings and can be integrated with distributed energy generation technologies, thermal and electrical energy storage technologies or electric vehicles, offering energy flexibility sources to the emerging smart grid. To date, there is a lack of a single flexibility metric for characterisation of the energy flexibility associated with residential buildings, mainly due to the different interpretations, properties, and requirements that characterise an energy flexible building. The scope of the study by **Bampoulas *et al.* (2021)** addresses this gap by presenting a fundamental flexibility quantification framework applicable to different electronic components commonly found in residential buildings (i.e. heat pumps, electric vehicles, thermal and electrical storage) and to assess the net energy cost of various demand response actions in the context of onsite electricity production. In this study, the flexibility potential of multi-component residential buildings is evaluated and the potential trade-off between the various systems involved are investigated. Consecutive and independent demand response actions are implemented at an individual electrical component level by utilising a calibrated white-box simulation model of a residential house. These indicators can be used to acquire the daily energy flexibility mappings which can benefit electricity aggregators to evaluate, optimise, and manage buildings energy portfolio **(Bampoulas *et al,.* 2021)**.

Findings/Discussion

One of the main energy policy actions to balance electricity supply and demand focuses on demand-side management is the demand response (DR) actions in the building sector. Buildings need to be energy-flexible to participate in DR programs. In this context, a generic energy flexibility quantification framework has been

[1] A grey-box model is a simplified building model which is developed using building physics equations and heat transfer dynamics. These models can simulate building thermal behaviour and energy use, especially when large-scale building modelling and optimisation is required and where the use of complex physical models is time-consuming.

proposed to characterise the DR potential of the most common electrical components found or could be installed in residential buildings. More importantly, the flexibility potential of the buildings envelope thermal mass, the hot water tank thermal energy storage (TES), and the electrical energy storage units, can be assessed by using the proposed energy flexibility indicators, namely storage capacity, storage efficiency, and self-consumption during a DR action. This methodology has the potential to be applied to all residential building models, showing the DR potential and quality of individual power modulation strategies, and illustrate it in a succinct and uniform way. Electricity aggregators can benefit from this mapping by optimising the portfolio of buildings with which to contract. Numerical simulations have shown that energy flexibilities obtained for each component are influenced by various factors such as weather conditions, occupant lifestyle, and energy use pattern of the integrated energy systems. This methodology has been developed for a residential house, however, the physical building energy model can be used to evaluate the energy flexibility of several residential buildings within communities or at urban-scale by taking advantage of data-driven approaches (**Bampoulas *et al,.* 2021**).

Different data-driven approaches have been used to develop building archetypes. The archetypes segmentation process is based on the dwelling type, year of construction and clustering method. The results show that bottom-up energy modelling at large-scale can be further improved by using multi-scale building archetypes. This will assist the local authorities, city planners and energy policymakers to analyse granular level building energy performance, that further helps to improve sustainable energy policy decisions **(Ali *et al,.* 2020)**.

The methodology used by **Ali *et al.* (2019)** indicates that archetypes developed at the national scale produce significantly different modelling results when used at a local scale, when using Ireland as a case study. A major problem in urban building energy modelling is the uncertainty associated with the characteristics of building archetypes. A lack of thermal properties and limited access to building energy audit data can significantly increase uncertainty levels. These uncertainties could lead to errors in urban-scale building energy performance modelling. The devised methodology will help in improving energy modelling results and reduce uncertainty at an urban scale by using the developed data-driven approach. The results show that the selection of an archetype scale introduces significant differences in the calculated values of energy use and carbon emissions. These multi-scale archetypes could be further used as benchmarks or reference buildings to evaluate various energy savings and energy efficiency strategies at a local area level **(Ali *et al,.* 2019)**.

A GIS-based approach can use limited available resources such as building energy performance certificates, geographical, spatial, census, and building thermal retrofit project data for large-scale building energy performance prediction. The methodology presented by **Ali *et al. (2020b)*** uses a data-driven technique to geocode building stock data for spatial mapping. Results show that a data-driven approach coupled with the spatial data can improve the quality of existing data and extract meaningful knowledge for decision making.

