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Aidan Duffy

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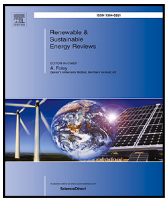

# Life-cycle assessment of non-domestic building stocks: A meta-analysis of current modelling methods

Julian Bischof [a,b,*], Aidan Duffy [b]

[a] Institute for Housing and Environment (Institut Wohnen und Umwelt (IWU)) - Research Institute of the State of Hesse and the City of Darmstadt, Darmstadt, Germany
[b] Dublin Energy Lab and School of Civil and Structural Engineering, Technological University Dublin, Dublin, Ireland

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## ABSTRACT

Building stock models (BSMs) are essential for simulating the contributions of regional and national building sectors to climate change under different policy scenarios, and for identifying pathways to climate change mitigation. To date, BSMs have focused on the operational life-cycle impacts of domestic dwellings; there has been less emphasis either on non-domestic buildings (NDBs) or full life-cycle analysis. This paper provides a first review of the theory and practice of NDB stock modelling which considers life-cycle energy, emissions and costs. A meta-analysis of the literature was undertaken involving a structured search of relevant articles in key scientific repositories. 98 in-scope studies were identified and data collected on their aims and objectives, methodologies, data sources, system boundaries, considered impacts, representativeness, uncertainty analysis, validation and verification techniques, further research identified, model transparency and software tools employed. The review necessitated the classification of modelling methodologies. The existing 'bottom-up' and 'top-down' groups were found to be ambiguous and led to confusion. Therefore, an alternative methodology classification is proposed, considering both the modelling technique and model simulation data used. The findings of the analysis indicate that most approaches use engineering models employing archetype data. However, almost all current life-cycle models of NDB stocks are incomplete. Only one study considered the full building life-cycle and most did not include uncertainty analysis. The reproducibility of study results is poor since most do not provide sufficiently-detailed information on the models and data used. Critically, there is a lack of representative input data which limits their usefulness as evidence in policymaking.

## 1. Introduction

Over the last 120 years, anthropogenic greenhouse gas emissions have increased average global temperatures by approximately one degree Celsius [1]. A significant proportion of these emissions (62%) relate to the combustion of fossil fuels and industrial processes, with buildings and the construction sector accounting for 36% of total global final energy use in 2018 [2]. As a result, this sector is estimated to be responsible for 39% [2] and 36% of global and European greenhouse-gas (GHG) emissions respectively [3–5]. Reducing the emissions' impacts of building stocks therefore represents an important objective in tackling climate change [6] and so 'should be a major target for GHG emissions mitigation efforts' [2].

Policymakers rely on various information sources to develop appropriate responses to the challenge of climate change mitigation. One important tool for testing and developing new policies in the building sector is the building stock model. In general, these models represent regional building stocks and use various economic and climate variable inputs to estimate energy, emissions and cost–benefit outputs. By varying stock characteristics, new outputs are estimated and evidence-based policies formulated. For example, such building stock models can be used to simulate different building stock refurbishment scenarios to estimate their energy, $CO_2$ and cost impacts. These results can be used to select the best-performing options (e.g. technology subsidies, taxes, information campaigns) to achieve climate change mitigation policies. Using projections of future building stock characteristics, these models can also be used to simulate associated energy demands and $CO_2$ emissions; this information can be used for policy and infrastructural planning purposes. This approach is well-recognized as best practice both in setting and auditing energy and emissions policies in the built environment [5,7,8].

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[*] Corresponding author at: Institute for Housing and Environment (Institut Wohnen und Umwelt (IWU)) - Research Institute of the State of Hesse and the City of Darmstadt, Darmstadt, Germany.

*E-mail addresses:* j.bischof@iwu.de (J. Bischof), aidan.duffy@tudublin.ie (A. Duffy).

*URLs:* http://www.iwu.de (J. Bischof), http://www.tudublin.ie (A. Duffy).

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**Nomenclature**

| | |
|---|---|
| BbB | Building-by-building |
| BoQ | Bills of quantities |
| BS | Building stock |
| BSM | Building stock model |
| CDA | Conditional demand analysis |
| $CO_2$ | Carbon dioxide |
| DBs | Domestic buildings |
| GHG | Greenhouse-gas |
| I–O | Input–output |
| LCA | Life-cycle assessment |
| LCA-BS | Life-cycle assessment building stock |
| LCIA | Life-cycle inventory assessment |
| MFA | Material Flow Analysis |
| ND&D | Non-domestic and domestic |
| NDB | Non-domestic building |
| DBSs | Domestic building stocks |
| NDBS | Non-domestic building stock |
| NDBs | Non-domestic buildings |
| NDBSs | Non-domestic building stocks |
| NZEBs | Nearly zero energy buildings |
| OAT | One at a Time |

To date, building stock models have largely focused on the domestic sector, with few examples that consider non-domestic buildings [9–13]. Domestic building stocks are relatively homogeneous compared to non-domestic stocks, which tend to have a greater range of building sizes, forms and uses. Therefore, modelling a non-domestic building stock (NDBS) is more complex than a domestic one and, partly for this reason, is less frequently undertaken. This represents an important omission, since non-domestic buildings contribute significantly to both energy use and emissions. For example, they are responsible for 11% of all global energy related GHG-emission; the equivalent figure for the domestic building stock is 17% [2]. In the UK, the NDBS accounts for one-quarter of building stock energy use and 17% of carbon emissions [14,15]. Commercial buildings account for 19% of total building energy use in the USA [16]. In 2010 the German non-domestic and domestic building stocks accounted for 14.2% and 27.4% of total final energy consumption respectively [17].

Over the last number of decades, building regulations in many economies have increasingly focused on reducing operational energy use so that by 2020, for example, all newly-constructed buildings in the EU must be nearly zero energy (NZEBs) [18,19]. More stringent energy efficiency standards necessitate more materials (such as energy systems and insulation) to minimize fabric and ventilation losses, thus increasing the energy and emissions ‘embodied’ in the building structure. In modern buildings adhering to current energy standards, embodied energy can equal cumulative lifetime operational energy [20–23]. It is therefore important that policymakers take account of all life-cycle phases when assessing building stock policies. Indeed, the European Union’s “Energy Performance of Buildings Directive” of 2010 [24] specifies such a requirement.

Life-cycle assessment (LCA) involves an analysis of the environmental burdens arising from a building’s entire life-cycle, from production and construction, through operation and eventual decommissioning/demolition (cradle to grave); this scope can be extended to include decommissioned materials’ recycling and reuse (cradle to cradle). Fig. 1 presents an overview of typical building life-cycle phases. Current building stock models tend to focus on the operational phase only; extending this to other phases will increase complexity. For example, models and data for estimating the embodied impacts of construction, maintenance and demolition would need to be added to those for estimating operational impacts. However, the outcome would provide a more complete analysis better suited to policymaking.

Reviews provide an overview over a field’s diversity and support the understanding of the readers. In the case of building stock modelling reviews help the modeller to reflect the possible modelling options and to choose a fitting methodology. Additionally the reviews can point out aspects that are not part of the existing models yet, but would further improve the model’s quality [5]. Therefore a focused review can advance the starting point in BSM development, leading ideally to higher quality models, consequently providing better guidance for model users. A review of NDBS models considering the whole life-cycle helps to support the development and use of such models, while a clear model categorization supports the communication in the modelling community.

Several reviews of building stock modelling methodologies and practices are reported in the literature. Studies by Swan and Ugursal [25], Kavgic [26] and Brøgger and Wittchen [5] cover a wide range of approaches specific to the domestic sector. The work of Lim and Zhai [16] addresses residential and non-residential stocks, but specifically addresses stochastic modelling methods rather than general models and their applications. Mastrucci et al. [27] reviewed environmental life-cycle assessment (LCA) studies, but only considered bottom-up approaches focusing on domestic buildings. No studies have reviewed non-domestic building stock models specifically, particularly from a life-cycle perspective.

The aim of this paper, therefore, is to present a first review of the theory and practice of non-domestic building stock modelling which considers life-cycle energy, emissions and costs. It summarizes the methodologies employed in each life-cycle phase and identifies relevant software tools. The current ‘bottom-up’ and ‘top-down’ stock model categorization is critically analysed and developed to incorporate both the modelling method and input data used. Because non-domestic stock modelling is an emerging and limited research domain, relevant aspects of the literature on domestic stock modelling are included here.

The remainder of the paper is structured as follows. Section 2 describes the characteristics of non-domestic building stocks which are important to the modelling process. It also highlights some key differences between domestic and non-domestic stocks which are important to understanding whether and how domestic modelling approaches are applicable to the non-domestic sector. Section 3 classifies and describes the structures of different stock modelling methodologies reported in the literature for the main building life-cycle phases: construction, operation, maintenance and demolition. Section 4 introduces the developed building stock model categorization system incorporating modelling method and input data used. Section 5 details the results of a meta-analysis of the international literature of life-cycle building stock simulation studies. Section 6 presents a summary of the main areas of research required to improve non-domestic life-cycle building stock models.

## 2. Non-domestic building stock characteristics

Building stocks can be classified as domestic or non-domestic. While domestic buildings (DBs) primarily provide living space, non-domestic buildings (NDBs) can be defined as those where more than half of the floor area [15,28] is used for purposes other than living [29]. The category is therefore diverse and includes commercial, industrial, educational, health and public buildings, as well as sheds, garages and even telephone booths. However, when defining the non-domestic building stock (NDBS) of relevance to energy and emissions policy-making, it is important to distinguish between those which are heated and cooled, and those which are not. The sub-group of thermally-conditioned NDBs typically includes buildings which are subject to national energy certification schemes [30]. Buildings that provide only elemental protection for manufacturing or production processes are normally excluded; here, no energy is required for thermal conditioning or air handling, but only for process energy needs.

Due to their greater functional diversity, non-domestic building stocks (NDBSs) are more varied than domestic ones (DBSs) in several ways. For example, they exhibit a wider variety of building forms, uses, occupancy patterns and energy requirements. This diversity must be considered when modelling NDBSs, thus making it more complex than for DBSs.

### 2.1. Domestic and non-domestic buildings

Table 1 provides an overview of the differences between the domestic and non-domestic building stocks in Germany. Although Germany is used for reasons of data availability, similar findings are reported by [31] for building stocks in Greece and by [32,33] for the United Kingdom. In general, the table highlights that both the DB and NDB stocks are quite different, and that the latter is more diverse and complex to model. For example, it can be seen that the NDBS encompasses significantly more building categories and space types. Dascalaki et al. [31] found a significant difference in the energy use of domestic and non-domestic Greek buildings; operational energy requirements for DBs were found to range form 108 to 189 $\frac{\text{kWh}}{\text{m}^2\ \text{a}}$ while those for NDBs ranged from 167 to 371 $\frac{\text{kWh}}{\text{m}^2\ \text{a}}$. This contrasted with average estimated Greek NDB energy end-use requirements of 280 $\frac{\text{kWh}}{\text{m}^2\ \text{a}}$, over 40% greater than that for DBs [15]. Furthermore, the average electricity consumption of NDBs in Europe is 55% greater than DBs (286 $\frac{\text{kWh}}{\text{m}^2\ \text{a}}$ and 185 $\frac{\text{kWh}}{\text{m}^2\ \text{a}}$ respectively) [15]. These higher energy end uses by NDBs may be explained by the greater prevalence of more complex mechanical and electrical systems in these building types.

A comparison of the characteristics of domestic and non-domestic stocks is highlighted in Table 1 which shows that NDBSs are more diverse and specialized than DBSs. This relates both to the physical nature of the buildings (e.g. design, construction and servicing) and the manner in which they are used (e.g. activities, occupancy patterns and life expectancy). While data on maintenance and refurbishment requirements are not readily available, as commercial investments NDBs are likely to be intensively used and thus have significant maintenance needs. Furthermore, commercial pressures and changing business practices may lead to frequent refurbishment cycles and explain the observed shorter building life expectancies for these building types [58, 59]. Many of the observed differences between DBs and NDBs therefore indicate that modelling the latter must involve more variables, parameters and governing equations [33,38,60].

In addition to system complexity, the availability of the data necessary for system modelling also differs significantly between DBSs and NDBSs. Because DBSs can be represented using a smaller number of variables, the associated data are easier to collect. This is one reason why most countries provide relatively better statistics for domestic than for non-domestic building stocks, the latter often being inconsistent, intermittent and of poor coverage [33]. Exceptions include the regular NDBS surveys undertaken in the USA, as part of the Commercial Building Energy Consumption Survey (CBECS) program [61–63], and the Canadian Commercial and Institutional Consumption of Energy Survey (CICES) [64]. Another country which consistently collates relevant NDBS data is the UK [65], although this is limited to floor areas and building uses, which are used for taxation purposes. In recent years this NDBS data gap has been identified in several countries [66,67] which has lead to the initiation of several data gathering projects [65–70]. However, while these data will eventually be useful for modelling national non-domestic building stocks, initially, at least, they will be limited and incomplete. It is likely to take significant time and effort before useful data, covering key variables and of sufficient sample sizes, are available internationally.

In summary, the diversity and complexity of NDBSs and the associated poor data availability represent significant hurdles to the modelling of this building stock.

### 2.2. Life-cycle energy and emissions

The life-cycle phases for a typical building together with the associated LCA boundary conditions are presented in Fig. 1. These phases do not differ between domestic and non-domestic buildings, although the types and quantities of materials used and energy end uses do.

The first phase of a building's life-cycle involves production and construction processes which are typically responsible for the majority of embodied impacts [74]. Practical completion and commissioning is followed by the operational phase which is typically the longest life-cycle phase. Assessing and limiting energy and emissions from this phase has, up till now, been the main focus of BSMs (see Section 5.1.1) and legislation [19,24,30,48,75–77]. The decommissioning phase represents the end of a buildings life-cycle. Maintenance and refurbishment relates to the ongoing upkeep of the building to maintain its level of performance, but typically excludes large projects such as extensions. Maintenance is characterized by regular day-to-day activities, while refurbishment involves less frequent but more extensive interventions in the building's fabric and services. The combination of the design and construction, maintenance and refurbishment, and the decommissioning phases can be referred to as the 'non-operational phase', and its impact is often quantified as embodied energy or emissions.

From a greenhouse gas mitigation policy perspective, only future emissions are of importance. Past emissions, referred to as 'sunk' emissions, cannot be undone. Therefore, building stock LCA simulations consider future construction as well as the operation, maintenance, refurbishment and decommissioning of the stock. In practice, decommissioning is largely neglected as its life-cycle impact is small, representing at most 5% of life-cycle impacts [10,27,71,78–81].

## 3. Review of modelling methodologies

This section describes how the literature search was undertaken and the resulting review of the methodologies used for building energy and emissions stock modelling, broken down by the main life-cycle phases: non-operational (construction, maintenance, refurbishment and decommissioning); and operational.

### 3.1. Review method

The scope of the review was set to capture all non-domestic building stock modelling methodologies covering LCAs on energy and emission, as well as models which focus on individual life-cycle phases.

The review was conducted using the ProQuest, ScienceDirect, SpringerLink and Google Scholar publication repositories. While the first three named repositories were used for the primary search, Google Scholar was used for a secondary search in order to verify results. Only scientific repositories were searched to ensure the quality and reliability of the review's studies and thus of the review results. By extension, most non-peer reviewed (primarily government) studies are included, since many of those are undertaken by research-performing organizations who publish in academic journals [82,83]. The following search terms were used:

- (building OR urban) AND
- stock AND
- (energy or emission or $CO_2$ or GHG) AND
- (model or simulation) AND
- ("non-domestic" OR "non-residential" OR "non domestic" OR "non residential" OR nondomestic OR nonresidential OR commercial) AND
- LCA OR "life-cycle" OR "life-cycle" OR "life-time" OR embodied OR "non-operational" OR "non operational" OR "life-cycle assessment"

**Table 1**
Modelling domestic and non-domestic buildings and building stocks — a comparison of complexity from a German perspective.

| Characteristics | Non-Domestic Buildings (NDBs) | Domestic Buildings (DBs) |
|---|---|---|
| Available building categories by usage | • 79 building categories by usage defined in the *announcement of the rules for assessment of the energy consumption and energy benchmarks of non-domestic buildings in Germany* [34].<br>• 29 and 99 building categories respectively in CIBSE-TM46 [36] and CIBSE Guide F [37].<br>• 17 principle NDB-Forms not considering roof types were identified in the Non-Domestic Building Stock Project [38]. | • four building categories considering building form defined by the TABULA project [35]. |
| Available space types (usage zones) | • 43 usage types definitions for NDBs in the German Standard DIN V 18 599–10 [39].<br>• 86 non-domestic space types are defined in the CIBSE Guide A [41] | • single usage type "living" for domestic buildings according to the German legislation and standard [39,40].<br>• six space types for dwellings recognized in the CIBSE Guide A [41]. |
| Size of usage zones | • Great diversity of zone areas and volumes.<br>• The room height varies from storage room (2 m) to high bay warehouse (50 m [42]) | • Generally smaller zone areas compared to NDBs.<br>• Smaller zone volumes due to generally room heights of about 2,4 to 2.6 m with a maximum of 4.02 m according to analysis of the representative rent index surveys of Darmstadt [43] and Frankfurt [44,45].<br>In Spain the average room height is approximately 3 metres [46]. |
| Mechanical and electrical Systems | • Great specialization and diversity in NDBs which have greater requirements for mechanical and electrical systems as well as controls.<br>• Specialized space needs (e.g. clean environment or biological laboratories) for (e.g. air quality, pressure, lighting, shading, security, temperature). | • The number of systems in the stock of DBs is smaller compared to the NDB-Stock. The complexity of the systems is also assumed to be lower due to less specialized requirements.<br>• Newly constructed energy efficient buildings become more complex due to more implemented systems and home automation. |
| Building envelopes | • Great diversity of envelopes: window area (non, partly, full glass), construction type (heavy to lightweight) and envelope (construction, layers and openings) depend greatly on building use.<br>• NDBs can be categorized as buildings for people (office buildings, hospitals, hotels, etc.) and technical buildings (storage buildings, industrial production buildings, etc.) which leads to different comfort requirements (heating, cooling, lighting) and, therefore, different envelope designs (e.g. insulation, windows, shading). | • Domestic buildings are all intended for housing people and are therefore designed with similar comfort requirements. However, different construction types (lightweight to heavy) can be utilized.<br>• Historically, domestic building construction varies greatly depending on their location in terms materials' availability, climate and traditions [47].<br>• From a buildings regulation perspective in Germany, non-domestic buildings envelopes are not treated differently to domestic buildings [30,40,48–55]. However, in other countries such as Denmark different requirement apply for DBs and NDBs [56]. |
| Building usage times and hours | • Very diverse, depends on purpose and usage. Up to 24/7 facilities. | • Average of 16:47 usage hours per person and day identified by [57].<br>However variance will be great due to diverse user groups (e.g. children, working singles/couples, retired people, unemployed). |
| Life expectancy | • The half-lives of NDBs is 140 years while it is 50 years for Industrial (production) buildings (sample of 1726 of 5250 Buildings in Ettlingen (Germany)) [58].<br>• The average estimated building age that is reached for NDBs in Zürich is 138 [59].<br>• The lower life expectancy leads to a greater stock dynamic compared to the DBS. | • DBs have longer life expectancies with a halve-live of 300 years reported in Ettlingen, Germany.<br>• and For Zürich, Switzerland an average estimated life-expectancy age of 202 years is recorded [58,59]. |

The search focused on the title, abstract and keywords of journal and conference publications or theses (ProQuest only). Where the available options did not allow this, the search terms were applied to the whole document (SpringerLink and ProQuest). The first structured search was conducted from the 16th to 20th of August 2018 and was updated on the 14th of April 2020. Fig. 2 provides an overview of the number of search results of the individual repositories, the screening process and the final omission duplicates and out-of-scope studies.

