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EU building stock characterization for whole life cycle assessment: Data challenges and key insights

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Abstract. The building sector plays an important role in achieving the climate objectives of the EU Green Deal. While prioritizing measures to reduce operational energy and GHG emissions has proven beneficial, it has shifted burdens by increasing embodied emissions. Quantifying and regulating emissions throughout the entire building life cycle is therefore crucial. An ongoing DG GROW project is investigating strategies to reduce life cycle GHG emissions within the EU. Various steps are being carried out to achieve the research goals: identification of data needs and sources, baseline analysis of the existing whole life carbon emissions of the EU building stock, modelling of future scenarios. This paper elaborates on the building stock characterization, demonstrating innovation through its level of granularity. Firstly, key data sources are chosen to provide the desired granularity. Secondly, archetypes are defined based on the data sources. Thirdly, attributes are chosen to describe the building stock in terms of geometry, building element composition, energy use, etc. The paper concludes by discussing challenges related to collecting attribute information and managing data gaps. The insights derived offer valuable recommendations for establishing a future data repository dedicated to environmental LCA of the EU building stock.

Keywords: Carbon footprint, embodied environmental impact, data gap filling, greenhouse gas emissions, building archetypes, stock modelling.

1. Introduction

The building sector is a prominent contributor to energy and resource consumption at the European level, accounting for about half of all extracted materials, one third of waste generation and 40% of total energy consumption. It is also responsible for 36% of greenhouse gas (GHG) emissions, making it a hotspot for interventions aimed at achieving the ambitious climate goals defined in the EU Green Deal [1–3].

The use phase has been identified to be the largest cause of environmental impacts across the entire life cycle of buildings; EU policy interventions have therefore prioritised measures aimed at increasing energy efficiency and reducing operational consumption, and thus operational emissions [4]. The Energy Performance of Buildings Directive [5] and the New Renovation Wave [6] are two of the most relevant legislative actions from this perspective, promoting significant efforts to improve the energy performance of buildings and decarbonise their energy consumption. This approach, while beneficial, has led to burden shifting, with embodied impacts growing more prominent, both in relative and absolute terms: it has been estimated that embodied emissions in new buildings are nearly the same as those associated with operational energy, but can reach values as high as two to four times higher than the operational ones [7]. It is therefore crucial to quantify and regulate emissions across the whole life cycle of buildings. Some EU Member States (MS) have already put forward legislation pertaining to this issue:

in Denmark, starting from January 2023, it is mandatory to report CO_2 emissions across the entire life cycle of all new buildings, and buildings with an area larger than 1000 m^2 must adhere to a yearly limit value of 12 kg CO_2-eq/m^2; in France, the new Environmental Regulation is targeting a progressively wider variety of building types and imposing increasingly strict carbon requirements across the life cycle of buildings; in the Netherlands, all new residential buildings, as well as offices larger than 100 m^2, must report their embodied impacts, which are then translated into an economic indicator subjected to progressively lower limits; in Sweden, all new buildings must be accompanied by a climate declaration reporting GHG emissions relative to the construction phase, which will be subjected to increasingly tight limits starting from 2027; in Finland, a new Building Act will enter into force in 2025, imposing carbon emission limits relative to the whole life cycle of new buildings [8–16]. Despite these actions being undertaken by individual MS, there is still a lack of a cohesive framework at the EU level. An ongoing project initiated by the DG GROW of the European Commission, *Analysis of Life-cycle Greenhouse Gas Emissions and Removals of EU Buildings and Construction* (referred to as DG GROW study in this paper), aims at bridging this gap by investigating strategies to reduce life cycle GHG emissions both at the EU and the national levels. The objectives of the study include modelling the whole life cycle environmental impacts of the EU building stock; assessing strategies for the reduction of whole life GHG emissions with a view to achieving climate neutrality by 2050; and improving data availability. Steps are therefore being undertaken to identify relevant data needs and sources, carry out a baseline analysis of GHG emissions and removals associated with the existing EU building stock and modelling future whole life carbon scenarios.

The aim of this paper is to describe the building stock characterisation process, demonstrating its innovation potential in connection to its levels of granularity and differentiation among EU MS, and to highlight the challenges emerged during this process, addressing potential solutions and providing recommendations for future work.