Uncertainty and sensitivity analysis is an important step in any building simulation and optimisation project to assess the accuracy, validity and relevance of the developed models for building energy performance analysis due to the existence of several thousand input parameters in physical and data-driven simulation models. To tackle this problem, an uncertainty analysis framework based on Monte Carlo technique[2] is proposed to identify, characterise, and quantify various sources of uncertainty in building energy performance simulation **(Shamsi *et al,.* 2020)** to overcome previous challenges associated with the characteristics of building archetypes.

For uncertainty analysis, the selected simulation input data includes weather conditions and the model parameters require inputs regarding heat gains and infiltration rates. As the uncertainty in the prediction of building energy use depends on various factors for the considered building, building managers need to address natural variations and uncertainty in building geometric and operational parameters to build confidence in

[2] The Monte Carlo technique models the probability of different outcomes or decisions that are not easy to predict as a result of intervention from random variables. This allows individuals to assess the associated risks and allows for better and more informed decision making.

simulation results. This would help the associated stakeholders evaluate energy prediction ranges under various possibilistic-probabilistic scenarios for facilitating decision making and design optimisation. Uncertainty analysis can be used for modelling possible future scenarios such as the effects of climate change on building energy demand, or to facilitate decision making in data collection and model improvement **(Shamsi *et al,*. 2020)**.

Once building archetypes are developed and sensitivity and uncertainty analysis is performed, the building model could be extended to an urban-scale prototype with a wide range of energy-design features. For example, Dublin represents 30% of the Irish residential building stock, which consists of about 203 building features. This makes the building thermal and technical systems retrofit selection challenging, especially when data for the whole residential building stock in Dublin is limited. Therefore, a generalised technique to optimise urban-scale energy retrofit decisions for residential buildings using data-driven approaches is developed **(Ali *et al,*. 2020)**. Extracting useful and important information from existing available energy-use data for urban-scale energy retrofit modelling is of significant importance for stakeholders. It enables the estimation the necessary retrofit capital investment costs, carbon emission reductions, and energy savings.