In total 770 results were generated by the search. The literature identified was then screened to ensure it was within in the study scope by reviewing the title, abstract and conclusions of each publication. The main reason for omission was that the study related to a single building, rather than a building stock (e.g. [84]). Further out-of-scope results such as those focusing on the building users (e.g.[85]) or health impacts (e.g. [86]) were excluded. The resulting 165 documents were then analysed in detail which revealed that 32 were duplicates of the same modelling methodology. A more detailed post-screening analysis identified a further 35 papers which considered single buildings only and so these were excluded also. The resulting collection of 98 studies formed the basis for the review reported in this paper.

### 3.2. Modelling embodied emissions

This section reports the modelling of embodied energy and emissions in BSMs, and focuses on inventory analysis and impact assessment. Inventory analysis involves data collection and its use to estimate all relevant in- and out-flows to and from a product system [73]. The literature identifies different levels of data aggregation associated with stock modelling approaches. For example, in some studies data were collected at an individual building level (e.g. wall, window and floor areas), and in others at an aggregated stock level (e.g. total fuel consumption by type). Since stock models are data-driven, modelling methods similarly fall into detailed and aggregated approaches. Where there is a high degree of data aggregation, a Material Flow Analysis (MFA) modelling methodology is often reported in the literature [27]; this method accounts for energy and material inflows and outflows at the building stock level [9,87–89]. It is often based on national-,

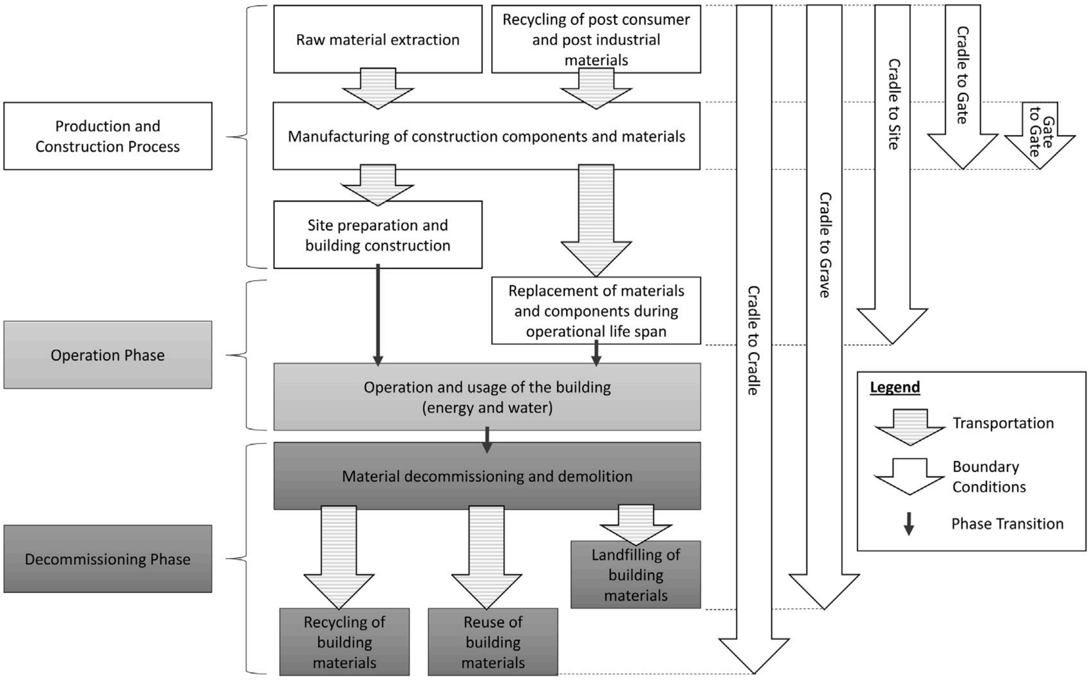


**Fig. 1.** Life-cycle phases of a typical building [71,72] and different possible LCA boundary conditions [72,73]. Own illustration.

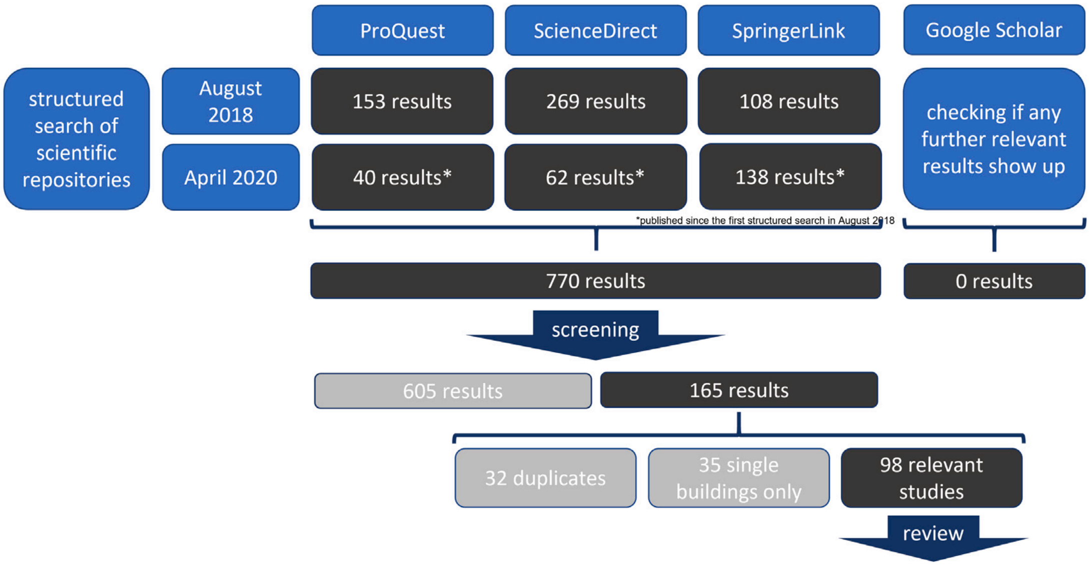
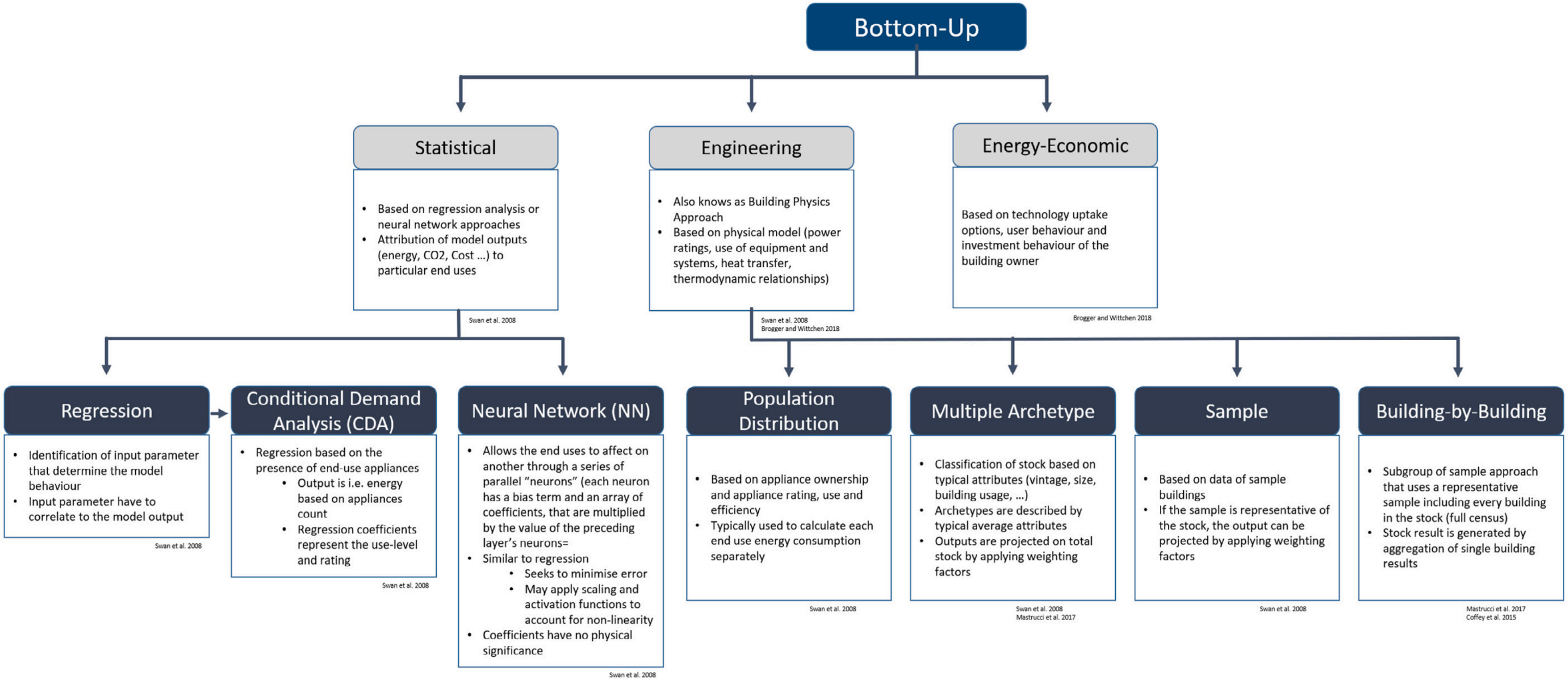


**Fig. 2.** Review methodology of the structured search. Own illustration.

regional- or urban economic statistics such as, for example, the production and sales of insulation materials. Models using disaggregated data reported the use of bills of quantities (BoQ), which consider building materials and elements at the individual building level, before aggregating individual simulation results to a building stock level [9,10,12,13,46,79–81,90–98]. A hybrid combination of both the MFA and BoQ approaches was reported in Seo et al. [99], Yang et al. [100] and Kohler et al. [9] where MFA was used to model past and current stock states, and BoQ were used for forecasting future development.

Stock model life-cycle inventory methods typically employed either process-based or input–output (I–O) techniques. The choice of approach was found to depend on the available data. Process-based approaches involved summing the fuel requirements and emissions for each step in the supply chain for all materials and processes. Therefore, detailed information on material and energy quantities, as well as their emissions factors is required. Input–output indicators require sectoral, regional or national economic-environmental input–output tables; typically these describe the emissions resulting from one euro of expenditure in each sector of an economy. In order to fill data gaps, process and I–O analysis can be combined in a hybrid framework. This can be used when material quantities for process analysis are not available, but expenditure is. In this case, I–O analysis is added to the process based information to form a hybrid approach, taking care not to double-count impacts. The choice of the model simulation scale depends on the available sample size and the level of data aggregation. Examples of the different approaches are given in Section 5.2.2.

The aim of the impact assessment stage is quantify the environmental impacts of the building stock [73] considering the stock inventory and the key life-cycle indicators.



**Statistical**

- Based on regression analysis or neural network approaches
- Attribution of model outputs (energy, CO2, Cost …) to particular end uses

Swan et al. 2008

**Engineering**

- Also knows as Building Physics Approach
- Based on physical model (power ratings, use of equipment and systems, heat transfer, thermodynamic relationships)

Swan et al. 2008
Brogger and Wittchen 2018

**Energy-Economic**

Based on technology uptake options, user behaviour and investment behaviour of the building owner

Brogger and Wittchen 2018

**Regression**

- Identification of input parameter that determine the model behaviour
- Input parameter have to correlate to the model output

Swan et al. 2008

**Conditional Demand Analysis (CDA)**

- Regression based on the presence of end-use appliances
    - Output is i.e. energy based on appliances count
    - Regression coefficients represent the use-level and rating

Swan et al. 2008

**Neural Network (NN)**

- Allows the end uses to affect on another through a series of parallel “neurons” (each neuron has a bias term and an array of coefficients, that are multiplied by the value of the preceding layer’s neurons=
- Similar to regression
    - Seeks to minimise error
    - May apply scaling and activation functions to account for non-linearity
- Coefficients have no physical significance

Swan et al. 2008

**Population Distribution**

- Based on appliance ownership and appliance rating, use and efficiency
- Typically used to calculate each end use energy consumption separately

Swan et al. 2008

**Multiple Archetype**

- Classification of stock based on typical attributes (vintage, size, building usage, …)
- Archetypes are described by typical average attributes
- Outputs are projected on total stock by applying weighting factors

Swan et al. 2008
Mastrucci et al. 2017

**Sample**

- Based on data of sample buildings
- If the sample is representative of the stock, the output can be projected by applying weighting factors

Swan et al. 2008

**Building-by-Building**

- Subgroup of sample approach that uses a representative sample including every building in the stock (full census)
- Stock result is generated by aggregation of single building results

Mastrucci et al. 2017
Coffey et al. 2015

**Fig. 3.** Literature assigned bottom-up model approaches. Own illustration based on [5,25,27,101].

### 3.3. Modelling operational emissions

The operation of a building results in day-to-day energy end uses for heating, hot water, cooling, lighting, appliances and auxiliary equipment. The general approach to modelling operational emissions uses these energy end-uses as the basis for estimating operational GHG-emissions. The products of all fuel consumption and their respective emissions factors are summed for all energy end uses. Energy end-uses are either measured or estimated. While measurement is only possible for existing buildings, simulation models can provide theoretical performance values for any type of building, whether proposed or existing. Generally the theoretical performance of buildings is estimated using computer simulation models that use information on building physics (e.g. geometry, materials, systems), usage (usage schedules and settings) and the environment (climate, weather and shading). Such models can vary from quite simple to very complex. Several modelling tools for operational energy simulation of buildings exist (see Section 5.6 for examples).

Building operational energy models involve estimating energy demands and related emissions in various time steps, typically hourly, monthly or annual [16,26,27,103]. In the case of dynamic stock forecast models which include all life-cycle phases, annual time steps are generally used. Operational energy data of smaller time steps aggregated to annual values (further information in Section 3.4).

#### 3.3.1. Literature-based categorization

In the literature, building operational stock modelling approaches are normally characterized based only on their levels of data input aggregation as 'bottom-up' or 'top-down' [25–27]. However, although this categorization is widely used in literature, no exact definition is presented and the difference between the two approaches is therefore not always clear. Therefore, we adopt the following definitions in this paper.

Top-down models incorporate aggregated building stock input data. A pure top-down model uses data which are representative of the whole stock modelled as a single entity, whereas a pure bottom-up one models each individual building separately. These definitions represent the extremes of a spectrum, between which different levels of data aggregation and modelling resolution lie.

*Bottom-up* The literature describes bottom-up operational stock models as those that use input data at the level of appliances, building systems, end uses or buildings. Analysis is undertaken at a granular level and then aggregated to the level of the building stock being analysed [16].

Approaches in this category include: statistical, building physics and energy-economic models [5,104]. These categories are described in Fig. 3.

Statistical models are generally described as including neural network, regression and conditional demand analysis (CDA), the latter being a regression model estimating operational energy based on the prevalence of end-use appliances in the building stock (see Fig. 3). Regression models utilize statistical relationships between independent input parameters and a dependent predictor, while neural network models identify relationships based on a network of parallel 'neurons' [104].

Engineering models rely on building physics to calculate energy requirements. Population distribution approaches use the ownership structure, concentration, use and efficiency of appliances as engineering model inputs to estimate energy end-use separately for each building [25]. The multiple archetype approach employs building archetypes which are representative of the building stock and have 'typical' attributes (e.g. building type, occupancy patterns). These are separately modelled and the results are proportionately scaled to represent the stock being analysed [25,27]. Instead of using archetypes or building types, the sample-approach uses representative samples of building data as inputs to engineering models. A further engineering model simulation approach documented in the literature is the building-by-building approach, also known as 'micro simulation' [105]. It is identical to the sample-approach except that the entire population of buildings is simulated and the building stock result is obtained by aggregating all single-buildings results [27].

Energy-economic approaches focus on the building user and rely on statistical methods. They attempt to replicate the user's behaviour (e.g. tenants and owners) with regard to technological uptake, energy end-use behaviour and the ecological and social influences affecting the use and development of building stocks [5].

*Top-down* Top-down modelling approaches treat the building stock system as a single energy user and do not differentiate between different energy end uses. They use regression methods and commonly employ [25,26] independent variables such as "macroeconomic indicators (gross domestic product, employment rates, and price indices), climatic conditions, housing construction/demolition rates, and estimates of appliance ownership and the number of units" [25].

The literature gives examples of top-down models which can be categorized as either statistical (including neural network) or hybrid (see Fig. 4). [25]. Statistical models can be further divided based on model input data into: econometric, technological and population-driven (see Fig. 4). For example, econometric models use monetary inputs such as prices or incomes (e.g. [106]) [25,26], whereas technological models use stock characteristics such as the prevalence of devices and systems, as well as technological developments and structural change [25,26]. Population-driven statistical models focus on the influence of regional populations on building stock performance [107].

### 3.4. Dynamic stock forecast model

Here, a model is considered dynamic when it represents the building stock's development over time. Different time intervals may be considered, such as monthly, annual or multi-annual. This results in changes in the values of variables including building stock attributes (e.g. number of buildings, floor area) and derived attributes (e.g. building retrofit share, area of envelope insulation). Dynamic stock forecast models can be used for simulation of future stock characteristics. This process is referred to as forecasting. Depending on the modelling objectives and the available data, several forecasting approaches were identified in the literature. These can be categorized as trend forecasting, aim targeting, stock turnover, environmental change and hybrid approaches.

Trend forecasting uses trends observed in historic data to estimate future building stock states including, for example, population, floor area per person or envelope U-values [11,100,108,109]. Aim targeting forecasts future states by considering likely future policies and targets such as legislative priorities or general building stock targets. For example, this could include GHG-emissions reduction targets to be achieved over a specified time horizon, or reaching particular legislative aims for the year 2050. The forecast is made by choosing certain building stock parameters (e.g. refurbishment rates and rates of boiler replacement) which are necessary to achieve policy or regulatory goals. Often a combination of trend forecasting and aim targeting is used. Hybrid approaches use a combination of trend forecasting and aim targeting for stock forecasts [32,56,103,106,110–126].