2. Methodology

2.1. Data sources

The EU building stock characterization dataset in the DG GROW study builds on the synthesis of information found in key data sources on the European building stock composition and relevant building characteristics, as shown in Table 1. The primary data sources are Hotmaps [17], AmBIENCe [18], and the Cost-effectiveness studies (CES) [19]. These three sources are identified as possessing the most complete and cohesive information, with Hotmaps and AmBIENCe being key data sources for previous work on the whole life cycle GHG emissions of the EU building stock [20]. Furthermore, as AmBIENCe is a synthesis of Hotmaps and TABULA [21], the information in the latter source can be skillfully cross-referenced and complemented with the information contained in Hotmaps. In addition to these three main sources of information, there are other data sources used to supplement or verify the information in the EU building stock characterization dataset. The additional sources consulted include TABULA/EPISCOPE, the EU Building Stock Observatory (BSO) [22], Buildings' renovation makerspace studies [23], Eurostat [24], and Odyssee [25].

Table 1. Overview of data sources (primary, secondary) used to establish the EU building stock characterization dataset developed in the DG GROW study.

Primary data sources	Secondary data sources
• Hotmaps • AmBIENCe • Cost-effectiveness studies	• TABULA/EPISCOPE • EU Building stock observatory • Buildings' renovation makerspace • Eurostat • Odyssee

2.2. Archetype definition

In order to characterise and model the EU building stock, representative buildings (archetypes) are defined by dividing the current building stock into clusters. The main characteristics selected to cluster the building stock and define the building archetypes, as indicated in Table 2, are: country; sector (residential, service); building type (e.g. single-family house, multi-family house, as well as office, trade, education, etc.); building age class (the original construction period). With regards to the latter, it should be noted that the archetypes represent the current state of a building; older buildings could therefore be defined either as-built or as having undergone renovation.

Table 2. The four key attributes for archetype definition.

Attribute	Description	Values
Country	Location of the buildings within the EU27	[Austria; Belgium; Bulgaria; Croatia; Cyprus, Czechia; Denmark, Estonia; France; Finland; Germany; Greece; Hungary; Italy; Ireland; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Romania; Slovakia; Slovenia; Spain; Sweden]
Sector	Two main sectors	[Residential sector; Non-residential sector]
Building type	Type of function the building is primarily used for, further distinguishing the sector	[Single-family houses; Multi-family houses; Apartment blocks; Offices; Trade; Education; Health; Hotels and Restaurants; Other service buildings]
Building age class	Construction period cohort that buildings belong to, based on original construction period	[1850 – 1918; 1919 – 1944; 1945 – 1969; 1970 – 1979; 1980 – 1989; 1990 – 1999; 2000 – 2010; 2011 – 2021]

2.3. Dataset structure

The dataset has a tabular structure and is organized along two axes. The rows (vertical axis) contain all the information established for each building archetype (1 row = 1 archetype). The columns (horizontal axis) contain the various attributes relative to the archetype characterization, holding two main aspects of information: 1) the number of buildings (archetypes) in the stock; 2) attributes to describe different building archetype characteristics, such as their geometry and material- or energy-related properties. These are key inputs for the life cycle inventory modelling.

2.4. Archetype characteristics

A total of 166 attributes are used to describe building archetypes, considering six main groups of characteristics relevant for whole life cycle modelling and environmental impact assessment (Table 3).

Table 3. Main groups of archetype characteristics and related attribute examples.

Main groups of characteristics	Examples of attributes
1. Building stock	Number of buildings, constructed area, heated area, cooled area, number of dwellings
2. Building geometry	building gross floor area, volume, shape factor, storeys below and above ground, storey height, envelope area, window/wall ratio
3. Occupational properties	number of users, area per person, ratio of occupied/vacant/secondary dwelling

4. Building element characteristics	storey floors, external and internal walls, roofs, windows: material characteristics and energy performance characteristics (reference (structural) materials ratio and thickness, insulation material and thickness, thermal conductivity, density, U-value
5. Energy performance	energy performance class, energy efficiency ratio, type and scope of building integrated photovoltaics use
6. Energy systems	system technology, energy demand and energy sources for space heating, space cooling, domestic hot water (DHW)

The present analysis focuses on a reduced set of attributes that were judged to be most relevant for the overall goal of the study, providing a comprehensive overview of building stock availability across the EU. The structure of the current work, inclusive of the geographical boundaries, building types and assessed attributes, is shown in Figure 1.