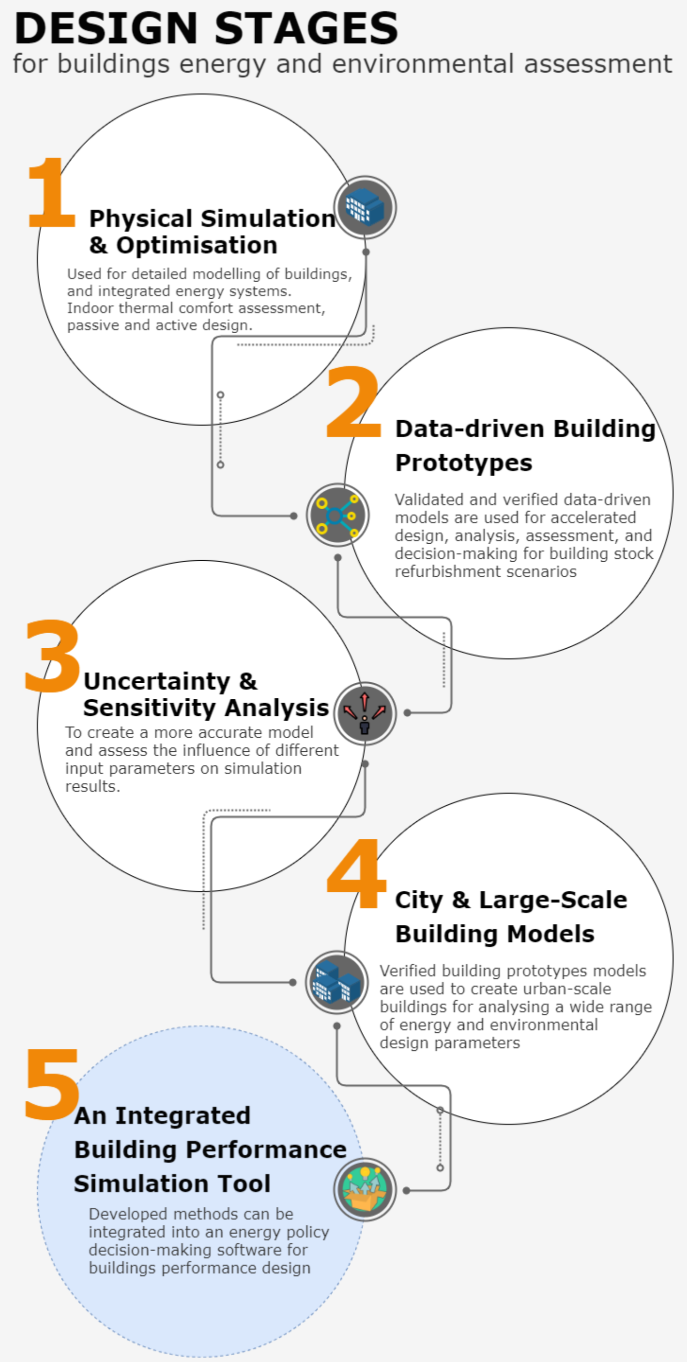

Figure 1. An overview of simulation, optimisation, and data-driven techniques developed in ESIPP (Energy Systems Integration Partnership Programme) project at UCD Energy Institute with the objective of improving buildings energy performance, facilitating large-scale building and energy system modelling and assessment, and provide innovative solutions for BER (building energy rating) and DR (demand response) techniques for a fully-integrated energy system.

The proposed knowledge-based technique comprises both building and building retrofit stock data, which could be used by stakeholders to help them analyse the energy performance of residential buildings and find feasible energy retrofit scenarios by leveraging scarce available resources at a city-scale.

Findings suggest that implementation of the data-driven approach improves the quality of existing data related to buildings, and facilitates the extraction of key features from big data. Results highlight the significance of data-driven retrofit simulation; the feature selection process reduces the number of features in Dublin's building stock database from 203 to 56 with a building rating prediction accuracy of 86%, where 16 features have been identified as recommended building energy retrofit measures for each energy-efficiency rating **(Ali *et al,*. 2020)**. A schematic of the methods and tools developed for buildings and urban energy performance modelling is shown in **Figure 1**.

Key Insights and Application

- The techniques and strategies presented in this Insights paper could be used in advanced home energy retrofit design, assessment, and BER (building energy rating) tools to improve the energy performance of building fabric and energy systems.
- Urban-scale energy analysis and optimisation is made possible for urban planners, energy policymakers, architects, and engineers. These artificial-intelligence-based models and optimisation methods yield technical and economic benefits, e.g. by estimating the required capital investment for energy retrofits, and carbon footprint reductions. Also, they facilitate formulating optimised retrofit design solutions for the residential building stock. Multi-scale building archetypes will help local authorities and city planners when analysing energy efficiency and consequently, help to improve sustainable energy policy decisions.
- The developed Demand Response energy flexibility indicators can be utilised to acquire the daily energy flexibility mappings for demand response facilities by aggregating the obtained energy results. This mapping can benefit electricity aggregators evaluate or optimise a portfolio of buildings. The methodology can be used by demand response services where there is a need to fully understand the potential of each building to shift and curtail the peak electricity load at peak consumption hours.
- Methodologies and models presented here could be used to design and develop a 'multi-purpose buildings and urban energy systems model' with the aim of facilitating decision making for building energy retrofits and energy policy implementation at regional and national scales.
- For multi-scale energy modelling, where residential buildings energy modelling is challenging, a GIS-based data-driven technique can be utilised to geocode building stock data for spatial mapping. This can enhance the quality of existing data and draw out important knowledge for decision making.
- Validation and verification of these innovative simulation, optimisation, and data-driven techniques for building energy performance modelling, especially for large-scale modelling, remain a challenging task which should be investigated further. Experimental building energy tests beds are required for validation and testing of different models.
- Data-driven building energy modelling techniques presented in this insight series could use input data from aerial thermography drones which detect thermal properties of building envelopes and surfaces (online or offline), and model a more realistic energy behaviour of large-scale buildings.

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