The stock turnover approach considers the interactions of different building stock characteristics. For example, not only might a refurbishment rate be defined, but this could be a function both of building age and the service life of different building components [4,13,107, 127–130]. A further extension is the inclusion of likely stakeholder behaviour; these are referred to as agent-based approaches [131–134]. System dynamics and MFA are also stock turnover approaches. The former is based on causal relationships that define the interaction between the building stock's in- and out-flows (see [135] for a detailed introduction). The latter uses material and energy balances to simulate the stock's development in time (see also Section 3.2. Examples include [87,88,102,136–139]).

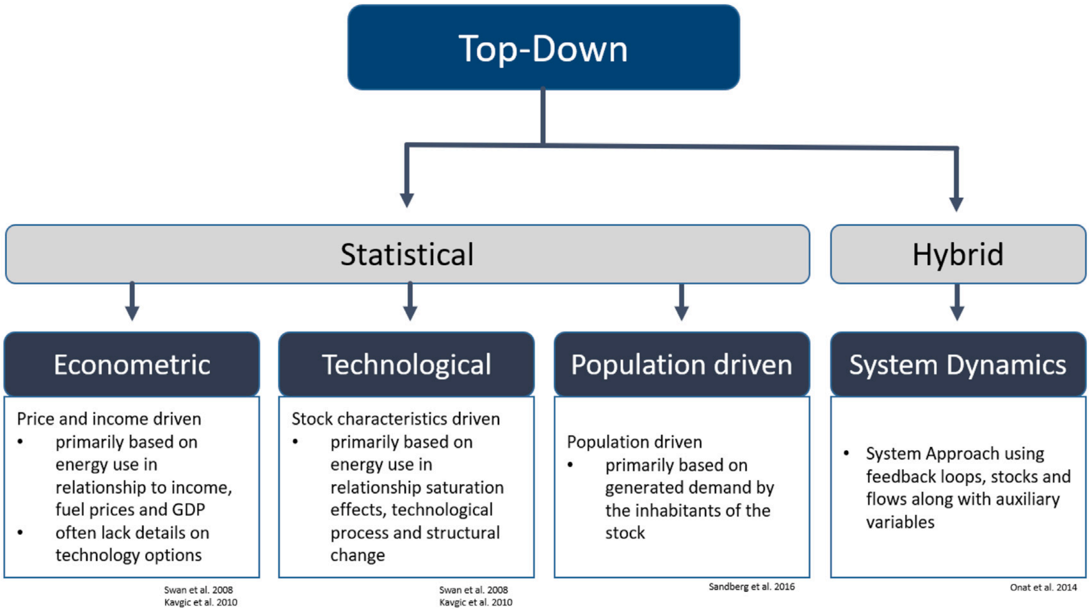


**Fig. 4.** Literature assigned top-down model approaches. Own illustration based on [25,26,102].

Apart from changing building stock parameters, the dynamic development of important input variables such as weather data can also be considered; this is referred to as climate model input. Typically this analysis is undertaken while holding building stock parameters constant and has been used to explore future stock characteristics such as internal comfort or cooling requirements [122,140].

### 3.5. Maintenance

For all modelling approaches it is necessary to include the replacement and service cycles of building materials, components and systems. Although the choice of these intervals is important, a scarcity of data was reported which affected the ability to model this life-cycle stage. While several standards and guidelines exist which consider maintenance as part of design-stage life-cycle costing [141,142], these provide little supporting data. The following small number of building efficiency- and LCA-studies provide component life expectancies [9,71,143–146].

## 4. Proposed categorization system

It can be seen from the foregoing that top-down and bottom-up statistical approaches are similar, thus making it very difficult to categorize BS models based either on modelling approach or data type employed. Similarly, confusion arises in the case where a top-down engineering approach is used to model a single archetype, since this is similar to the multiple archetype approach [11]. It can be observed that the main difference between the bottom-up and top-down classes is not the type of model used, but rather the level of input data aggregation when simulating the building stock. Therefore, when discussing building stock modelling, it is important to distinguish the modelling technique (engineering, data science etc.) from the scale of the model simulation (building-by-building, archetype etc.). The lack of specificity, and the widespread use of the classification system in the literature, complicates the comparison and discussion of stock modelling methodologies and sometimes results in the ambiguous allocation of a modelling approach to one of the two groups [135]. Therefore, an alternative operational phase building stock model classification system, based both on the level of input data aggregation and the modelling technique employed, is proposed below in Sections 4.1 and 4.2.

### 4.1. Modelling method classification

It has been mentioned above that there are currently two main classes of operational stock modelling methods reported in the literature: ‘statistical’ and ‘engineering’. However, the term ‘statistical’ does not encompass a number of techniques such as neural networks and machine learning. For this reason, the modelling method classes ‘data science’ and ‘engineering’ are adopted here. Data science models, which are empirical models, include regression and neural networks, while engineering models represent the systems on a building physics basis. Both approaches use data at all levels of data aggregation, but differ in the independent variables required. Data science models require both system input and output variables and model the system even where there is no direct physical relationship between these. Pure engineering models require only independent input variables, and model outputs based on the laws of physics. System output variables are required in engineering models only for the case of validation.

*Data science* All the data science models reviewed use either statistical techniques such as statistical regression [12,106,109,120,147–156] or machine learning techniques like neural networks [104]. The only neural network approach noted in the literature by Swan et al. was, however, used in combination with a building physics approach for operational energy simulations; no pure neural network approach was identified.

*Engineering* Engineering approaches to estimating operational energy incorporate building physics-based models including computational fluid dynamics or steady state thermodynamic models. These models all are based on heat transfer, mass flows, thermodynamic relationships, external radiation gains and internal gains of occupants, lighting and appliances. They estimate operational energy demand based on building, occupant and environmental parameters as well as the physical relationships of the building with its environment and internal interactions (e.g. heat gains from occupants and equipment). Additionally, they may model fuel consumption and emissions based on the characteristics of the relevant supply technologies. Building physics building stock models have been developed by many researchers (see Section 5.2.3 for more details) and can be applied at different levels of data aggregation. For example, a single archetype approach involves modelling the entire stock based on one ‘average’ or representative building type. The use of multiple representative archetypes increases modelling resolution. This can be further improved using large building samples or building-by-building approaches [25,27,101].

*Hybrid approach* The combination of the data science and engineering modelling approaches is called hybrid modelling. These models use the benefits of both modelling techniques by combining two or more modelling methodologies. One example is the Canadian Hybrid Residential End-use Energy and Emission Model (CHREM) by Swan et al. [104].

Fig. 5 provides an overview on which studies belong to each modelling category.

### 4.2. Model simulation classification

Model simulation involves inputting a data set into the model to simulate output results. Therefore, the model simulation classification should include information on the nature and level of input data aggregation (see Fig. 6).

Where data are highly aggregated, two types of model input are possible: lumped stock and single archetype. The former represents a building stock as a single entity (for example see Sandberg and Brattebø [136]), while the latter identifies 'average' stock building attributes combined into one representative archetype (see Teh et al. [11]).

Multiple archetype inputs can be seen as the next level of aggregation. Here, a number of representative archetype buildings are selected from available data, with the size and scope of the sample determining the number and nature of archetypes.

The next level of data aggregation is the individual building level, comprising individual building elements including their geometries and material properties. Simulations using building level data use, for example representative sample data of a subset of the population, as done by Mutani et al. [154] and Oliveira Panão and Brito [157]. Simulations using population-level data are resulting in building-by-building results. Examples of these data being used are [106,149–151,155] for the use as inputs to data science models as well as [91,95,158–161] for the use in engineering models.

There are several studies in the literature which use building component and content input data, the most granular being at the level of individual appliances (see Kadian et al. [106]).

### 4.3. Combined classification system

The foregoing highlights the need to consider both the model employed and the level of data aggregation used in the model simulation, when characterizing building stock modelling studies. Therefore a clear classification should include both the modelling technique and model simulation data involved. Fig. 7 presents such a classification 4.1 and 4.2 respectively.

The reference studies in the dark grey bubbles use model simulation input data from only one aggregation category, while the studies in the light grey bubbles use data from two categories.

## 5. Literature meta-analysis

In addition to the general review of stock modelling literature reported above, a quantitative study of the prevalence of different methodological approaches used to model the building stock was undertaken. The meta-analysis involved the systematic collection, collation and classification of relevant study data in order to: (1) identify the main reasons for undertaking such studies; (2) establish the variety of building stock modelling approaches; (3) understand how they are used for forecasting; and (4) highlight possible research gaps. It considered the 26 building stock life-cycle assessment studies identified above

### 5.1. Modelling goal and scope

The goal and scope of each study was reviewed using the ISO 14040 categories [73] in order to understand: the life-cycle phases considered; the building elements and components included; the extent to which operation, maintenance and retrofitting are addressed; the nature of the building stocks modelled; and study objectives. Relevant results are described below and summarized in Table 2.

#### 5.1.1. Life-cycle phases in life-cycle assessment building stock models

The cradle-to-site life-cycle phase, which includes building materials' manufacturing and stock construction was included in all the studies analysed. Operation was considered in almost all studies (85%), while refurbishment was included in 81%. End-of-life was most frequently omitted and featured in only 35% of studies, with maintenance only considered 42% of the time. While cradle-to-site, operation and refurbishment typically are the main contribution phases to the whole life-cycle impact of buildings, the less influential end-of-life [27] and maintenance were often neglected. The significant uncertainties regarding end-of-life impacts, which occur many years into the future, may have brought model developers to the decision to omit their effects. And the scarcity of maintenance data may have also resulted it the omission of this stage from most models.

Only one whole life-cycle building stock study included non-domestic buildings [9]. This study also considered forecasting, costs and GHG-emissions, but did not include uncertainty analysis. It can be observed that the more complex the model output, the less likely it is to be considered in the literature. For example, many models consider energy and, to a lesser extent, emissions, while very few address cost–benefits. This omission is likely due to the limited resources available for modelling exercises.

#### 5.1.2. Building components and systems

The extent to which different building components and systems are considered is important when comparing models. Five main representations were identified in the literature:

- *buildings* distinct existing buildings are represented and are considered in their entirety. This includes the building envelope, internal structure and divisions, systems and may include new construction and demolition;
- *new buildings* are buildings that will be added to the existing building stock (new construction);
- *envelope refurbishment* involves all materials, components and actions as part of a future refurbishment of the building envelope.
- *infrastructure* encompasses existing road and public transport, fuel, electricity and water supply, that are necessary for the building to work as intended;
- *systems* includes the building services such as lighting, HVAC, renewable energy generators, electricity distribution, water distribution, heating and cooling.

Fig. 8 and Table 2 summarizes the scope of building components and systems addressed in the studies reviewed. Table 2 shows that the entire building scope is considered in four models [9,79,88,136,162,163], the building without systems in four [10,11,13,94] and buildings including supporting infrastructure by three [12,89,100]. One study each focused on new buildings with [97] or without [80] infrastructure. Refurbishment was also found to be a significant focus area: eight studies assess the refurbishment of both the envelope and building systems [81,82,92,95,96,98,164,165] with a further four addressing envelope refurbishment only [87,90,91,93,99] (one excluding windows) [90,91]. One study involved a façade refurbishment excluding windows, roof and basement refurbishments [46].

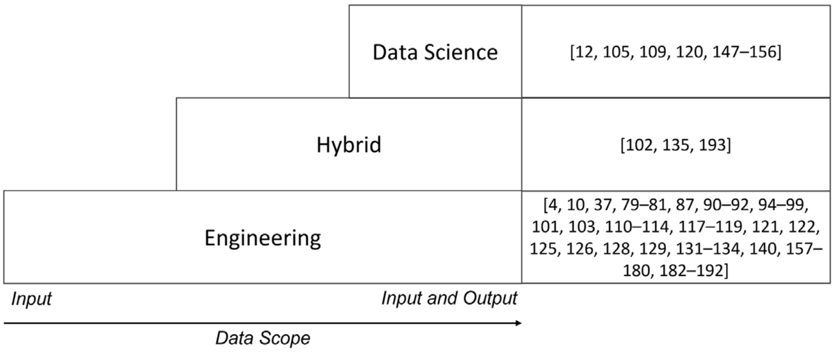


**Fig. 5.** Model classification in modelling technique categories. Own illustration.

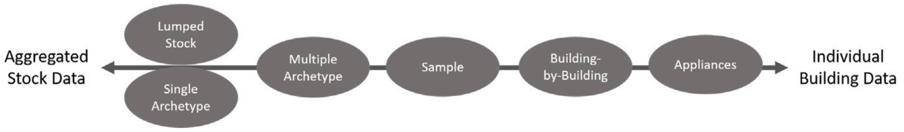


**Fig. 6.** Model categorization based on input data aggregation level of model simulations. Own illustration.

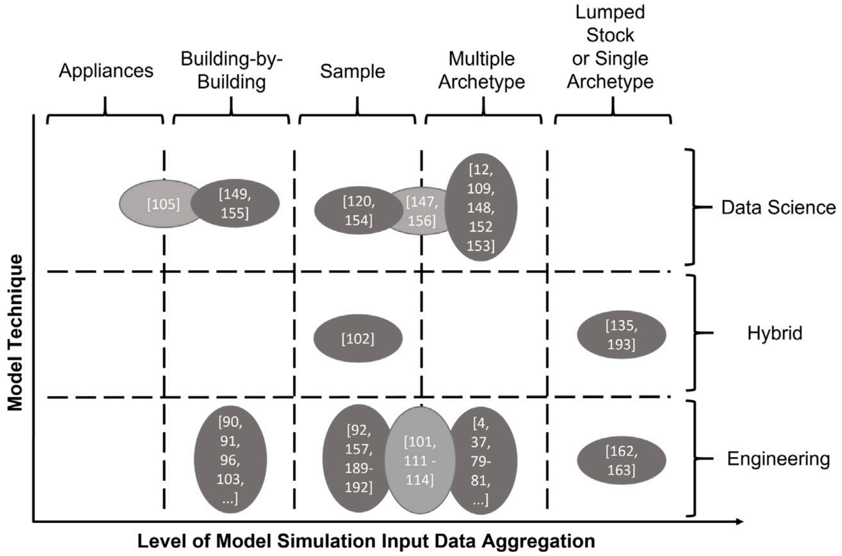


**Fig. 7.** Combined BS model simulation classification system based on simulation input data aggregation and modelling technique, with reference studies. Own illustration.

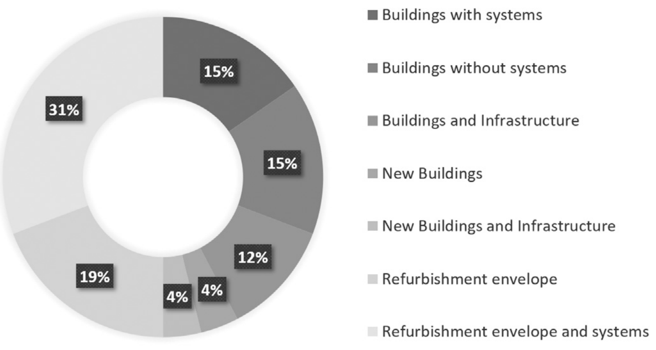


**Fig. 8.** Covered objects in LCA-models.

### *5.1.3. Operation, maintenance and refurbishment*

Most life-cycle building stock models involved estimating the material and energy requirements associated with refurbishment and maintenance cycles; . only four did not [11,13,89,97] (Table 2).

As stated above, 26 BSM studies were identified which encompassed at least the production and construction life-cycle phase (cradle-to-gate), while a further 72 covered only building operation. However, given the importance of the operational phase, all 98 studies are included in the following sections, discussing operation.

### *5.1.4. Building stock category*

Table 3 shows that more than half of the studies (51%) consider domestic buildings only, while 33% include both domestic and non-domestic buildings, of which only five are LCA-models [9–13] (see Table 2). Just 16 studies (16%) specifically focus on the non-domestic sector of which only one is an LCA [82] (see Table 2). There is obviously a research gap of models focusing on the more complex NDBS. Beside the higher complexity of the NDBS also data covering this stock is scare (see Section 5.2.1) and might lead to this negligence.