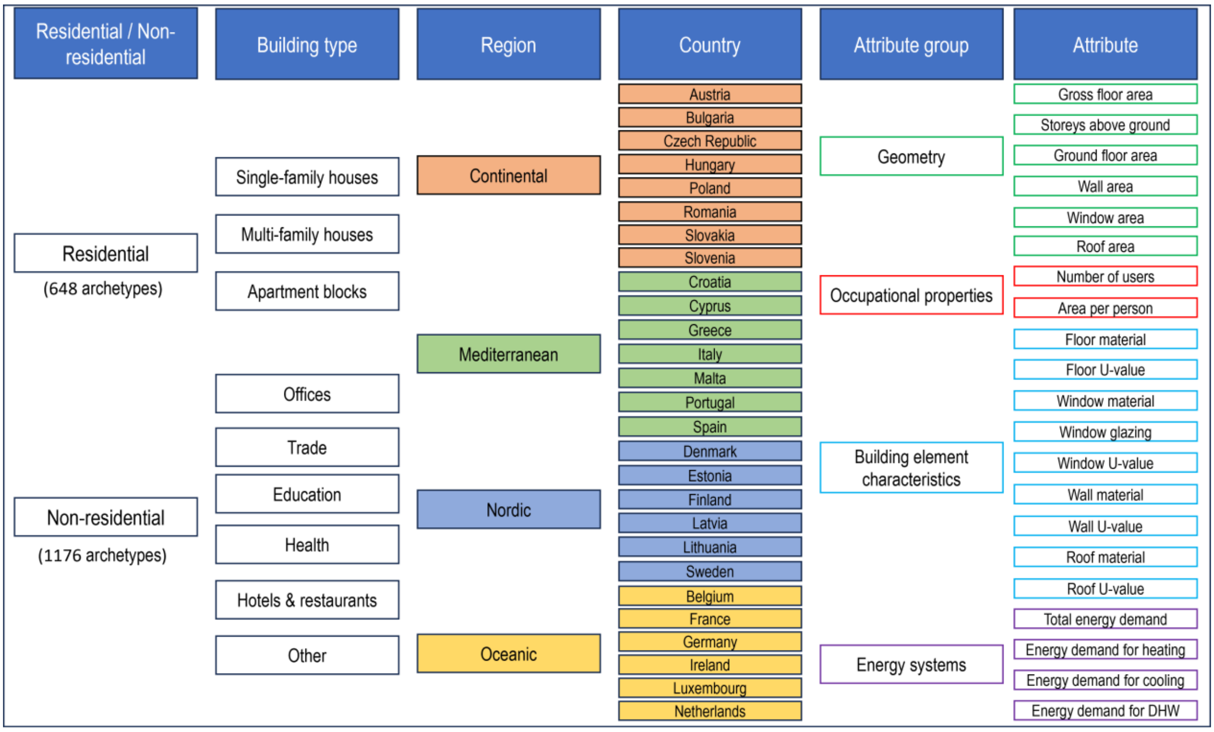

Figure 1. Structure of the analysis, showing the relevant building types, countries and regions, as well as the attributes considered.

2.5. *Methodology for the collection of attribute values*

In order to collect attribute information for each building archetype in a harmonised manner, a set of rules is defined, establishing a common procedure for data collection and data gap filling.

In a first step, the attribute value collection activity involves the extraction of relevant information from the appropriate primary sources; in a second step, the data thus collected are recalculated, where necessary, to align with the construction periods defined in the DG GROW study. Once this process is finalised, there emerges a clear overview of the existing data gaps; in a third step, the data gaps are filled by employing secondary sources. To achieve transparency as to the origin of the information and assess data quality, each data item is accompanied by a short description indicating its source and any calculations or assumptions made. Furthermore, in the case of building element characteristics, a detailed review of the attribute data is conducted, as primary and secondary sources are not always fully reliable and representative where these aspects are concerned. The review is carried out relying on national sources and expert judgement. Hereinafter, attribute information gathering and data gap filling are described according to the main group of characteristics to which they belong (as defined in Table 3).

Building stock attributes are mainly sourced from Hotmaps, referring to statistical data in order to provide a comprehensive understanding of the existing EU built environment. Data relative to the non-residential sector are used as they are, while further elaborations are necessary for residential buildings belonging to the pre-1945 and post-2011 age classes. As AmBIENCe provides more precise information for these construction periods, often articulating them in several sub-periods, it is used as a source, following an adjustment procedure to ensure the information fits the age classes used in the DG GROW study.