**Table 2**
Key characteristics of the LCA studies reviewed including life-cycle phases and model attributes considered (D — Domestic; ND — Non-Domestic; ND&D — Non-Domestic and Domestic).

| Study | LCA Inventory | | LC-Phases | | | | | LCA Impact | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stock | Coverage | Cradle to site | Operation | Maintenance | Refurbishment | End-of-life | Forecast | Cost | GHG | Uncertainties | Impact assessment approach |
| [162,163] | D | Buildings | Yes | Yes | Yes | Yes | Yes | No | No | Yes | No | Process-based |
| [81] | D | Refurbishment envelope and systems | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | No | Hybrid |
| [46] | D | Refurbishment facade (no windows) | Yes | No | No | Yes | No | No | No | Yes | No | Process-based |
| [82] | ND | Refurbishment envelope and systems | Yes | Yes | Yes | Yes | Yes | No | No | Yes | Yes | Process-based |
| [90] | D | Refurbishment envelope (no windows) | Yes | Yes | No | Yes | No | No | No | No | Big sample | Process-based |
| [79] | D | Buildings | Yes | Yes | No | Yes | Yes | No | Yes | Yes | No | Process-based |
| [87] | D | Refurbishment envelope | Yes | Yes | No | Yes | Yes | Yes | No | Yes | No | Process-based |
| [92] | D | Refurbishment envelope and systems | Yes | Yes | No | Yes | No | No | Yes | Yes | Yes | Process-based |
| [93] | D | Refurbishment envelope | Yes | No | No | Yes | Yes | No | No | Yes | No | Process-based |
| [165] | D | Refurbishment envelope and systems | Yes | Yes | No | Yes | No | Yes | No | Yes | No | Process-based |
| [164] | D | Refurbishment envelope and systems | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Big sample | Process-based |
| [88,136] | D | Buildings | Yes | Yes | No | Yes | No | Yes | No | Yes | No | Estimation |
| [99] | D | Refurbishment envelope | Yes | Yes | Yes | Yes | No | No | Yes | Yes | No | Input–output |
| [94] | D | Buildings (no systems) | Yes | Yes | No | Yes | No | No | No | No | No | Process-based |
| [10] | ND&D | Buildings (no systems) | Yes | Yes | Yes | Yes | No | No | No | Yes | Yes | Hybrid |
| [11] | ND&D | Buildings (no systems) | Yes | No | No | No | No | Yes | No | Yes | Yes | Hybrid |
| [95] | D | Refurbishment envelope and systems | Yes | Yes | No | Yes | No | Yes | Yes | Yes | No | Process-based |
| [9] | ND&D | Buildings | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | Hybrid |
| [12] | ND&D | Buildings and Infrastructure (Transport and Utilities) | Yes | Yes | Yes | No | No | No | Yes | Yes | No | Estimation |
| [89] | D | Buildings and Infrastructure (Transport and Utilities) | Yes | Yes | No | No | No | No | No | Yes | No | Input–output |
| [96] | D | Refurbishment envelope and systems | Yes | Yes | No | Yes | No | No | No | No | No | Process-based |
| [97] | D | New Buildings, Infrastructure (Transport) | Yes | Yes | No | No | Yes | No | No | Yes | No | Process-based |
| [13] | ND&D | Buildings (no systems) | Yes | No | No | No | No | Yes | No | Yes | No | Process-based |
| [80] | D | New Buildings | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | No | Process-based |
| [98] | D | Refurbishment envelope and systems | Yes | Yes | Yes | Yes | No | No | No | Yes | No | Process-based |
| [100] | D | Buildings and Infrastructure (Transport and Utilities) | Yes | Yes | Yes | Yes | No | Yes | No | Yes | No | Process-based |

**Table 3**
Building stocks considered in the review study.

| Stock | Share |
|---|---|
| Domestic building stock | 51% (n = 50) |
| Domestic and non-domestic building stock | 33% (n = 32) |
| Non-domestic building stock | 16% (n = 16) |

**Table 4**
Aims and objectives of stock modelling studies: directly stated and implied.

| Aim | Directly stated | Implied |
|---|---|---|
| **A:** methodology development and proof of concept | 12% (n = 12) | 88% (n = 86) |
| **B:** embodied and/or operational impacts (implies A) | 38% (n = 37) | 53% (n = 52) |
| **C:** impacts of measures/policies (implies A and B) | 46% (n = 43) | 9% (n = 8) |
| **D:** policy information/support (implies A and B and C) | 22% (n = 22) | 0 |
| **E:** historic development | 4% (n = 4) | 0 |
| **F:** forecasting (implies A and B) | 27% (n = 26) | 0 |
| **G:** uncertainty analysis/impact (implies A and B) | 2% (n = 2) | 0 |
| **H:** flexibility options (implies A and B and C) | 1% (n = 1) | 0 |
| **I:** exergy efficiency (implies A and B) | 2% (n = 2) | 0 |

### *5.1.5. Aims and objectives*

Aims and objectives were categorized based on the statements in the aim and objective sections of the studies. Where these were unclear or missing, findings were used to imply a study's aims. It can be seen in Table 4 that of the 98 studies dealing with methodological development and model testing, only twelve directly state these aims. The overall aim of the majority of studies (91%) is to estimate the operational and/or the embodied impacts of a particular building stock, both in its current form and under different simulated future scenarios. In this context 'impacts' are either input (e.g. energy, material and cost) or output flows (e.g. $CO_2$, GHG, waste and other environmental impacts). The most common simulation scenario (56%) is to identify the effects of energy efficient refurbishment measures on the building stock or its supply systems (e.g. electricity, transport, green materials) and/or to investigate the effects of policies (regulations and market interventions); 50% and 65% of NDBS and LCA-BS studies respectively specifically mention this aim. 22 (22%) studies target the generation of knowledge for policymaking, while forecasting the impacts of building stock development is mentioned in 26 (27%) studies. Very few studies focus on historic stock development (4%), uncertainty analysis (2%), the identification of flexibility options of grid power peaks (1%) and exergy efficiency in the building stock (2%)

Mastrucci et al. reviewing 15 LCA-BSMs identified three main study goals; these are similar to the findings reported above: 'evaluation of the environmental impacts in the current state' (40%), 'comparison with an ideal future state of the stock' (40%) and 'assessment of the evolution of the stock in medium-long term scenarios' (20%) [27]

### *5.1.6. Functional units*

The functional unit measures the primary purpose of the building stock model and allows for the comparative analysis and communication of the simulation results. The functional units used in the studies are not part of this review since an overview is already provided in [27]. In summary, typical functional units include per unit area of building (e.g. heated-, gross-floor-, living-, land-area), per capita, per retrofitting measure and per construction measure; both annualized and over the life-cycle.

## *5.2. Inventory analysis approaches*

This section describes the approaches to:

- estimating non-operational inventory life-cycle impacts (material- and energy-flows);
- estimating operational inventory life-cycle impacts;
- forecasting building stock development;
- model validation and calibration.

### *5.2.1. Inventory-data approaches*

Section 4.3 describes that it is possible to characterize building stock modelling approaches by either the type of modelling technique used (mainly engineering and data science — see Section 5.2.3) or by the level of input data aggregation. Section 4.2 gives an overview of the different input data aggregation types (data approach categories) available for stock modelling, and it is observed that the methodology used often depends on the available data. Therefore, this section characterizes the literature by the data approach categories of the input data used.

Table 5 shows that just over half (53%) of studies use archetype data and fall into the archetype approach category. One possible explanation for its popularity is that the archetype approach to stock modelling is sufficiently flexible to combine archetype-specific information with average statistical data in order to fill data gaps where necessary; at the same time, more detailed, representative archetype data can be used where available. Also, depending on the number of archetypes used, the approach can be a statistical representation of the stock (i.e. using a single archetype), or closer to a BbB approach (multiple representative archetypes). For this reason, many stock modelling approaches are combined with available archetype data. For example, 12% of the sample which use a BbB approach utilize archetype data to supplement the available building-specific data. Three of the 'sample-data' approaches specified in Section 4.2 also use this approach. Two studies combined archetypes with a lumped stock approach [9,162,163], while one study used a single archetype [11]. Of the remaining 28 studies that do not utilize archetypes, twelve employ building-by-building, nine sample and seven lumped stock data sets.

The data aggregation categories used in studies focusing on NDBSs were archetype, building-by-building, sample and lumped stock. These were not appear to be correlated to the type of stock being assessed, whether domestic, non-domestic or mixed. 20 of 26 LCA-BSM studies use archetypal data (14 archetype, three BbB & archetype, two archetype & lumped stock and one single archetype); of the remaining six, four used building-by-building, one sample and one lumped stock. There is a clear tendency towards the use of archetypal input data for LCA-BSMs, which is possibly related to a lack of computational power, resources or data. Nonetheless, a wide diversity of LCA-BSM data input variables and sample sizes used in the models, indicating that it is sometimes possible to obtain detailed data sets with a high granularity.

*Input data types* A wide range of input data types was observed in the study sample. In total, 86 different categories of data were identified. The most widely-used input data related to the physical buildings, and are categorized as the 'building' input data category. The sample contains 380 distinct building category variables and includes, for example, 'building age', 'building use', 'building typology', 'building energy systems' or 'thermal envelope data'. The next most common input data category is 'stock' (46 instances), which includes numbers of existing buildings, refurbishments, new constructions and households. Other common categories include: 'Occupant' (27 instances),

**Table 5**
Data approaches of reviewed studies.

| Data approach category | Share in stock-category and number | Studies |
|---|---|---|
| **Archetype approach — 71% (n = 70)** | | |
| Archetype | 53% (n = 52) | [4,12,13,33,38,79–82,87–89,93,94,97–100,107–110,115–119,121–126,128–134,138–140,148,152,153,166–181] |
| Building-by-building in combination with Archetypes | 13% (n = 12) | [10,46,95,150,151,159,161,182–186] |
| Sample in combination with Archetype | 3% (n = 3) | [103,111–114,147,156] |
| Archetype in combination with lumped stock | 2% (n = 2) | [9,162,163] |
| Single Archetype | 1% (n = 1) | [11] |
| **Other approaches — 29% (n = 28)** | | |
| Building-by-Building | 13% (n = 12) | [90,91,96,101,106,149,155,158,160,164,165,187,188] |
| Sample | 9% (n = 9) | [32,92,104,120,154,157,189–192] |
| Lumped stock | 7% (n = 7) | [56,88,102,107,127,135,136,193] |

'Weather/Climate' (27 instances), 'Energy use' (25 instances) and 'Environmental' (25 instances) data. Less frequent categories include: 'Economic' (10 instances), 'Geographic' (9 instances), 'Infrastructure' (5 instances) and 'Uncertainty' (2 instances) information.

The input data categories are presented in Fig. 9 including their observed frequency in the study sample.

While most input data types are used with both engineering and data science modelling techniques, some are only employed in one or the other. For example, geometry, location, construction numbers, component typology and year of last refurbishment are input data types to engineering models only. Tenure, maintenance status, GDP, employment data and household income, amongst others, are only used in data science models. Engineering models use either information that can be directly used for building energy calculation or classifying data (e.g. building age) which points towards statistical data (e.g. average u-value of building age class) which can be used to compliment the available data. In comparison, data science models typically use statistical data.

*Input data sources* Input data sources are very diverse since every country, if not every region, collects building stock data in a non-standardized way. While a detailed analysis of input data sources is beyond the scope of this review, some data sources which were commonly observed include:

- Building input data, including:
    - Data on a building's geometry generally provided by Cadastral Registers, Land Registers, Open Street Map (OSM) and Regional cartography data;
    - Information on the other physical attributes of the building's are typically obtained from building typologies (i.e TABULA [194] and EPISCOPE [195]), census data, building surveys (i.e. Commercial Building Energy Consumption Survey (CBECS) [62] or English Housing Survey (EHS) [196]), stock asset ratings, building statistics, building standards (i.e. DIN 4108-4 [197]), sample buildings, building energy certificate databases, building insurance companies and national regulations;
    - Data on life-cycle impacts (i.e. building carbon footprint), life expectancies, building internal layout, components and material properties are in most studies drawn form other scientific studies, life-cycle impact indicator databases (i.e. Ökobaudat [198]) and standards (i.e. VDI 2067 [141]);
    - Further building related data usually for data science models like building and property values, energy expenditure, equipment possession rate, water consumption, number of energy metres or number of bathrooms are taken from tax assessor data, census, national statistics, energy providers and family expenditure surveys.
- Economic data is reported from three sources: Cost databases (i.e. BKI [199] or EnergyPLAN [200]), other scientific studies and national statistics.
- Energy use data is drawn from building energy certificate databases, building surveys, sample buildings, energy providers and smart metre data.
- Environmental data for example life-cycle impact indicators and embodied energy impacts come from life-cycle impact databases and tools such as Ecoinvent [201], GABI [202], ÖKOBAUDAT [198], SimaPro [203] and GEMIS [204], but also from other scientific studies.
- Geographic data, for example location data, elevation models, urban area types, travel and transport distances are obtained from cadastral, land registers, Open Street Map (OSM) [205], regional cartography data, LiDAR data, other scientific studies and national or global topology/elevation models.
- Infrastructure data, such as typical infrastructure materials, infrastructural typology, and infrastructural GIS models are taken from other scientific studies, Open Street Map (OSM) [205] and Google Maps [206]
- Occupant data (i.e. occupant composition, tenure, household income and energy patterns) is typically obtained from census, survey data and standards.
- Regional data on energy and material flows, industrial production, modal split, population development, GDP, employment data and income development are obtained from national statistics, census and other scientific studies.
- Stock data, typically numbers on buildings, households, new construction, refurbishments and the overall stock development are provided by cadastral databases, land registers, buildings statistics, building surveys, census, stock asset rating survey and other scientific studies (i.e. ENTRANZE [207] and ODYSSEE [208]).
- Input data distribution for uncertainty assessment were used from building surveys, building statistics and other scientific studies.
- Weather/Climate data sets are taken from national regulations, national meteorological data sets (i.e. DWD [209]), global meteorological data sets (i.e. NOAA [210]), standards, other scientific studies and climate models.

### 5.2.2. Non-operational phase inventory-model approach

Many of the LCA building stock modelling studies (69%) referred to in Table 2 use a process-based LCA approach. This involves modelling a system's inventories at the process- and material-levels [27,211]. Only two of the studies use an input–output LCA methodology [89,99] utilizing sectoral economic and environmental data from national accounts [27,211], while four use a hybrid of process-based and input–output LCA [9–11,81]. While modelling and analysis concludes at the LCIA stage for the majority of studies, a simple estimation of life-cycle impacts is conducted in two works [12,88,136]. In these instances, estimation is undertaken using the results from other studies which estimate the life-cycle impact of representative buildings. For example, the specific embodied energy per square metre, used in combination with the building stock floor area is used to estimate the embodied energy in the stock. One possible reason for the dominance of process-based LCA approaches is that it is the best approach for estimating

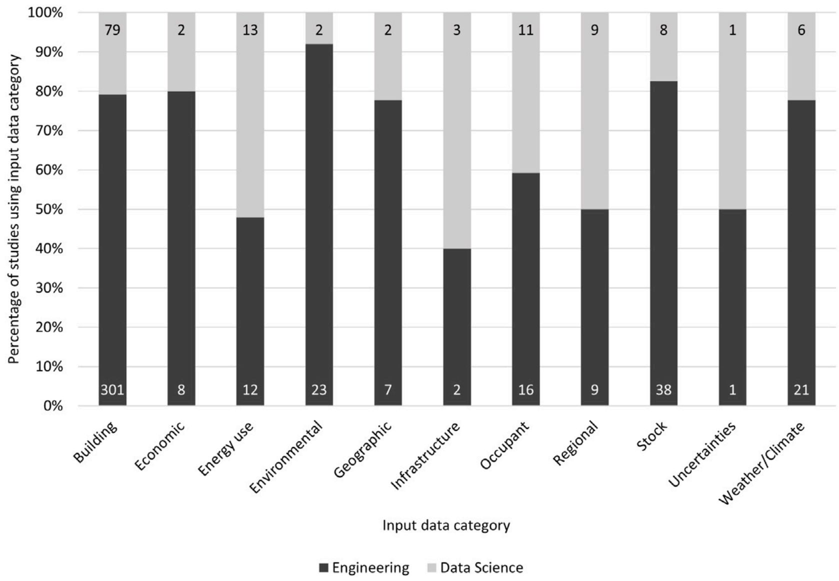


**Fig. 9.** Input data fields used in the reviewed studies. Count and share of studies reporting input data types assigned to the input data fields by model approach.

the future impacts of building stocks. Input–output analysis uses economic emissions intensities which rely on past sectoral economic and environmental data and are complex to derive; they are not easily projected into the future. Process-based approaches use, for example, fuel emissions factors, which are more easily forecast. Consequently, only process-based LCA approaches are useful for models considering future states of the BS.

### *5.2.3. Operational phase inventory-model approach*

An engineering/building physics approach was used as a modelling method for operational energy and emissions in the majority of models reviewed during this study (58%). A possible reason for this is the flexibility of this approach. Such models can be fed either with aggregated data (e.g. single archetype) or detailed information (e.g. BbB). In contrast to data science models (e.g neural network or regression), the engineering/building physics approach does not require large representative training data-sets. Five studies use an engineering/building physics approach; these are used with energy use intensities in conjunction with building type dependent normalized energy use intensities $(\frac{\mathrm{kWh}}{\mathrm{m}^2\ \mathrm{a}})$ estimated by others (n = 3) [99,160,162,163], neural networks (n = 1) [104] or regression (n = 1) [193]. Regression techniques are the second most used approach, accounting for 14 studies of which 12 use pure regression; one combines the approach with stochastic-sensitivity [156] and the other also uses a conditional demand analysis approach [106]. Of the remaining 22 studies reviewed, 14 apply energy use intensities, one uses a system dynamics approach to determine US housing stock GHG-emissions [135] while the remaining studies do not consider the operation phase (n = 7). No preferred modelling approach was observed for domestic or non-domestic stocks. The tendency towards engineering/building physics approaches was also reported by Mastrucci et al. [27] as well as Brøgger and Wittchen [5].

### *5.2.4. Forecasting models*

Of the 98 studies reviewed, a total of 40 (41%) include forecasting for simulating the future development and impacts of the building stock.

The approaches taken are shown in Fig. 10. Trend forecasts account for 4% of studies, while aim targeting is used in 8%. Nine studies (10%) were observed in the survey combining both trend forecasting and aim targeting in a hybrid approach. Stock turnover models were used in 14% of the studies.

Furthermore, agent-based and climate model input approaches were observed in 3% and 2% of studies respectively.

There was no significant difference in forecasting method observed for domestic and non-domestic stock models. Two agent-based forecasting approaches were applied to NDBS models [131,134] and one to a entire building stock model (ND&D) [132,133]. No agent based forecasting approaches have been applied to DBS models. The forecasting methods applied to the small number (n = 9; 35%) of LCA-BSMs were mainly based on turnover models, including MFA (stock turnover: n = 2, MFA: n = 3) but also trend forecasting (n = 2), policy aims (n = 1) and a combination of trend forecast & policy aims (n = 1). Only 20% of the 15 LCA-BSM studies reviewed by Mastrucci et al. considered stock dynamics and evolution [27].

All models use one or more key independent variables to explore future stock development, hereafter referred to as “drivers”. It was found that the maximum number of drivers used in any forecast was three, while most studies consider just one or two. The use of only few drivers may be due to the significant forecast uncertainties associated with key stock model drivers, which are often model outputs themselves. Therefore, the greater the number of model drivers, the greater the BSM output uncertainties. This, in combination with the uncertainties in the typical BSM input data and the problems with validation (see Section 5.2.5] may explain the limited use of drivers in a single simulation. In total fifteen different driver types were identified and are described in Table 6.

### *5.2.5. Model validation and verification*

Validation is the comparison of the model results to the behaviour of the real system [212–214] and so requires suitable system data. For this reason, full validation of LCA building stock models is not feasible, since measuring the behaviour of such a complex system is practically impossible [27]. Verification does not require system data [212,213,215] and can be conducted in different ways, for example via peer review or expert opinion, comparison with other studies or by confirming the appropriate behaviour of the model under different input conditions.

No reference was found to either validation or verification in 35% of the studies reviewed, with the balance applying some form of validation and/or verification.