Attributes relative to building geometry are distinguished by two different levels of detail: those of a more general character (e.g. reference building wall area) are retrieved from AmBIENCe, whereas the more specific ones (e.g. reference building storey height) are obtained from the CES. It is worth mentioning that any information collected from CES has been treated on a case-by-case basis, due to a lack of standardisation in the data provided. A two-step process is carried out to ensure that CES data are used appropriately: firstly, it is necessary to check which reference buildings are available in the CES and to what degree they match the archetypes of the DG GROW study. Secondly, the available data are examined and, where appropriate, processed to conform to the archetype definition in the present work. This proves particularly relevant where CES include multiple archetypes per building type in a given country; that could be the case for education buildings, for instance, where a distinction could be made among primary school, secondary school and gymnasium. To proceed, the building most closely aligned with the useful floor area of the corresponding AmBIENCe archetype is selected.

The attributes relative to occupational properties are fully based on Hotmaps, and only supplemented with Eurostat population data to calculate the surface area per person. To this end, the constructed area relative to each residential building type (Hotmaps) is summed across the different construction periods and multiplied by Eurostat population data for 2016, to ensure that a common reference year is used.

The field of building element characteristics is of crucial importance for the assessment of the environmental impacts of the existing building stock, as it defines each archetype in terms of materials, performance and construction technologies. This set of information is lacking at the statistical level and is generally covered with reference to specific real-case buildings which are, however, not necessarily representative of the entire building stock. As a consequence, attributes belonging to this group are challenging to define and call for particular attention in order to avoid the risk of distorting outcomes. To close the gap, the attribute filling is carried out in a series of steps, with the aim of making the most of all available sources. Firstly, Hotmaps is used to define the composition of floors, walls, roofs and windows in terms of percentage of different materials (e.g., a specific archetype can be characterised by 50% concrete walls and 50% masonry walls) and constructive solutions (e.g., solid wall and/or cavity wall). The construction technologies are then detailed in terms of layer thickness and performance properties (e.g., conductivity, density, U-value) using AmBIENCe. Note that when AmBIENCe reports a set of different characteristics for reference building envelope elements, they are all taken into consideration for the archetype definition. Secondly, in order to fill data gaps, additional information is retrieved by interviewing regional experts, with the goal of maximising the collection of data on the constructive and material heterogeneity of the existing building stock and to validate the uncertain information previously systematised. Thirdly, some attributes are subjected to a review process, with the aim of handling outliers (e.g. in terms of U-value) [26] and critical materials (e.g., asbestos use in compliance with regulatory constraints). In this stage, special attention is given to building insulation, by calculating the thickness of the material layer to obtain the stated U-values for walls, ground floors and roofs. Depending on the available data, assumptions to use inputs from neighbouring countries to fill data gaps are included in a post-processing step.

Attributes relative to the energy performance of buildings are retrieved from Hotmaps, while any information concerning the building energy performance class is extracted from CES. It is important to emphasise that information about the performance class of the archetypes falls to the specific classification of the country in which the reference building is located. In general, the following nomenclature is adopted: ES = pre-2005 (pre-EPBD); NS = post-2005 (acc. EPBD); AS = Advanced (e.g. NZEB, passive house).

AmBIENCe is taken as the reference source for the energy systems, obtaining sufficiently exhaustive data for all the periods concerned (1850-2021). The AmBIENCe data detail the most common system technology, efficiency and fuel used for space heating, space cooling, and domestic hot water. Attribute information relative to useful energy demand and final energy consumption is retrieved from Hotmaps.

3. Results and discussion

3.1. Archetype characterization

3.1.1. Data availability and gaps

Data gaps are identified for the building archetypes included in the stock characterisation. The assessment highlighted differences in data availability across European countries, as shown in Figure 2, which provides an overview of the relevance of these data gaps with respect to the total data collected. For the purpose of this analysis, calculations carried out to align data extrapolated from the primary sources with the age classes adopted in the current work are not considered as data gap filling.

Data gaps never exceed 30% of the overall data requirement. Countries in the Mediterranean region however appear to have lower data availability compared to those in the other regions, for both residential and non-residential buildings. On average, data gaps are more prominent for service buildings than for the residential sector, with the Nordic region representing the main exception.

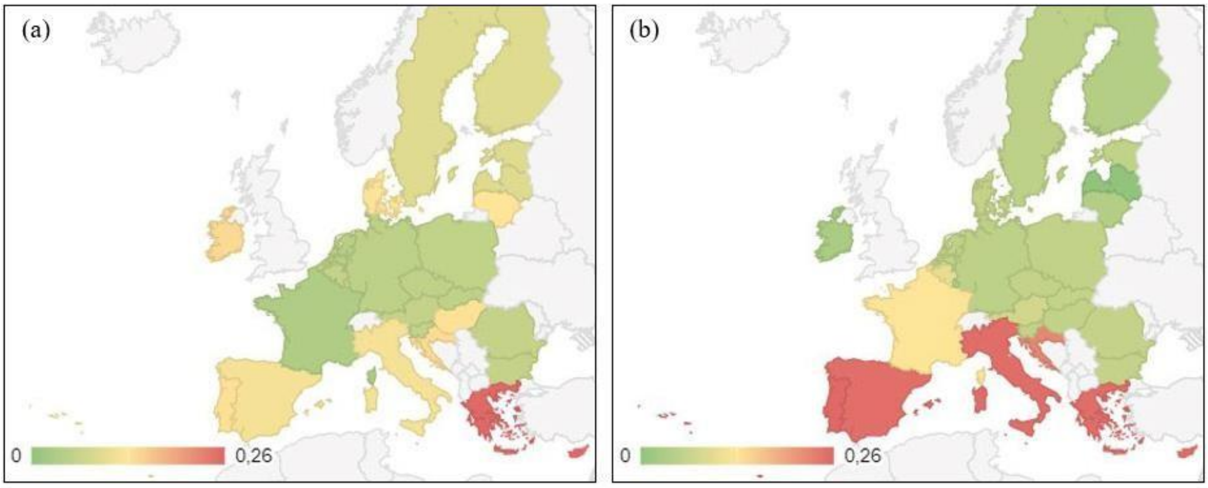

Figure 2. Share of total data gaps per country in (a) residential and (b) non-residential buildings.

Figure 3 shows the data gaps per attribute in each country. The largest and most common data gaps are those associated to some of the geometry-related parameters; specifically, gross floor area and number of storeys. The values for these attributes are extracted from CES; the missing information is therefore due to the lack of standardised reporting in CES, which leads to significant variations across countries in terms of assessed reference buildings and available information. Other geometry-related attributes also show a significant incidence of data gaps in the residential sector in particular, due to the lack of information regarding one of the relevant building categories (generally multi-family houses or apartment blocks) in the primary source (AmBIENCe). This issue mostly affects countries in the Nordic and, to a lesser extent, Mediterranean regions and its effects are also noticeable in other attributes derived from the same source; namely, the U-values of the building envelope. Information on building materials is lacking in particular for non-residential buildings in the Mediterranean region; these gaps are subsequently filled by relying on expert judgement. As for the energy system attributes, the Mediterranean region is the only one affected by data gaps, with most of its countries containing a share of data based on assumptions.