In general, validation was based on building-level data or national statistics, and verification by comparison with other studies and other approaches. A detailed summary of the approaches adopted are provided in Table 7. In general LCA-BSMs are practically impossible to

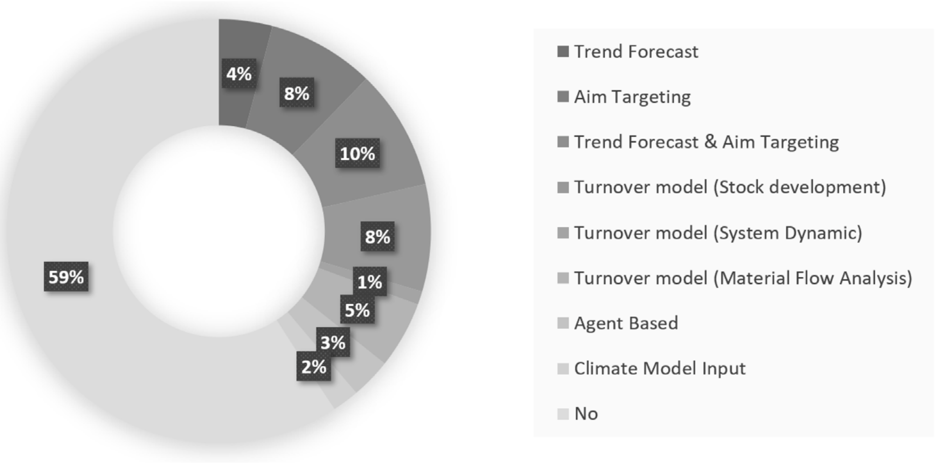


**Fig. 10.** Forecast approaches taken in the reviewed studies.

**Table 6**
Forecasting drivers identified in the literature.

| Driver type | Description of driver | Number of drivers |
|---|---|---|
| Population development | How has and probably will the number of the inhabitants (users) of a building stock develop | 7<br>[100,102,106,107,109,128,130] |
| Building owner behaviour | How is the behaviour of the building owners in regards to the buildings (investments, refurbishment and so on) and how will they probably react in the future to e.g. economic changes, policies, climate change | 1<br>[134] |
| Building stock development | How has the building stock developed in the past and how might it develop in the future | 12<br>[4,9,11,103,111–114,117,119–121,126,127,129,130] |
| Building construction | How many buildings have been constructed in a certain time step in the past and how will that likely be in the future. What is a possible demand for new buildings. | 4<br>[13,115,116,135] |
| Building refurbishment | How many buildings have been refurbished in a certain time step in the past and how will that likely be in the future. What is a possible demand for refurbishing buildings. | 12<br>[87,95,110,115–117,119,123–125,131,135,164,165] |
| Building demolition | How many buildings have been demolished in a certain time step in the past and how will that likely be in the future. What is a possible necessary demolition requirement. | 3<br>[13,87,116] |
| Floor space development | How has the total or specific floor space developed in the past and how might it develop in the future based on population grows, life style changes and so on. | 5<br>[32,88,107,108,110,136] |
| Policy aims | What are the policy aims and which are the requirements to reach them. Future policy implementation dates and their impacts. | 5<br>[95,103,111–114,118,130,132,133] |
| Life style (Floor Space per Person) | How does the life style change and e.g. how does that influence the demand of the specific floor area per person. | 3<br>[106,107,131] |
| Financial situation | How is the economic situation in general and in specific of the building stakeholders. How has that been in the past and how might it be in the future. | 4<br>[106,131–133,164] |
| Energy system development | How have and how will the energy system possibly develop under consideration of more renewable energies in the grids as well as a more decentralized energy generation. | 2<br>[56,119] |
| Climate change | What is the likely effect of climate change. | 3<br>[95,122,140] |
| Technology availability | Which kind of technology might be available in the market and when. Will the technology be accepted and used by the stakeholders. | 2<br>[125,132,133] |
| Energy demand development | How was the energy demand development in the past and how might it change in the future. | 1<br>[127] |
| Workforce availability | How is the availability of workers for construction, refurbishment and demolition, how was it in the past and how might it change in the future. | 1<br>[164] |

validate since embodied energy and emissions can only be measured by detailed measurements of each single activity upstream of the modelled building stock. This could be done in theory but would require enormous resources for implementation. This is reflected in the fact that the majority of the LCA-BSMs are not even partially validated [11–13,46,79–82,87–89,92,93,100,136,162–164]. No validated non-operational models were identified the literature, although three studies addressing model verification were noted where results were compared to similar studies [96–98]. One study compared the results of different models applied to the same stock using both bottom-up and top-down approaches [9]. Two studies use measured data of reference buildings for partial validation (e.g. energy demand and material use) [10,95]. With regard to operational phase models, one validated [90] and two verified studies were noted, the latter using the standardized test procedure BESTEST [99] or national statistics [94]. One study used the measured energy use of the entire building stock for operational model validation [165]. The foregoing illustrates that there is no commonly used verification procedure for LCA-BSMs, while full validation is not reported.

### 5.3. Model impact assessment

In keeping with the ISO14044 LCA specification, the model inventory analysis stage is followed by impact assessment, whereby inventory data are associated with relevant environmental impact categories [73]. Below, the impact categories used in the review studies are described.

#### 5.3.1. Operational phase output categories

Studies involving operational modelling methods (see Section 5.2.3) describe a variety of outputs which are summarized in Table 8. In almost all cases, only energy-related outputs are considered (n = 89), with the exception of those that considered either GHGs (n = 1) or materials (n = 1). Energy-related output categories can be divided into: energy; heat; cooling; electricity; and total energy usage. Heat includes thermal energy used for both space heating and hot water. Cooling is the energy required for space cooling, while electricity incorporates lighting, appliances, devices, plug loads and auxiliary energy. Some studies considered cooling as part of the electricity demand. The heating and cooling category combines both electricity and other fuel demands. The category 'total energy usage' refers to studies where end use is not disaggregated, and heating, cooling and electricity are reported in one figure.

Of the LCA studies reviewed (see Table 2), 88% report GHG as an impact category. This is in contrast with models focusing on the operational phase, where energy is the primary impact category. These findings are comparable to Mastrucci et al. who also evaluated impact categories, and found that GHG and energy were used in 93% and 80% of studies, respectively [27].

#### 5.3.2. Cost impacts

Where building stock models are used for the purpose of providing knowledge for policymaking, it is important to estimate both the costs and GHG abatement potential of any stock improvements being investigated. Of the studies reviewed, 27% (n = 26) include an estimation of costs, of which, 81% (n = 21) explicitly aim to identify the impacts of measures/policies. Of these, 43% (n = 9) also state that policy interventions are being investigated. However, 34 policy-oriented studies do not consider cost at all. Only two ND-BSM studies consider costs [32,123,124], while nine whole building stock models (ND&D) [9,12,56,118,121,132,133,148,176,177,179,180] consider associated monetary impacts. Table 2 summarizes the extent to which LCA-BSMs cover costs.

#### 5.3.3. Greenhouse-gas-emission impacts

After energy demand, greenhouse-gas-emissions are the most common model output in the studies analysed. A high proportion of the sample (57%) considers this indicator, given its importance in assessing energy-related climate impacts and its relevance to policymaking. For LCA-BSMs, GHG impacts are estimated in 23 of the 26 studies (see Table 2).

**Table 7**
Validation and verification approaches of building stock models (Percentages might not sum up to 100% due to rounding errors).

| Validation and/or verification approach | Number of studies using that approach |
|---|---|
| **Measurement data — 20% (n = 20)** | |
| Building stock measurement | 11% (n = 11) |
| Building stock measurement and national statistics | 1% (n = 1) |
| Reference building measurement | 6% (n = 6) |
| Reference building measurement and national statistics | 1% (n = 1) |
| Reference building measurement and other studies and BESTEST | 1% (n = 1) |
| **National statistics — 23% (n = 22)** | |
| National statistics | 19% (n = 18) |
| National statistics and other studies | 4% (n = 4) |
| **Other studies — 9% (n = 8)** | |
| Other studies | 7% (n = 7) |
| Other studies and top-down to bottom-up | 1% (n = 1) |
| **Other — 14% (n = 13)** | |
| Training and test data set | 2% (n = 2) |
| Total Absolute Error (TAE) and Percentage Absolute Error (PTAE) | 1% (n = 1) |
| Expert knowledge | 1% (n = 1) |
| Validated model parts | 2% (n = 2) |
| BESTEST verification | 1% (n = 1) |
| Scenario analysis | 5% (n = 5) |
| Sensitivity analysis | 2% (n = 2) |
| **No validation or verification — 34% (n = 32)** | |
| No | 30% (n = 29) |
| Not mentioned | 5% (n = 5) |

### 5.4. Interpretation

The interpretation of model simulation results requires an understanding of their representativeness, while information on uncertainty is also very desirable. The extent to which these issues are addressed in the literature survey is described below.

#### 5.4.1. Representativeness

The statistical representativeness of the case studies was assessed under three categories: 'representative', 'unrepresentative' and 'representativeness unknown'. Case studies were allocated to the representative category when it was stated that the modelled building stock was based on building data which was gathered by means of a randomly drawn sample from the whole stock or, alternatively, where a population of buildings was used. In some studies, sample data were supplemented by national or regional stock data or estimations by experts. In these cases, the results were categorized as representative where the majority of the input data were deemed to be statistically representative of the stock. All other studies were either categorized as unrepresentative or, in the case where data sources were unclear, as representativeness unknown.

In total 55% of the studies were categorized as unrepresentative, while 43% of the studies fell into the representative category. Two could not be categorized as it was unclear what data had been used and were categorized as representativeness unknown [101,149]. Only four of the 26 LCA-BSMs studies [9,82,164,165] were thought to be representative.

#### 5.4.2. Uncertainty analysis

An understanding of model output uncertainty is important when interpreting LCA results [216]. The review indicated that most building stock modelling practitioners are aware of this fact, but that only a

**Table 8**
Operational phase output categories for the reviewed studies (Percentages might not sum up to 100% due to rounding errors).

| Operational phase output-category | Number of studies providing the output category |
|---|---|
| Energy (Heat, Cooling, Electric) | 43% (n = 42) |
| Energy (Heat and Electric) | 19% (n = 19) |
| Energy (Heat and Cooling) | 4% (n = 4) |
| Energy (Space heating and Electric) | 1% (n = 1) |
| Heat | 15% (n = 15) |
| Heat and auxiliary electricity | 2% (n = 2) |
| Heat (Space heating) | 5% (n = 5) |
| Total energy usage | 1% (n = 1) |
| Material | 1% (n = 1) |
| GHG | 1% (n = 1) |
| None | 7% (n = 7) |

few undertake the task of quantifying uncertainty. A minority (19%) of the studies consider uncertainties, while 5% of the studies use large sample sizes to estimate uncertainties quantified as the variances of key output variables. Of the 26 LCA-BSMs, only 15% of the models estimate uncertainty (see Table 2).

Four approaches to estimating stock modelling uncertainty were noted in the literature. The first was to estimate or assess the probable uncertainty of input parameters and analyse their impacts on model outputs by applying scenarios analysis with best-case and worst-case input data sets. This works best for models with one or a few key input variables. Either the variable input ranges are varied one-by-one to estimate output ranges (sensitivity analysis), or a plausible set of input variable ranges are simultaneously varied to estimate model output ranges (scenario analysis). An example of best-case, worst-case scenarios is presented in [82,102]. Examples of scenario analysis with several scenarios applied (second approach) are found in [10,88,124]. All three of these studies first quantify uncertainty using sensitivity analysis and investigate scenarios as second step [10,88,124]. The third approach for estimating uncertainties, the sensitivity analysis, is conducted via the 'One at a Time' (OAT) [11,88], interval analysis [10,158] and Monte Carlo analysis [38,119,152,157,192] techniques.

A fourth approach is to utilize statistical regression models that quantify the standard error of the model along with the results. This approach is pursued by [150,151,155,156,193].

By way of comparison, Mastrucci et al. found that 53% of their reviewed studies carried out a uncertainty estimation of which 63% were based on sensitivity analysis [27]. These proportions are higher than those observed in this study, possibly due to the different review scope applied, as Mastrucci et al. considered 15 selected bottom-up LCA-BSMs only compared to the sample of 96 here. Both the high percentage of studies not considering uncertainty and the small number of representative simulations may be due to a lack of high qualify input data.

### 5.5. Model transparency

Being able to use and experiment with stock simulation models allows for a better understanding of how they work and their underlying operation and assumptions. Unfortunately, most studies in the review do not give detailed information on the implementation of the model used. Of those which did provide further information, some are directly available for use, or at least provide detailed information that enables the reader to replicate them. The openly available category includes models that are available in their entirety, in parts (for example, open-source models are identified, partial models are made available, or combined open and a commercial models are employed), governing equations are provided, code or pseudo code are published and references to standards are provided.

In total, 42% of the studies provide structured information allowing a detailed understanding of the models developed or employed, while the remaining 58% do not provide a sufficient level of detail to understand model input–output relationships.

Of the 16 NDBS models only three (19%) are openly available [82,119,178].

**Table 9**
The most common modelling tools used in building stock models. Ranked by observed frequency. Categorized into 'Building energy model', 'Generic-programming' and 'Life-cycle assessment'.

| Modelling tool | Number of studies using the tool | Tool category |
|---|---|---|
| EnergyPlus | n = 14 | Building energy model |
| Matlab/Simulink | n = 10 | Generic-programming |
| Microsoft Excel | n = 9 | Generic-programming |
| Python/ArcPy | n = 8 | Generic-programming |
| ArcGIS/ArcMap | n = 5 | Generic-programming |
| QGIS | n = 5 | Generic-programming |
| R | n = 4 | Generic-programming |
| GaBi | n = 3 | Live-cycle assessment |
| eQuest | n = 3 | Building energy model |
| SimaPro | n = 3 | Live-cycle assessment |
| Transys | n = 3 | Generic-programming |
| Microsoft Access | n = 2 | Generic-programming |
| ESP-r | n = 2 | Building energy model |
| AccuRate | n = 2 | Building energy model |
| GRASS-GIS | n = 2 | Generic-programming |

### 5.6. Modelling tools

A total of 39 modelling tools were employed in the studies reviewed. Of those, 62% were used in one study only, while 38% were used in more than one study and accounted for about three-quarters of the studies reviewed; these are listed in Table 9. The 39 tools can be grouped into generic-programming (n = 55), building energy models (n = 26), life-cycle assessment models (n = 7), stock models (n = 6) and others (n = 5). The category "others" includes climate models, cost calculation tools, optimization tools and Monte Carlo simulation tools.

The use of a wide range of modelling tools shows that there is no established and commonly accepted building stock modelling tool for either the DBS nor the NDBS yet available. However, for the embodied and operational sub-models there are tools such as EnergyPlus or GaBi that are frequently used and so seem to be widely accepted for their sub-purpose in the overall building stock model (see most frequently used tools mentioned above). Additionally the ISO 13790 [217] standard has been directly implemented in 11 studies and partly implemented in further 5 studies, implemented using different generic-programming tools. The use of this standard may be due to its relative simplicity, resulting in low computational complexity for simulations of large building stocks. The succession standard ISO 52016 [218] was not used in any models, probably since most have been developed before the standard's introduction. However, compared to ISO 13790, the new standard is more complex, leading to longer calculation times [219] and higher uncertainties, since the necessary data are generally not available for building stocks. This may explain the continued popularity of ISO 13790 for BS modelling. In a review of stochastic building stock models by Lim and Zhai [16], the ISO 13790 based [220] Energy Performance Standard Calculation Toolkit (EPSCT) was most commonly used, followed by EnergyPlus [16]. These may be favoured due to their easy accessibility as well as the availability of validation studies and good documentation.

In summary, what appears to be missing is a flexible building stock modelling framework that utilizes and combines accepted sub-models in a way that incorporates building energy performance simulation, LCA, stock and environmental forecasting as well as cost calculations. Ideally, this would be an open-source solution.

### 5.7. Further research required

Further research which could be undertaken either in the general field of building stock modelling or on improving existing models was identified as part of the literature review and is detailed in Table 10. The main topics identified include:

- model improvement, extension of outputs or linkages to other models;
- improvement of input data sources;
- improvement of embodied phase LCA methodologies and models;
- validation and/or verification;
- undertaking scenario analysis (e.g. identification of $CO_2$ reduction options and policy impacts).

### 5.8. Discussion

The following sub-sections provide a summary and discussion of the main issues presented in this paper.

#### 5.8.1. Life-cycle assessment building stock models

Life-cycle assessment building stock models (LCA-BSMs) have diverse study objectives. The operational life-cycle phase as well as the retrofitting and maintenance phases are considered in most of the LCA-BSMs identified in the literature. A similar finding for the operational phase is reported by Mastrucci et al. [27] who analysed a smaller sample of studies. However, they found that the retrofitting and maintenance phases were not as commonly addressed. However, this review established that there is no LCA-BSM available that is specifically aimed at catering for the particular characteristics of the NDBS. Additionally, LCA-BSMs that take consideration of the entire life-cycle from cradle to grave are rare. Uncertainty is rarely considered: only one such model addressed uncertainty by applying scenario analysis with best-case and worst-case input data sets for two variables [82]. Kohler et al. [9] is the most complete study which considered a cradle to grave LCA-BSM, including non-operational and operational life-cycle phases (the latter with significant simplification), as well as costs and dynamic stock development. No other study considered all of these aspects together.

#### 5.8.2. Data availability

The observed popularity of archetype approaches is probably due to the fact that building stock data is from secondary sources and is therefore of limited in size and scope. For this reason, several sources have to be utilized and combined into archetypes for modelling purposes. This popularity is also attributable to the availability of published building archetypes; for example in Europe these are readily available from the TABULA and EPISCOPE projects. If bespoke, well specified, large representative primary data sets were available there would be no need for archetype data input, other than for reducing calculation complexity and resource requirements. This lack of data availability is evident in the high share of studies using archetype data. While 52% and 56% of studies modelling the domestic and combined domestic/non-domestic stocks respectively use archetype data, for NDBS models (where data are most scarce) this share is 69%. This seems to correlate with the greater complexity of NDBs compared to DBs discussed above, as well as the poor data availability in this sector. Mastrucci et al. as well as Brøgger and Wittchen identified also a strong tendency towards archetype approaches. A lack of available data is also evident in the modelling approaches adopted in the studies. For example, the absence of large data sets may explain the small number of studies using regression models. The majority of the models utilize a building physics approach, which requires less data and can integrate disparate data sources. The representativeness of the modelling results depends on the quality and representativeness of input data. Data were limited in a majority of the studies reviewed, thus leading to non-representative results. The problems of data availability and quality have been recognized in many countries and monitoring projects have been initiated [61,62,64–67,70]. Brøgger and Wittchen found that none of their reviewed studies “addresses the issue of what makes a building representative or why the ‘representative buildings’ in the given study is representative of the building stock it is meant to represent” [5]. The representatives of simulation results and therefore of the model input data is a major problem of BSMs, that can only be solved by representative data sources as proposed by the monitoring projects mentioned above. Representative stock monitoring therefore is the essential basis for the stock modelling, especially where robust policy advice is needed.

#### 5.8.3. Open and commonly accepted models

The majority of the studies do not provide detailed information on the operation of the models used. Most models are not open source, nor are they accompanied with detailed descriptions necessary to replicate them. Models are generally developed by the studies’ authors and a widely adopted state-of-the-art model was not identified. Most studies combine or integrate existing building modelling tools, embodied assessment methodologies and other useful programmes into their models, and develop the building stock modelling framework around these components. While a wide variety of modelling tools are used as BS LCA sub-models, a small number dominate particular modelling aspects such as: Matlab/Simulink, Microsoft Excel and Python for scripting and programming; Energy Plus for building energy modelling; and GaBi and SimaPro for LCA. The review indicates the absence of a commonly accepted building stock modelling framework that integrates widely-used sub-models. Such a model would combine building energy performance simulation, LCA, stock and environmental forecasting, and cost estimation.

#### 5.8.4. Forecasting

Forecasting energy uses, environmental impacts and costs are important functions of building stock modelling, especially for policy-making. It was found that approximately 40% of the studies reviewed included stock development forecasts, and that several forecast drivers are used in this process. However, a more limited set of forecasting drivers are used for NDB-LCA-BSMs where only building stock development, construction and demolition are used; no economic or social forecasting drivers were observed. This is surprising, since the development of NDBS is strongly influenced by economic drivers, such as the growth of certain economic sectors. Therefore, there is scope to improve the forecasting quality of NDBS models by including a broader range of forecasting inputs, such as economic and social drivers.

#### 5.8.5. Uncertainties

In general, LCA-building stock simulations do not contain uncertainty analysis. It appears that, from the outset, uncertainty analysis was generally outside the scope of the studies reviewed: only 2% of studies included uncertainty in their aims and objectives. Considering model output uncertainties would greatly enhance their value, particularly given the significant uncertainties involved in the data used and forecasting assumptions.

#### 5.8.6. Comparability, verification and validation

The overall comparability of the studies reviewed is poor due to differing study objectives, so that the models used apply different system boundaries thus hindering a clear comparison and cross-verification. Several different functional units are reported in the literature which also reduces the comparability of the BSM results. The use of standard functional units in BSMs would improve the comparability of results. Only a small number of studies consider validation using building stock data, reference building energy data or national statistics. More often than not, however, the data necessary for validation do not exist; this is especially true for the validation of embodied energy and carbon. The review studies of Mastrucci et al. [27] and of Brøgger and Wittchen [5]

**Table 10**
Further research identified by authors of the reviewed studies.

| Further research category | Number of studies |
|---|---|
| **Model improvement, extension of model outputs or linkages to other models** | |
| Improvement of model, add more detail, increase spatial distribution, scale model, add dynamic, add smaller time steps | 18 |
| Inclusion of cost and economic aspects, also from an macro economics point of view | 11 |
| Improvement or implementation of forecast dynamic models (new construction, maintenance, demolition) | 10 |
| Inclusion of stakeholders and user behaviours and general social aspects | 9 |
| Inclusion of non-domestic buildings | 7 |
| Inclusion and quantification of uncertainty as well as input data sensitivity and variation | 7 |
| Linking to energy system models | 5 |
| Inclusion of climate change forecast weather data | 2 |
| Inclusion of embodied energy and life-cycle assessment | 2 |
| Linking of building stock model to infrastructure and mobility | 2 |
| **Improvement of data sources** | |
| Better data on building stocks, better archetypes, representative data | 15 |
| Better data on life-cycle indicators and upstream chain | 10 |
| Better data on life expectancies | 5 |
| Better data on material composition | 4 |
| **Conducting of scenario analysis, e.g. to identify $CO_2$ reduction possibilities and policy impacts** | |
| Conducting of scenario analysis, e.g. to identify $CO_2$ reduction possibilities and policy impacts | 13 |
| **Improvement of embodied phase LCA-methodologies and models** | |
| Improvement of LCA-methodologies and life-cycle inventory | 4 |
| Forecasting the LCA-indicators development | 1 |
| **Validation and/or verification of the model** | |
| Validation and/or verification of the model | 6 |

report the same lack of validation and verification in most studies. As Hong [221] states, these validation problems are often not addressed in the studies, which leads to the incorrect interpretation and use of simulation results.

### *5.8.7. Further research identified by the reviewed studies*

Further research referred to within the studies reviewed supports many of the above-mentioned shortcomings and research gaps. The improvement of existing models by including NDBs, uncertainty quantification, LCA, forecasting, user and stakeholder behaviour and cost are most commonly highlighted. A second area of general concern relates to the availability of suitable data, with a lack of representative data, better life-cycle indicators, data on life expectancies and the material composition of buildings highlighted by several researchers. In addition, many studies propose undertaking further detailed simulations with the existing models in order to identify more $CO_2$ reduction strategies and policy options.

## 6. Conclusions

This paper presents a first review of the current state-of-the-art in non-domestic building stock modelling. In doing so, it addresses the shortcomings in stock model categorization generally, and proposes an alternative approach which considers both the modelling technique and the data types employed in the model simulation process.

In conclusion, there is no complete non-domestic life cycle building stock model reported in the literature. While operational, retrofitting and maintenance life cycle phases are considered in most of the LCA-BSMs, construction and demolition rarely are, and never are in the specific case of non-domestic stocks. Furthermore, uncertainty is rarely considered in any building stock model, either domestic or non-domestic. The representativeness and functionality of BSMs is dependent on data input quality; however, all building stock data are from secondary sources and are therefore of limited quality. This problem is most pronounced for non-domestic stocks, where little secondary data are available, and these are typically of poor quality. As a result, modellers rely on ‘flexible’ models which can utilize small samples of disparate data, most commonly involving engineering techniques using archetype simulations. Few consider verification or validation and most models, not just those for non-domestic stocks, do not provide economic output parameters, a key consideration for policymaking end-users. It is thus evident that there is considerable scope for further research in the field of building stock modelling generally, and for non-domestic stocks in particular.

Some of the most important research gaps which need to be addressed in order to advance the current state-of-the-art in modelling the life-cycle impacts of non-domestic building stocks include:

- the development of a modelling framework that utilizes and combines commonly accepted building, building stock and LCA modelling tools;
- the extension of this framework to encompass a cradle-to-grave life cycle scope, all building stock life cycle phases, forecasting and costings;
- incorporation of uncertainty quantification into simulation results and
- the collection of comparable, statistically representative building stock data.

In summary, to date there is no life-cycle tool for non-domestic building stock modelling that utilizes and combines accepted submodels to generate an open-source model that incorporates building operation, embodied aspects, stock and environmental forecasting as well as cost calculations. In addition, an accepted approach to validation/verification and uncertainty analysis would be beneficial.

## CRediT authorship contribution statement

**Julian Bischof:** Conceptualization, Methodology, Investigation, Formal analysis, Project administration, Visualization, Writing – original draft. **Aidan Duffy:** Conceptualization, Supervision, Writing – review & editing, Visualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

[1] IPCC. Global warming of 1.5 °C. Switzerland: IPCC; 2018, Available from: http://www.ipcc.ch/report/sr15/.

[2] International Energy Agency. 2019 global status report for buildings and construction: Towards a zero-emissions, efficient and resilient buildings and construction sector. United Nations Environment Programme; 2019, Available from: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwj12N_X4dPqAhVoMewKHc6_CeIQFjABegQIFRAB&url=https%3A%2F%2Fwww.iea.org%2Freports%2Fglobal-status-report-for-buildings-and-construction-2019&usg=AOvVaw2lKXHgErPVd7lboqfC75bv.

[3] Seo S, Zelezna J, Hajek P, Birgisdottir H, Nygaard Rasmussen F, Passer A, Lützkendorf T, Balouktsi M, Yokoyama K, Chae C-U, Malmqvist T, Wiberg AH, Mistretta M, Moncaster A, Yokoo N, Oka T. Evaluation of embodied energy and CO2eq for building construction (Annex 57). IEA - Energy Build Communities Program 2016;22, Available from: http://www.annex57.org/wp/wp-content/uploads/2017/05/Summary-Report.pdf.

[4] Tuominen P, Holopainen R, Eskola L, Jokisalo J, Airaksinen M. Calculation method and tool for assessing energy consumption in the building stock. Build Environ 2014;75:153–60, Available from: http://linkinghub.elsevier.com/retrieve/pii/S036013231400033X.

[5] Brøgger M, Wittchen KB. Estimating the energy-saving potential in national building stocks – a methodology review. Renew Sustain Energy Rev 2018;82:1489–96, Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032117308857.

[6] UNEP DTIE. Buildings and climate change - Summary for decision makers. UNEP DTIE - Sustainable Consumption and Production Branch, UNEP, editor; 2009, Available from: http://www.greeningtheblue.org/sites/default/files/Buildings%20and%20climate%20change_0.pdf.

[7] Vásquez F, Løvik AN, Sandberg NH, Müller DB. Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock. Energy Build 2016;111:37–55, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778815303832.

[8] Piette MA, Pass RZ, Singh R, Hong T. Review of city energy and emissions analysis needs, methods, and tools. In: 2018 ACEEE summer study on energy efficiency in buildings, Vol. 11. 2018, p. 13, Available from: https://www.researchgate.net/publication/326825411_Review_of_City_Energy_and_Emissions_Analysis_Needs_Methods_and_Tools?enrichId=rgreq-67a1fcea3926ef669ca3383508541b14-XXX&enrichSource=Y292ZXJQYWdlOzMyNjgyNTQxMTtBUzo2NjExOTgxMDIwNzc0NjZAMTUzNDY1MzMyMDU5OA%3D%3D&el=1_x_3&_esc=publicationCoverPdf.

[9] Kohler N, Hassler U, Paschen H, editors. Stoffströme und Kosten in den Bereichen Bauen und Wohnen. Berlin, Heidelberg: Springer Berlin Heidelberg; 1999, Available from: http://link.springer.com/10.1007/978-3-642-58503-6.

[10] Stephan A, Athanassiadis A. Quantifying and mapping embodied environmental requirements of urban building stocks. Build Environ 2017;114:187–202, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360132316304747.

[11] Teh SH, Wiedmann T, Schinabeck J, Moore S. Replacement scenarios for construction materials based on economy-wide hybrid LCA. Procedia Eng 2017;180:179–89, Available from: https://linkinghub.elsevier.com/retrieve/pii/S1877705817316843.

[12] Nichols BG, Kockelman KM. Life-cycle energy implications of different residential settings: Recognizing buildings, travel, and public infrastructure. Energy Policy 2014;68:232–42, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0301421513013268.

[13] Reyna JL, Chester MV. The growth of urban building stock: Unintended lock-in and embedded environmental effects: Urban buildings, lock-in, and environmental effects. J Ind Ecol 2015;19(4):524–37, Available from: http://doi.wiley.com/10.1111/jiec.12211.

[14] Tian W, Choudhary R. A probabilistic energy model for non-domestic building sectors applied to analysis of school buildings in greater London. Energy Build 2012;54:1–11, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778812003544.

[15] D'Agostino D, Cuniberti B, Bertoldi P. Energy consumption and efficiency technology measures in European non-residential buildings. Energy Build 2017;153:72–86, Available from: https://linkinghub.elsevier.com/retrieve/pii/S037877881730676X.

[16] Lim H, Zhai ZJ. Review on stochastic modeling methods for building stock energy prediction. Build Simul 2017;10(5):607–24, Available from: http://link.springer.com/10.1007/s12273-017-0383-y.

[17] IEA-BEEP. Buildings energy efficiency policies database - Germany: Final energy consumption of the buildings sector 2010. International Energy Agency, IEA-BEEP, editor; 2019, Available from: https://www.iea.org/beep/germany/.

[18] European Commission. Commission recommendation (EU) 2016/ 1318 - of 29 July 2016 - on guidelines for the promotion of nearly zero-energy buildings and best practices to ensure that, by 2020, all new buildings are nearly zero-energy buildings. Off J Eur Union 2016;L 208/46(2016/1318):12, Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016H1318&from=EN.

[19] D'Agostino D, Zangheri P, Cuniberti B, Paci D, Bertoldi P. Synthesis report on the national plans for nearly zero energy buildings (NZEBs). JRC Science for Policy Report, 2016, p. 98, Available from: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC97408/reqno_jrc97408_online%20nzeb%20report(1).pdf.

[20] Thormark C. A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. Build Environ 2002;37(4):429–35, Available from: http://www.sciencedirect.com/science/article/pii/S0360132301000336.

[21] Bischof J. Bischof J (Ed.) Life cycle energy and CO2 assessment of a university building utilising building information and building energy modelling: A comparison between Irish and German context: Master of engineering. Nordhausen (Germany) and Galway (Ireland); 2016. Available from: https://www.researchgate.net/publication/308986436_Life_Cycle_Energy_and_CO2_Assessment_of_a_university_building_utilising_Building_Information_and_Building_Energy_Modelling_A_comparison_between_Irish_and_German_context.

[22] Acquaye A, Duffy A, Basu B. Assessment of the embodied CO2eq in buildings towards a sustainable building design and construction. In: Dublin energy lab - Conference paper 2009. 2009.

[23] Acquaye AA, Duffy AP, Basu B. Stochastic hybrid embodied CO2-eq analysis: An application to the irish apartment building sector. Energy Build 2011;43(6):1295–303, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778811000156.

[24] European Parliament. Directive 2010/31/EU of the European parliament and of the council of 19 May 2010 on the energy performance of buildings. Off J Eur Union 2010;L 153/13:23, Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:en:PDF.

[25] Swan LG, Ugursal VI. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renew Sustain Energy Rev 2009;13(8):1819–35, Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032108001949.

[26] Kavgic M, Mavrogianni A, Mumovic D, Summerfield A, Stevanovic Z, Djurovic-Petrovic M. A review of bottom-up building stock models for energy consumption in the residential sector. Build Environ 2010;45(7):1683–97.

[27] Mastrucci A, Marvuglia A, Leopold U, Benetto E. Life Cycle Assessment of building stocks from urban to transnational scales: A review. Renew Sustain Energy Rev 2017;74:316–32, Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032117302794.

[28] ENOB:DataNWG. In: Hörner M, editor. Non-domestic building defintion of the DataNWG-Project. IWU, IÖR, BUW; 2016, Available from: https://datanwg.de/screening/definition-nichtwohngebaeude/.

[29] UN. International recommendations for construction statistics. Statistical paper series M, New York: United Nations; 1997, Available from: https://unstats.un.org/unsd/EconStatKB/KnowledgebaseArticle10188.aspx.

[30] EnEV2016. Verordnung über energiesparenden Wärmeschutz und energiesparende anlagentechnik bei Gebäuden (Energieeinsparverordnung - EnEV). Bundes Gesetz Blatt 24. Oktober 2015 (BGBl. I S. 1789), EnEV, editor; 2015, Available from: http://www.gesetze-im-internet.de/enev_2007/EnEV.pdf.

[31] Dascalaki EG, Droutsa K, Gaglia AG, Kontoyiannidis S, Balaras CA. Data collection and analysis of the building stock and its energy performance—An example for hellenic buildings. Energy Build 2010;42(8):1231–7, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778810000459.

[32] Pout CH. N-DEEM: The national nondomestic buildings energy and emissions model. Environ Plan B 2000;27(5):721–32, Available from: http://journals.sagepub.com/doi/10.1068/bst12.

[33] Bruhns H, editor. Identifying determinants of energy use in the UK nondomestic stock. Building Performance Congress; 2008.

[34] Worm. Bekanntmachung der regeln für energieverbrauchswerte und der vergleichswerte im nichtwohngebäudebestand. BMWE, BMUB, editor; 2015.

[35] Loga T, Stein B, Diefenbach N. TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable. Energy Build 2016;132:4–12, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778816305837.

[36] CIBSE - TM46 - Energy benchmarks: 2008 - Energy-benchmarks. London: The Chartered Institution of Building Services Engineers; 2008.

[37] CIBSE guide-F 2012 - Energ efficiency in buildings. London: The Chartered Institution of Building Services Engineers; 2012.

[38] Smith ST. Modelling thermal loads for a non-domestic building stock. Associating a priori probability with building form and construction - using building control laws and regulations: PhD-Thesis. Nottingham, UK: The University of Nottingham; 2009, Available from: http://eprints.nottingham.ac.uk/10895/1/Thesis.pdf.

[39] DIN. DIN V 18599-10 - Energetische bewertung von gebäuden - Berechnung des nutz-, end- und primärenergiebedarfs für heizung, kühlung, lüftung, trinkwarmwasser und beleuchtung - Teil 10: Nutzungsrandbedingungen, klimadaten. DIN; 2016.

[40] EnEV2014. Zweite verordnung zur änderung der energieeinsparverordnung - 2014. Bundes Gesetz Blatt BGBl. I S. 3951; 2013.

[41] CIBSE-Guide-A. CIBSE guide a 2015 - Environmental design. London: The Chartered Institution of Building Services Engineers; 2006.

[42] VoestAlpine. voestalpine krems finaltechnik - Palettenhochregallager (HRL). Online Document: VoestAlpine, editor; 2018, Available from: https://web.archive.org/web/20110606140300/http://www.voestalpine.com/finaltechnik/de/products/storage_technology/highbay_warehouse/highbay_warehousing.html.

[43] Krapp M-C, von Malottki C, Nuss G, Lohmann G, Rodenfels M, Tilly A. Die ortsüblichen vergleichsmieten in darmstadt 2018 gutachten zur erstellung eines mietspiegels nach § 558 d BGB. Darmstadt: Institut Wohnen und Umwelt GmbH, IWU, editor; 2018.

[44] von Malottki C, Krapp M-C, Partschefeld H, Nuss G, Vaché M, Tilly A. Die ortsüblichen vergleichsmieten in frankfurt a. m. 2018 gutachten zur erstellung des qualifizierten mietspiegels 2018. Darmstadt: Institut Wohnen und Umwelt GmbH, IWU, editor; 2018.

[45] Bischof J, Krapp M-C, Nuss G. Auswertung der Raumhöhen der Mietspiegel Frankfurt und Darmstadt 2018 - Evaluation of the room heights in the representative rent indices of the cities Frankfurt and Darmstadt (Germany) in 2018. Darmstadt: Institut Wohnen und Umwelt GmbH, IWU, editor; 2018.

[46] García-Pérez S, Sierra-Pérez J, Boschmonart-Rives J, Lladó Morales G, Romero Calix A. A characterisation and evaluation of urban areas from an energy efficiency approach, using geographic information systems in combination with life cycle assessment methodology. Int J Sustain Dev Plan 2017;12(02):294–303.

[47] Klauß S, Kirchhof W, Gissel J. Erfassung regionaltypischer materialien im gebäudebestand mit bezug auf die baualtersklasse und ableitung typischer bauteilaufbauten. Kassel, Germany: Swen Klauß, editor; 2009, Available from: http://www.zukunft-haus.info/fileadmin/zukunft-haus/energieausweis/Gesetze_Verordnungen/EnEV/2009-10-28_Deutschlandkarte_Endbericht_barrierefrei_NEU.pdf.

[48] EnEG2005. Gesetz zur einsparung von energie in gebäuden (Energieeinsparungsgesetz - EnEG). Bundes Gesetz Blatt, EnEG, editor; 2005, Available from: https://www.gesetze-im-internet.de/eneg/EnEG.pdf.

[49] WSchV77. Verordnung über einen energiesparenden Wärmeschutz bei Gebäuden (Wärmeschutzverordnung – WärmeschutzV) - 1977. Bundes Gesetz Blatt; 1977.

[50] WSchV82. Verordnung über einen energiesparenden Wärmeschutz bei Gebäuden (Wärmeschutzverordnung – WärmeschutzV) - 1982. Bundes Gesetz Blatt; 1982.

[51] WSchV94. Verordnung über einen energiesparenden Wärmeschutz bei Gebäuden (Wärmeschutzverordnung - WärmeschutzV) - 1994. Bundes Gesetz Blatt; 1994.

[52] EnEV2002. Verordnung über energiesparenden Wärmeschutz und energiesparende anlagentechnik bei Gebäuden (Energieeinsparverordnung – EnEV) - 2001. Bundesgesetzblatt Jahrgang 2001 Teil I Nr. 59, ausgegeben zu Bonn am 21. November 2001; 2001.