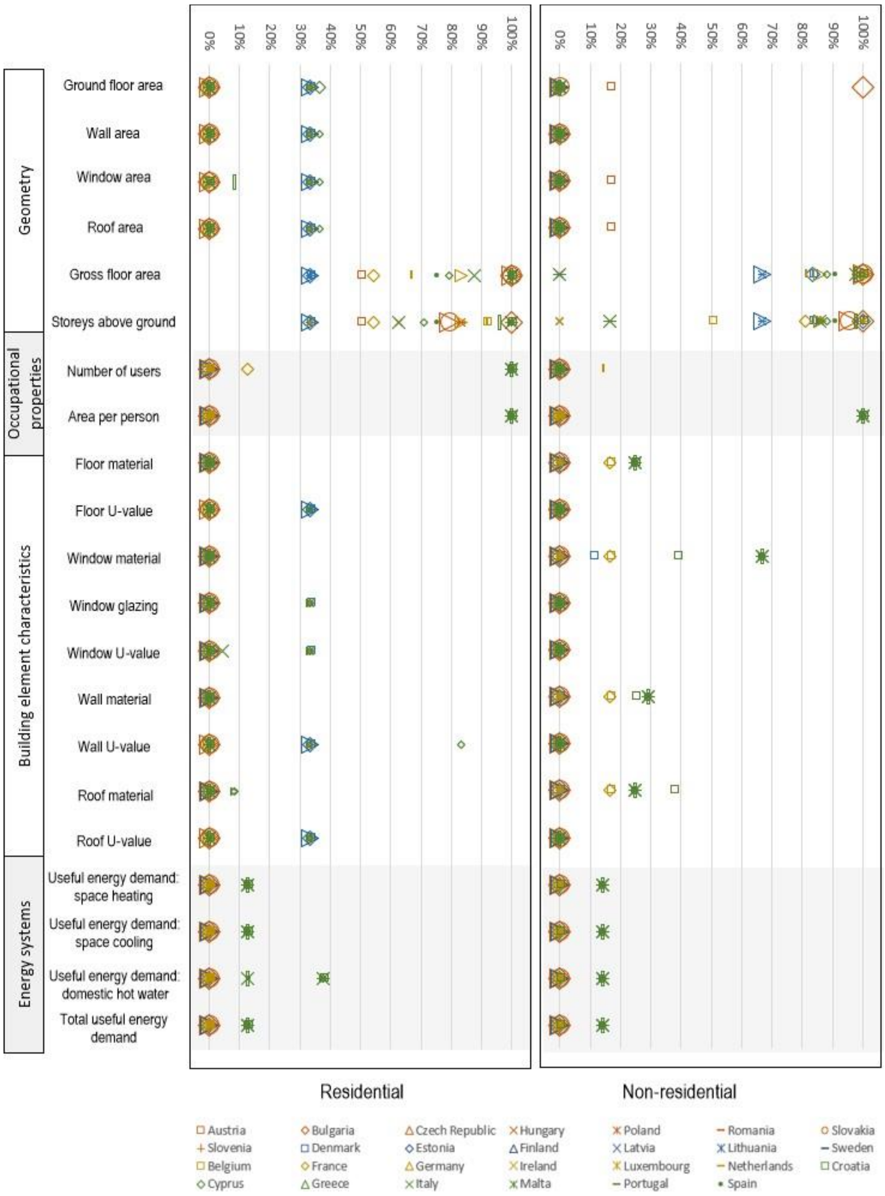

Figure 3. Share of data gaps per parameter, country and building type (residential/non-residential). Countries within a specific region are indicated by the same colour (Continental: orange; Nordic: blue; Oceanic: yellow; Mediterranean: green).

From the data gap analysis, it emerges that there are significant distinctions, in terms of data availability, across countries, building sectors (residential and non-residential) and attributes. Figure 4 shows where these gaps are largest. As previously mentioned, there is a lack of reliable data to fill in attributes relative to building geometry for residential buildings. Indeed, there are significant uncertainties connected to all geometry-related attributes within the residential sector, while only gross floor area and number of storeys are consistently affected in the case of non-residential buildings. The only exception is the Continental region, where some gaps relative to the areas of envelope elements are present. These gaps, pertaining to Austria in particular, are due to inaccurate data in the primary source used for these attributes (AmBIENCe).

Building element characteristics also show a lack of consistent data, which mostly affects the U-values of the envelope in residential buildings; in non-residential buildings, it is the material composition of the elements to be most affected, with gaps being largely concentrated in the Oceanic and Mediterranean regions. Countries in the Mediterranean region are associated with the largest number of data gaps; these also include information connected to the energy systems, for both residential and non-residential buildings, while that information is largely assumed to be known with relative certainty in most other cases.

		Geometry						Occupational		Building element characteristics									Energy systems			
		Ground floor area	Wall area	Window area	Roof area	Gross floor area	Storeys above ground	Number of users	Area per person	Floor material	Floor U-value	Window material	Window glazing	Window U-value	Wall material	Wall U-value	Roof material	Roof U-value	Useful energy demand - Space heating	Useful energy demand - Space cooling	Useful energy demand - DHW	Total useful energy demand
Residential	Continental	8	8	8	8	180	157	24	0	0	8	0	0	8	0	8	0	8	0	0	0	0
	Nordic	48	48	48	48	48	48	0	0	0	48	0	48	16	0	48	0	48	0	0	0	0
	Oceanic	8	8	8	8	113	109	3	0	0	0	0	24	8	0	8	0	8	0	0	0	0
	Mediterranean	16	16	18	16	154	145	168	168	0	16	0	48	17	0	28	16	16	21	21	45	21
Non-residential	Continental	7	0	7	7	336	320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Nordic	0	0	0	0	161	168	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0
	Oceanic	0	0	0	0	210	169	6	0	56	0	42	0	0	56	0	21	0	0	0	0	0
	Mediterranean	0	0	0	0	241	237	0	294	294	0	553	0	0	336	0	315	0	36	36	36	36

Figure 4. Heatmap highlighting the number of data gaps per region, attribute and building sector. The numbers in the table refer to the number of missing or uncertain data points out of a total of 648 per attribute in the residential sector and 1134 in the non-residential sector.