[53] EnEV2005. Bekanntmachung der neufassung der energieeinsparverordnung (EnEV) - 2004. Bekannt gemacht im Bundesgesetzblatt I S. 3146; 2004.

[54] EnEV2007. Verordnung über energiesparenden Wärmeschutz und energiesparende anlagentechnik bei Gebäuden (Energieeinsparverordnung – EnEV) - 2007. Bundesgesetzblatt Jahrgang 2007 Teil I Nr. 34, ausgegeben zu Bonn am 26. Juli 2007; 2007.

[55] EneV2009. Verordnung zur änderung der energieeinsparverordnung - 2009. Bundes Gesetz Blatt; 2009.

[56] Drysdale D, Mathiesen BV, Paardekooper S. Transitioning to a 100% renewable energy system in Denmark by 2050: Assessing the impact from expanding the building stock at the same time. Energy Effic 2018. Available from: http://link.springer.com/10.1007/s12053-018-9649-1.

[57] Statistisches Bundesamt (German Federal Statistical Office). Zeitverwendungserhebung - Aktivitäten in stunden und minuten für ausgewählte personengruppen - 2012/2013: Statistical summary. Zeitverwendungserhebung, Wiesbaden, Germany: DESTATIS, editor; 2015, Available from: https://www.destatis.de/DE/Publikationen/Thematisch/EinkommenKonsumLebensbedingungen/Zeitbudgeterhebung/Zeitverwendung5639102139004.pdf?__blob=publicationFile.

[58] Aksözen M, Hassler U, Kohler N. Reconstitution of the dynamics of an urban building stock. Build Res Inf 2016;45(3):239–58, Available from: https://www.tandfonline.com/doi/full/10.1080/09613218.2016.1152040.

[59] Aksözen M, Hassler U, Rivallain M, Kohler N. Mortality analysis of an urban building stock. Build Res Inf 2017;45(3):259–77, Available from: https://www.tandfonline.com/doi/full/10.1080/09613218.2016.1152531.

[60] Stein B, Hörner M, Jedek C, Ihrig M. Typologie-gestützte Kennwerte für die energetische Bewertung bestehender Nichtwohngebäude. IWU 2015;2015:112, Available from: http://www.iwu.de/fileadmin/user_upload/dateien/energie/typo_NWG/IWU_2015_Typologie-gest%C3%BCtzte_Kennwerte_NWG.pdf.

[61] U S Energy Information Administration. 2003 commercial buildings energy consumption survey: Detailed tables. Energy Information Administration, U S Energy Information Administration, editor; 2006, Available from: https://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/2003set19/2003pdf/alltables.pdf.

[62] U S Energy Information Administration. U.S. Energy Information Administration (EIA) - Commercial Buildings Energy Consumption Survey (CBECS) - USA. U S Energy Information Administration, editor; 2019, Available from: https://www.eia.gov/consumption/commercial/.

[63] Winiarski DW, Halverson MA, Butzbaugh JB, Cooke AL, Bandyopadhyay GK, Elliott DB. Analysis for building envelopes and mechanical systems using 2012 CBECS data. Pacific Northwest National Laboratory, editor; 2018, Available from: http://www.osti.gov/servlets/purl/1430427/.

[64] Commercial and institutional consumption of energy survey: 2005 ; summary report. Ottawa ON: Office of Energy Efficiency Natural Resources Canada, Office of Energy Efficiency Natural Resources Canada, editor; 2007, Available from: http://oee.nrcan.gc.ca/publications/statistics/cices06/pdf/cices06.pdf.

[65] Bruhns H, Steadman P, Herring H. A database for modeling energy use in the non-domestic building stock of England and Wales. Appl Energy 2000;66(4):277–97, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0306261900000180.

[66] ENOB:DataNWG. Forschungsdatenbank nichtwohngebäude: Projektbeschreibung. IWU, editor; 2017.

[67] Scheer J. Extensive survey of the commercial buildings stock in the Republic of Ireland. SEAI, Sustainable Energy Authority of Ireland, editor; 2015.

[68] Hjortling C, Björk F, Berg M, Klintberg Ta. Energy mapping of existing building stock in Sweden – Analysis of data from energy performance certificates. Energy Build 2017;153:341–55, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0378778817321850.

[69] Ravetz J. State of the stock—What do we know about existing buildings and their future prospects? Energy Policy 2008;36(12):4462–70, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421508004667.

[70] Amitrano L, Isaacs N, Saville-Smith K, Donn M, Camilleri M, Pollard A, Babylon M, Bishop R, Roberti J, Burrough L, Hills A, Cory S. Building energy end-use study. Judgeford: BRANZ, BRANZ, editor; 2014.

[71] Scheuer C, Keoleian GA, Reppe P. Life cycle energy and environmental performance of a new university building: Modeling challenges and design implications. Energy Build 2003;35(10):1049–64, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778803000665.

[72] Khasreen M, Banfill PF, Menzies G. Life-cycle assessment and the environmental impact of buildings: A review. Sustainability 2009;1(3):674–701, Available from: http://www.mdpi.com/2071-1050/1/3/674.

[73] ISO 14040. ISO14040 - Environmental management – Life cycle assessment – Principles and framework (ISO 14040:2006); German and English version EN ISO 14040:2006. Berlin: DIN Deutsches Institut für Normung e.V; 2009.

[74] Mercado Burciaga U, Sáez PV, Javier Hernández Ayón F. Strategies to reduce CO2 emissions in housing building by means of CDW. Emerg Sci J 2019;3(5):274–84.

[75] European Parliament. DIRECTIVE 2012/27/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:en:PDF.

[76] Department of the Environment, Heritage and Local Government of Ireland. Building regulations 2008 L - Conservation of fuel and energy other than dwellings 2008. STATIONERY OFFICE, Dublin; 2008.

[77] Department of the Environment, Community and Local Government of Ireland. Building regulations 2011: Technical guidance document. L, L. Department of the Environment, Community and Local Government of Ireland; 2011.

[78] Lavagna M, Baldassarri C, Campioli A, Giorgi S, Dalla Valle A, Castellani V, Sala S. Benchmarks for environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock. Build Environ 2018;145:260–75, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360132318305560.

[79] Nemry F, Uihlein A, Colodel CM, Wetzel C, Braune A, Wittstock B, Hasan I, Kreißig J, Gallon N, Niemeier S, Frech Y. Options to reduce the environmental impacts of residential buildings in the European Union—Potential and costs. Energy Build 2010;42(7):976–84, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778810000162.

[80] Moschetti R, Mazzarella L, Nord N. An overall methodology to define reference values for building sustainability parameters. Energy Build 2015;88:413–27, Available from: https://linkinghub.elsevier.com/retrieve/pii/S037877881401038X.

[81] Famuyibo A. Reducing life cycle impacts of the existing irish housing stock: PhD. Dublin: DIT, editor; 2012.

[82] Ghose A, McLaren SJ, Dowdell D. Upgrading New Zealand's existing office buildings – An assessment of life cycle impacts and its influence on 2050 climate change mitigation target. Sustain Cities Soc 2020;57:102134.

[83] Evans S, Liddiard R, Steadman P. Modelling a whole building stock: domestic, non-domestic and mixed use. Build Res Inf 2019;47(2):156–72.

[84] Buso T, Corgnati SP. A customized modelling approach for multi-functional buildings – application to an Italian Reference Hotel. Appl Energy 2017;190:1302–15.

[85] Azar E. A comprehensive framework to assess, model, and enhance the human role in conserving energy in commercial buildings (Ph.D. thesis), Wisconsin-Madison: University of Wisconsin-Madison; 2014.

[86] Geels C, Andersson C, Hänninen O, Lansø AS, Schwarze PE, Skjøth CA, Brandt J. Future premature mortality due to O3, secondary inorganic aerosols and primary PM in Europe–sensitivity to changes in climate, anthropogenic emissions, population and building stock. Int J Environ Res Public Health 2015;12(3):2837–69.

[87] Pauliuk S, Sjöstrand K, Müller DB. Transforming the norwegian dwelling stock to reach the 2 degrees celsius climate target: Combining material flow analysis and life cycle assessment techniques. J Ind Ecol 2013;17(4):542–54, Available from: http://doi.wiley.com/10.1111/j.1530-9290.2012.00571.x.

[88] Sandberg NH, Sartori I, Brattebø H. Sensitivity analysis in long-term dynamic building stock modeling—Exploring the importance of uncertainty of input parameters in norwegian segmented dwelling stock model. Energy Build 2014;85:136–44, Available from: http://linkinghub.elsevier.com/retrieve/pii/S037877881400721X.

[89] Norman J, MacLean HL, Kennedy CA. Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions. J Urban Plan Dev 2006;132(1):10–21, Available from: http://ascelibrary.org/doi/10.1061/%28ASCE%290733-9488%282006%29132%3A1%2810%29.

[90] Munoz Hidalgo ME. Enriching the digital cadastre with material properties for an urban simulation of heat demand and life cycle analysis. In: IBPSA BS2015. 2015, Available from: http://www.ibpsa.org/proceedings/BS2015/p2916.pdf.

[91] Muñoz Hidalgo ME. Construction of regional building typologies with a material catalog. Manage Environ Qual: Int J 2016;27(6):663–80, Available from: http://www.emeraldinsight.com/doi/10.1108/MEQ-05-2015-0096.

[92] Brown NWO, Olsson S, Malmqvist T. Embodied greenhouse gas emissions from refurbishment of residential building stock to achieve a 50% operational energy reduction. Build Environ 2014;79:46–56, Available from: http://linkinghub.elsevier.com/retrieve/pii/S036013231400122X.

[93] Mastrucci A, Popovici E, Marvuglia A, de Sousa L, Benetto E, Leopold U. GIS-based Life Cycle Assessment of urban building stocks retrofitting- a bottom-up framework applied to Luxembourg. In: Proceedings of enviroinfo and ICT for sustainability 2015. Atlantis Press; 2015, Available from: http://www.atlantis-press.com/php/paper-details.php?id=25836150.

[94] Sharma A, Marwaha BM. A methodology for energy performance classification of residential building stock of Hamirpur. HBRC J 2017;13(3):337–52, Available from: https://linkinghub.elsevier.com/retrieve/pii/S1687404815000735.

[95] Wang D, Landolt J, Mavromatidis G, Orehounig K, Carmeliet J. CESAR: A bottom-up building stock modelling tool for Switzerland to address sustainable energy transformation strategies. Energy Build 2018;169:9–26, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0378778817337696.

[96] Saner D, Vadenbo C, Steubing B, Hellweg S. Regionalized LCA-based optimization of building energy supply: Method and case study for a swiss municipality. Environ Sci Technol 2014;48(13):7651–9, Available from: http://pubs.acs.org/doi/10.1021/es500151q.

[97] Anderson JE. Expanding the use of life-cycle assessment to capture induced impacts in the built environment: PhD Dissertation. TUM, editor; 2015, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360132315300895.

[98] Wang Q, Laurenti R, Holmberg S. A novel hybrid methodology to evaluate sustainable retrofitting in existing Swedish residential buildings. Sustain Cities Soc 2015;16:24–38, Available from: https://linkinghub.elsevier.com/retrieve/pii/S2210670715000165.

[99] Seo S, Foliente G, Ren Z. Energy and GHG reductions considering embodied impacts of retrofitting existing dwelling stock in greater melbourne. J Clean Prod 2018;170:1288–304, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652617322084.

[100] Yang W, Kohler N. Simulation of the evolution of the Chinese building and infrastructure stock. Build Res Inf 2008;36(1):1–19.

[101] Coffey B, Stone A, Ruyssevelt P, Haves P. An epidemiological approach to simulation-based analyses of large building stocks. In: 14th conference of the international building performance simulation association. IBPSA, editor; 2015, p. 1916–23, Available from: http://www.ibpsa.org/proceedings/BS2015/p3030.pdf.

[102] Bergsdal H, Brattebø H, Bohne RA, Müller DB. Dynamic material flow analysis for Norway's dwelling stock. Build Res Inf 2007;35(5):557–70.

[103] Mata E, Kalagasidis AS, Johnsson F. A modelling strategy for energy, carbon, and cost assessments of building stocks. Energy Build 2013;56:100–8, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778812004926.

[104] Swan L, Ugursal VI, Beasuoleil-Morrison I. A new hybrid end-use energy and emissions model of the canadian housing stock. In: Proc. int. conf. on building energy and environment. 2008, Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.667.9972&rep=rep1&type=pdf.

[105] Muñoz Hidalgo ME, Peters I. In: Muñoz Hidalgo ME, editor. A Makrov-Chain Monte-Carlo quasi-dynamic spatial-microsimulation model. DRAFT!!!; 2017.

[106] Kadian R, Dahiya R, Garg H. Energy-related emissions and mitigation opportunities from the household sector in Delhi. Energy Policy 2007;35(12):6195–211, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421507003291.

[107] Sandberg NH, Sartori I, Heidrich O, Dawson R, Dascalaki E, Dimitriou S, Vimm-r T, Filippidou F, Stegnar G, Šijanec Zavrl M, Brattebø H. Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. Energy Build 2016;132:26–38, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778816304893.

[108] McKenna R, Merkel E, Fehrenbach D, Mehne S, Fichtner W. Energy efficiency in the german residential sector: A bottom-up building-stock-model-based analysis in the context of energy-political targets. Build Environ 2013;62:77–88, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0360132313000152.

[109] MATSUMOTO T, editor. Energy demand model of residential and commercial sectors of cities: A case study of Tokyo. iGES; 2002.

[110] Diefenbach N, Loga T, Stein B. Reaching the climate protection targets for the heat supply of the german residential building stock: How and how fast? Energy Build 2016;132:53–73.

[111] Mata E. Energy efficiency and carbon dioxide mitigation in building stocks - Development of methodology using the Swedish residential stock: Licentiate of engineering. Göteborg: CHALMERS UNIVERSITY OF TECHNOLOGY, Chalmers Reproservice, editor; 2011.

[112] Mata E, Sasic Kalagasidis A, Johnsson F. Energy usage and technical potential for energy saving measures in the Swedish residential building stock. Energy Policy 2013;55:404–14, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421512010683.

[113] Mata e, Medina Benejam G, Sasic Kalagasidis A, Johnsson F. Modelling opportunities and costs associated with energy conservation in the spanish building stock. Energy Build 2015;88:347–60, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778814010615.

[114] Gauer T. Energy efficiency potential of the European building stock: Case study for Germany - Thesis for the degree in mechanical engineering: Masters Thesis. Göteborg, Sweden: CHALMERS UNIVERSITY OF TECHNOLOGY, Chalmers Reproservice, editor; 2013.

[115] Schimschar S, Blok K, Boermans T, Hermelink A. Germany's path towards nearly zero-energy buildings—Enabling the greenhouse gas mitigation potential in the building stock. Energy Policy 2011;39(6):3346–60, Available from: http://www.sciencedirect.com/science/article/pii/S0301421511002096.

[116] Uihlein A, Eder P. Policy options towards an energy efficient residential building stock in the EU-27. Energy Build 2010;42(6):791–8, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778809003120.

[117] Johnston D, Lowe R, Bell M. An exploration of the technical feasibility of achieving CO2 emission reductions in excess of 60% within the UK housing stock by the year 2050. Energy Policy 2005;33(13):1643–59, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421504000370.

[118] Bürger V, Hesse T, Köhler B, Palzer A, Engelmann P. German energiewende—different visions for a (nearly) climate neutral building sector in 2050. Energy Eff 2018. Available from: http://link.springer.com/10.1007/s12053-018-9660-6.

[119] García Kerdan I, Raslan R, Ruyssevelt P, Morillón Gálvez D. The role of an exergy-based building stock model for exploration of future decarbonisation scenarios and policy making. Energy Policy 2017;105:467–83, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0301421517301647.

[120] Kelly S. Decarbonising the english residential sector: PHD. 2013.

[121] Petrovic S, Karlsson K. Model for determining geographical distribution of heat saving potentials in danish building stock. ISPRS Int J Geo-Inf 2014;3(1):143–65, Available from: http://www.mdpi.com/2220-9964/3/1/143.

[122] Wang H, Chen Q. Impact of climate change heating and cooling energy use in buildings in the United States. Energy Build 2014;82:428–36, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778814005726.

[123] Coffey B, Borgeson S, Selkowitz S, Apte J, Mathew P, Haves P. Towards a very low-energy building stock: Modelling the US commercial building sector to support policy and innovation planning. Build Res Inf 2009;37(5–6):610–24.

[124] Coffey B. Towards a very low energy building stock: Modeling the U.S. commercial building sector to support policy and innovation planning. Lawrence Berkeley National Laboratory; 2010, p. 1–23, Available from: http://escholarship.org/uc/item/29f6t1cz.

[125] Heeren N, Jakob M, Martius G, Gross N, Wallbaum H. A component based bottom-up building stock model for comprehensive environmental impact assessment and target control. Renew Sustain Energy Rev 2012;20:45–56.

[126] Hesse T, Bürger V. In: Hesse T, editor. How to transform the German building stock into a climate-neutral state by 2050 – a stock modelling approach. Öko-Institut e.V; 2016.

[127] Hong L, Zhou N, Feng W, Khanna N, Fridley D, Zhao Y, Sandholt K. Building stock dynamics and its impacts on materials and energy demand in China. Energy Policy 2016;94:47–55, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0301421516301276.

[128] Novikova A, Csoknyai T, Szalay Z. Low carbon scenarios for higher thermal comfort in the residential building sector of South Eastern Europe. Energy Eff 2018;11(4):845–75, Available from: http://link.springer.com/10.1007/s12053-017-9604-6.

[129] Petersdorff C, Boermans T, Harnisch J. Mitigation of CO2 emissions from the EU-15 building stock. Beyond the EU directive on the energy performance of buildings. Umweltwiss Schadst-Forschung 2006;18(4):270, Available from: http://www.springerlink.com/index/10.1007/BF03039568.

[130] Sartori I, Wachenfeldt BJ, Hestnes AG. Energy demand in the norwegian building stock: Scenarios on potential reduction. Energy Policy 2009;37(5):1614–27, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421508007593.

[131] Foliente G, Seo S. Modelling building stock energy use and carbon emission scenarios. Smart Sustain Built Environ 2012;1(2):118–38, Available from: http://www.emeraldinsight.com/doi/10.1108/20466091211260578.

[132] Kranzl L, Hummel M, Müller A, Steinbach J. Renewable heating: Perspectives and the impact of policy instruments. Energy Policy 2013;59:44–58, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0301421513002280.

[133] Kranzl L, Müller A, Toleikyte A, Kockat J, Steinbach J. What drives the impact of future support policies for energy efficiency in buildings? ECEEE Summer Stud Proc 2014;12.

[134] Martinez-Moyano IJ, Graziano DJ, Zhao F, Conzelmann G. Modeling the commercial buildings sector: An agent-based approach. ASHRAE Trans 2011;9.

[135] Onat NC, Egilmez G, Tatari O. Towards greening the U.S. residential building stock: A system dynamics approach. Build Environ 2014;78:68–80, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0360132314000900.

[136] Sandberg NH, Brattebø H. Analysis of energy and carbon flows in the future norwegian dwelling stock. Build Res Inf 2012;40(2):123–39.

[137] Sandberg NH, Sartori I, Brattebø H. Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock. Energy Build 2014;82:287–95, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778814005398.

[138] Sandberg NH, Sartori I, Vestrum MI, Brattebø H. Explaining the historical energy use in dwelling stocks with a segmented dynamic model: Case study of Norway 1960–2015. Energy Build 2016;132:141–53, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778816304881.

[139] Sartori I, Sandberg NH, Brattebø H. Dynamic building stock modelling: General algorithm and exemplification for Norway. Energy Build 2016;132:13–25, Available from: http://linkinghub.elsevier.com/retrieve/pii/S037877881630487X.

[140] Collins L, Natarajan S, Levermore G. Climate change and future energy consumption in UK housing stock. Build Serv Eng Res Technol 2010;31(1):75–90, Available from: http://journals.sagepub.com/doi/10.1177/0143624409354972.

[141] Verein Deutscher Ingenieure. VDI 2067 - Wirtschaftlichkeit gebäudetechnischer Anlagen - Grundlagen und Kostenberechnung: VDI 2067. Düsseldorf: Verein Deutscher Ingenieure (VDI); 2012.

[142] DFG. DFG-Geräteverzeichnis und -Nutzungsdauer (ND) in Monaten. 2017, Available from: http://www.uni-kiel.de/verw/zv/abteilung4/sg415/download/dfgliste2012.

[143] Euw Rv, Alimpic Z, Hildebrand K, Lüthy R. Gebäudetechnik: Systeme integral planen. In: Nachhaltiges Bauen und Erneuen, Zürich: Faktor-Verl.; 2012.

[144] Hegger M, Fuchs M, Zeumer M. Integration vergleichender Nachhaltigkeitskennwerte von Baumaterialien nach Bauteilschichten in einem Baustoff Atlas der DETAIL Atlantenserie. TU Darmstadt; 2005, Available from: ttp://www.ee.architektur.tu-darmstadt.de/media/architektur/fachgruppe_c/ee/forschung_dissertationen_4/ordner/schlussberichtdbu_baustoff.pdf.

[145] Hegger M, Fuchs M, Stark T, Zeumer M. Energie atlas: Nachhaltige architektur. Walter de Gruyter; 2007.

[146] Zeumer M, John V, Hartwig J. Nachhaltiger materialeinsatz–graue energie im lebenszyklus. Detail Green 2009;(01). Available from: http://www.ibi.ethz.ch/sc/people/assistance/vjohn/Nachhaltiger.Materialeinsatz.Graue.Energie.pdf.

[147] Dall'O' G, Galante A, Torri M. A methodology for the energy performance classification of residential building stock on an urban scale. Energy Build 2012;48:211–9.

[148] Girardin L, Marechal F, Dubuis M, Calame-Darbellay N, Favrat D. EnerGis: A geographical information based system for the evaluation of integrated energy conversion systems in urban areas. Energy 2010;35(2):830–40, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0360544209003582.

[149] Kolter JZ, Jr. JF. A large-scale study on predicting and contextualizing building energy usage. In: Proceedings of the twenty-fifth aaai conference on artificial intelligence. 2011, p. 8, Available from: http://www.aaai.org/ocs/index.php/AAAI/AAAI11/paper/download/3759/4088.

[150] Howard B, Parshall L, Thompson J, Hammer S, Dickinson J, Modi V. Spatial distribution of urban building energy consumption by end use. Energy Build 2012;45:141–51, Available from: http://linkinghub.elsevier.com/retrieve/pii/S037877881100524X.

[151] Mastrucci A, Baume O, Stazi F, Leopold U. Estimating energy savings for the residential building stock of an entire city: A GIS-based statistical downscaling approach applied to rotterdam. Energy Build 2014;75:358–67.

[152] Urban-scale energy modelling of food supermarket considering uncertainty: Proceedings of BS2013: 13th conference of international building performance simulation association, Chambéry, France, August 26-28. Proceedings of the 13th international IBPSA, IBPSA, editor; 2013, Available from: www.ibpsa.org/proceedings/BS2013/p_1172.pdf.

[153] Kipping A, Trømborg E. Modeling aggregate hourly energy consumption in a regional building stock. Energies 2017;11(1):78, Available from: http://www.mdpi.com/1996-1073/11/1/78.

[154] Mutani G, Delmastro C, Gargiulo M, Corgnati SP. Characterization of building thermal energy consumption at the urban scale. Energy Procedia 2016;101:384–91, Available from: https://linkinghub.elsevier.com/retrieve/pii/S1876610216312589.

[155] Choudhary R. Energy analysis of the non-domestic building stock of greater London. Build Environ 2012;51:243–54.

[156] Mastrucci A, Pérez-López P, Benetto E, Leopold U, Blanc I. Global sensitivity analysis as a support for the generation of simplified building stock energy models. Energy Build 2017;149:368–83, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0378778816320023.

[157] Oliveira Panão MJ, Brito MC. Modelling aggregate hourly electricity consumption based on bottom-up building stock. Energy Build 2018;170:170–82, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0378778817330797.

[158] Österbring M, Mata E, Thuvander L, Mangold M, Johnsson F, Wallbaum H. A differentiated description of building-stocks for a georeferenced urban bottom-up building-stock model. Energy Build 2016;120:78–84, Available from: http://linkinghub.elsevier.com/retrieve/pii/S037877881630216X.

[159] Li Q, Quan SJ, Augenbroe G, Yang PP-J, Brown J. Building energy modelling at urban scale: Integration of reduced order energy model with geographical information. In: Proceedings of BS2015. 2015, p. 9.

[160] Evans S, Liddiard R, Steadman P. 3DStock: A new kind of three-dimensional model of the building stock of England and Wales, for use in energy analysis. Environ Plan B 2017;44(2):227–55.

[161] Lauster M, Mans M, Remmen P, Fuchs M, Müller D. Scalable design-driven parameterization of reduced order models using archetype buildings with teaser. In: Proceedings of the 6th German-Austrian IBPSA conference. 2016, pp. 535–41.

[162] Allacker K, Castellani V, Baldinelli G, Bianchi F, Baldassarri C, Sala S. Energy simulation and LCA for macro-scale analysis of eco-innovations in the housing stock. Int J Life Cycle Assess 2019;24(6):989–1008.

[163] Lavagna M, Baldassarri C, Campioli A, Giorgi S, Dalla Valle A, Castellani V, Sala S. Benchmarks for environmental impact of housing in europe: Definition of archetypes and LCA of the residential building stock. Build Environ 2018;145:260–75.

[164] Österbring M, Mata E, Thuvander L, Wallbaum H. Explorative life-cycle assessment of renovating existing urban housing-stocks. Build Environ 2019;165:106391.

[165] Mastrucci A, Marvuglia A, Benetto E, Leopold U. A spatio-temporal life cycle assessment framework for building renovation scenarios at the urban scale. Renew Sustain Energy Rev 2020;126:109834.

[166] Csoknyai T, Hrabovszky-Horváth S, Georgiev Z, Jovanovic-Popovic M, Stankovic B, Villatoro O, Szendrő G. Building stock characteristics and energy performance of residential buildings in eastern-European countries. Energy Build 2016;132:39–52.

[167] Pittam J, O'Sullivan PD, O'Sullivan G. Stock aggregation model and virtual archetype for large scale retro-fit modelling of local authority housing in Ireland. Energy Procedia 2014;62:704–13, Available from: http://linkinghub.elsevier.com/retrieve/pii/S1876610214034651.

[168] Pittam J, O'Sullivan PD, O'Sullivan G. An archetype based building stock aggregation methodology using a remote survey technique. In: Littlewood J, Spataru C, Howlett RJ, Jain LC, editors. Smart Energy Control Systems for Sustainable Buildings. vol. 67, Cham: Springer International Publishing; 2017, p. 89–115, Available from: http://link.springer.com/10.1007/978-3-319-52076-6_4.

[169] Wittchen KB, Kragh J. Danish building typologies. In: SBi 2012: 01. 2012, p. 89.

[170] Kragh J, Wittchen KB. Development of two danish building typologies for residential buildings. Energy Build 2014;68:79–86, Available from: http://linkinghub.elsevier.com/retrieve/pii/S037877881300604X.

[171] Azar E, Menassa CC. A comprehensive framework to quantify energy savings potential from improved operations of commercial building stocks. Energy Policy 2014;67:459–72, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421513012755.

[172] Ballarini I, Corgnati SP, Corrado V. Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project. Energy Policy 2014;68:273–84, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421514000329.

[173] Ballarini I, Corrado V. A new methodology for assessing the energy consumption of building stocks. Energies 2017;10(8):1102, Available from: http://www.mdpi.com/1996-1073/10/8/1102.

[174] Clarke JA, Johnstone CM, Kim JM, Tuohy PG. Energy, carbon and cost performance of building stocks: Upgrade analysis, energy labelling and national policy development. Adv Build Energy Res 2009;3(1):1–20.

[175] García Kerdan I, Morillón Gálvez D, Raslan R, Ruyssevelt P. Modelling the energy and exergy utilisation of the mexican non-domestic sector: A study by climatic regions. Energy Policy 2015;77:191–206, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421514005680.

[176] Krarti M. Evaluation of large scale building energy efficiency retrofit program in Kuwait. Renew Sustain Energy Rev 2015;50:1069–80, Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364032115005341.

[177] Krarti M, Dubey K. Review analysis of economic and environmental benefits of improving energy efficiency for UAE building stock. Renew Sustain Energy Rev 2018;82:14–24, Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364032117312455.

[178] Armitage P, Godoy-Shimizu D, Palmer J. The Cambridge Non-Domestic Energy Model. Cambridge Energy, Cambridge Architectural Research Limited, editor; 2015, Available from: http://www.carltd.com/sites/carwebsite/files/CNDM%20Report%20260215.pdf.

[179] Mata e, Sasic Kalagasidis A, Johnsson F. Building-stock aggregation through archetype buildings: France, Germany, Spain and the UK. Build Environ 2014;81:270–82, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0360132314001991.

[180] Mata E, Sasic Kalagasidis A, Johnsson F. Description of the European building stock through archetype buildings. In: 8th conference on sustainable development of energy, water and environment systems–SDEWES conference, September 22-27, 2013, Dubrovnik, Croatia. SDEWES, editor; 2013, p. 19.

[181] Nemry F, Uihlein A, Studies IfPT. Environmental improvement potential of residential buildings IMPRO building. Luxembourg: Publications Office; 2008.

[182] Davila CC, Reinhart C, Bemis J. Modeling boston: A workflow for the generation of complete urban building energy demand models from existing urban geospatial datasets. Energy 2016;117(Part 1):27, Available from: http://web.mit.edu/sustainabledesignlab/projects/BostonEnergyModel/_doc/CWES_MIT_SDL_NOV15.pdf.

[183] Caputo P, Costa G, Ferrari S. A supporting method for defining energy strategies in the building sector at urban scale. Energy Policy 2013;55:261–70, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421512010518.

[184] Heiple S, Sailor DJ. Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy consumption profiles. Energy Build 2008;40(8):1426–36, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778808000200.

[185] Agugiaro G, Benner J, Cipriano P, Nouvel R. The energy application domain extension for citygml: Enhancing interoperability for urban energy simulations. Open Geospat Data Softw Stand 2018;3(1). Available from: https://opengeospatialdata.springeropen.com/articles/10.1186/s40965-018-0042-y.

[186] Jakob M, Wallbaum H, Catenazzi G, Martius G, Ngeli C, Sunarjo B. Spatial building stock modelling to assess energy-efficiency and renewable energy in an urban context. In: Proceedings of CISBAT. CISBAT, editor; 2013, p. 1047–52.

[187] Muñoz Hidalgo ME. A national heat demand model for Germany. In: Namazi-Rad M-R, Padgham L, Perez P, Nagel K, Bazzan A, editors. Agent based modelling of urban systems. vol. 10051, Cham: Springer International Publishing; 2017, p. 172–88, Available from: http://link.springer.com/10.1007/978-3-319-51957-9_10.

[188] Planning support systems and smart cities: articles presented at the cupum (computers in urban planning and urban management) conference ... july 2015 at mit in boston, usa. In: Lecture notes in geoinformation and cartography, Cham: Springer; 2015.

[189] Mata E, Kalagasidis AS. Calculation of energy use in the swedish housing - description of the building energy simulation model EABS: Energy assessment of building stocks. CHALMERS UNIVERSITY OF TECHNOLOGY; 2009.

[190] Bauer A, Lazemi-Wanjani S. Bottom-up characterization of the residential: Master Thesis. Göteborg: Chalmers Reproservice, editor; 2012, Available from: http://publications.lib.chalmers.se/records/fulltext/170378/170378.pdf.

[191] Hughes M, Palmer J, Pope P. The Cambridge Housing Model Guide v 3.0.pdf. Cambridge Architectural Research Limited; 2013, p. 1–27, Available from: https://spaces.hightail.com/receive/M8AzP/fi-076ce589-092a-4c51-b158-a973f27706b6/fv-382b58a4-b313-48b3-9668-83a9fe6edd1a/The%20Cambridge%20Housing%20Model%20Guide%20v%203.0.pdf.

[192] Nägeli C, Camarasa C, Jakob M, Catenazzi G, Ostermeyer Y. Synthetic building stocks as a way to assess the energy demand and greenhouse gas emissions of national building stocks. Energy Build 2018;173:443–60, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0378778817336423.

[193] Zhao F, Lee SH, Augenbroe G. Reconstructing building stock to replicate energy consumption data. Energy Build 2016;117:301–12, Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778815303157.

[194] Loga T, Diefenbach N, Stein B, Born R. TABULA - Scientific Report Germany - Further Development of the German residential building typology. 2012, p. 146, Available from: http://www.building-typology.eu/downloads/public/docs/scientific/DE_TABULA_ScientificReport_IWU.pdf.

[195] Stein B, Loga T, Diefenbach N, editors. Inclusion of new buildings in residential building typologies: steps towards nzebs exemplified for different european countries. In: EPISCOPE synthesis report, Darmstadt: Institut Wohnen und Umwelt GmbH, EPISCOPE and Wohnen und Umwelt, Institut, editor; 2014.

[196] English Housing Survey. GOV.UK; 2013, Available from: https://www.gov.uk/government/collections/english-housing-survey.

[197] DIN 4108-4. Wärmeschutz und Energie-Einsparung in Gebäuden – Teil 4: Wärme- und feuchteschutztechnische Bemessungswerte. 2020, 2020.

[198] Im BBSR, ÖKOBAUDAT. ÖKOBAUDAT. 2021, Available from: https://www.oekobaudat.de/.

[199] BKI - Baukosteninformationszentrum für Architekten. 2021, Available from: https://bki.de/.

[200] EnergyPLAN. EnergyPLAN. 2021, Available from: https://www.energyplan.eu/.

[201] BlueMouse GmbH. Ecoinvent. 2021, Available from: https://www.ecoinvent.org/.

[202] Ökobilanz Software. 2021, Available from: https://gabi.sphera.com/deutsch/index/.

[203] SimaPro. SimaPro | The world's leading LCA software. 2021, Available from: https://simapro.com/.

[204] GEMIS - IINAS. 2021, Available from: http://iinas.org/gemis.html.

[205] OpenStreetMap. OpenStreetMap. 2021, Available from: https://www.openstreetmap.org/#map=6/51.330/10.453.

[206] Google maps. 2021.

[207] Entranze :: Welcome to ENTRANZE project page. 2021, Available from: https://www.entranze.eu/.

[208] Energy efficiency trends & policies | ODYSSEE-MURE. 2021, Available from: https://www.odyssee-mure.eu/.

[209] Wetter und Klima - Deutscher Wetterdienst - Leistungen - Kostenfreie Gradtagzahlen/Gradtage. 2021, Available from: https://www.dwd.de/DE/leistungen/gtz_kostenfrei/gtz_kostenfrei.html.

[210] Land-based stations | national centers for environmental information (NCEI). 2021, Available from: https://www.ncei.noaa.gov/products/land-based-stations.

[211] Lotteau M, Loubet P, Pousse M, Dufrasnes E, Sonnemann G. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Build Environ 2015;93:165–78, Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360132315300445.

[212] Calder M, Craig C, Culley D, de Cani R, Donnelly CA, Douglas R, et al. Computational modelling for decision-making: Where, why, what, who and how. R Soc Open Sci 2018;5(6):172096, Available from: http://rsos.royalsocietypublishing.org/lookup/doi/10.1098/rsos.172096.

[213] Sargent RG, editor. Proceedings of the 2009 winter simulation conference: Verification and validation of simulation models. New York: IEEE; 2009, Available from: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5429327.

[214] Carson J, editor. Model verification and validation: Proceedings of the 2002 winter simulation conference E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, eds., Vol. 2002. IEEE; 2002.

[215] Sergant R. Verification and validation of simulations models: Proceedings of the 2011 winter simulation conference S. Jain, R.R. Creasey, J. Himmelspach, K.P. White, and M. Fu, Eds.. Piscataway, NJ: IEEE; 2011, Available from: http://ieeexplore.ieee.org/servlet/opac?punumber=6135535.

[216] ISO 14044. ISO14044 - Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006); German and English version EN ISO 14044:2006. Berlin: DIN Deutsches Institut für Normung e.V; 2006.

[217] ISO 13790. ISO 13790 - Energy performance of buildings – Calculation of energy use for space heating and cooling (ISO 13790:2008); German version EN ISO 13790:2008. Berlin: DIN Deutsches Institut für Normung e.V; 2008.

[218] ISO 52016. DIN EN ISO 52016-1 - Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - Part 1: Calculation procedures (ISO 52016-1:2017); German version EN ISO 52016-1:2017. Berlin: ISO; 2018.

[219] Felsmann C, Perschk A, Franke R. Test of ISO 52016-1 energy performance of buildings calculation procedure. In: Corrado V, Fabrizio E, Gasparella A, Patuzzi F, editors. Proceedings of building simulation 2019: 16th conference of IBPSA. Building simulation conference proceedings, IBPSA; 2020, p. 3910–6.

[220] Lee SH, Fei Z, Augenbroe G. The use of normative energy calculation beyond building performance rating systems: proceedings of building simulation 2011: 12th conference of international building performance simulation association, sydney, 14-16 november. In: Proceedings of building simulation 2011, Vol. 2011. 2011, p. 2753–60, Available from: http://www.ibpsa.org/proceedings/BS2011/P_1865.pdf.

[221] Hong T, Langevin J, Sun K. Building simulation: Ten challenges. Build Simul 2018. Available from: http://link.springer.com/10.1007/s12273-018-0444-x.