While this analysis provides an informative overview of where the missing data is located, these numbers alone do not provide a full understanding of the situation. The definition of data gap includes several different categories, ranging from data obtained from secondary sources, to assumptions, and data adapted from archetypes of a different country in the same region. It should be pointed out that the Mediterranean region is the only one which explicitly details which contributions are due to expert judgement; it is also the only one for which two countries are used as a basis to obtain missing data (e.g., Italy is used to fill in gaps relative to residential buildings in other countries in the region, while Malta is used for this same purpose for non-residential buildings). These differences may partly explain the larger uncertainties connected to this region. A further explanation might be due to the human component: each region is handled by a different project partner, and while there is a uniform procedure in place to handle data gaps, different choices might have been made when it came to highlighting and classifying these gaps.

Overall, the residential sector has a slightly lower share of data gaps compared to the non-residential one, though they are more widely spread across different attribute categories.

3.2. Challenges and solutions

The primary challenges encountered in this study can be categorized into three main areas: defining archetypes and their characteristics, determining the appropriate level of detail for information and attribute listing, compiling data and filling data gaps.

Initially, challenges emerged in establishing a coherent definition of archetypes. Each source presented its unique interpretation of archetypes, with varying construction period classifications over time; for instance, AmBIENCe's age classes varied across countries. Furthermore, discrepancies existed in the presentation and categorization of archetypes among different sources, often leading to contradictory information that posed difficulties in cross-referencing. Additionally, CES did not cover all archetypes and the information that was covered differed from country to country. Consequently, data gaps varied depending on the archetype and geographical context. To address this issue, a methodological approach was devised: examining the definitions provided by each source for each archetype and synthesizing them into a unified definition that captures the essence of diverse perspectives. It is worth noting that incorporating multiple sources complicated this task significantly.

Secondly, challenges emerged regarding determining the appropriate level of detail for attribute listing. Each information source presented an abundance of attributes tailored to uniquely describe archetypes. For instance, statistical data related to construction solutions and materials are often derived from a sample of real buildings considered representative of a segment of the building stock, such as those found in TABULA and CES, providing highly precise information on specific cases. However, this specificity can hinder cross-referencing with data from other sources that may offer more generalized statistics. Consequently, there arose a necessity to precisely define archetypes and consistently characterize the attributes used to describe them, thus enabling seamless comparison of data across different sources. As a result, reconciling these attributes across sources for meaningful cross-referencing became a complex endeavour. To address this challenge, an approach was proposed: compiling a list of attributes while ensuring that the level of detail remains manageable, thereby facilitating cross-source comparisons without unacceptable disparities.

Lastly, challenges pertained to the compilation of data itself. Once archetypes were defined and attributes listed, data compilation was contingent on selecting the most accurate information from the various sources, often yielding contradictory or incomplete datasets. In such cases, efforts were made to mitigate discrepancies and fill data gaps, recognizing the inherent limitations. For attributes with consistent data gaps, guidelines were established for filling these gaps based on secondary sources, utilizing calculation rules. Moreover, within regions, consideration was given to leveraging data from other countries within the same geographic area. This involved assuming similar materials for buildings of the same type and construction periods across regions or employing analogous ratios between various components of building geometry.

This study underscores the discrepancies in data availability among EU countries and advocates for an improved data gathering system at both national and European levels, with a focus on using these data for whole life carbon studies. As previously mentioned, CES in particular vary significantly from one country to another, covering different building types and construction periods, and providing different types of data: it would be advisable for all MS reports to include detailed information not only about the energy performance of the buildings and their basic geometry, but also about common material build-ups, and, potentially, to do so for standardised reference buildings. Furthermore, providing a common reporting format would represent an improvement in terms of data accessibility, as it would facilitate data collection and comparison among countries. This, given the overall EU-wide scope of CES, would be an effective step towards unifying the results into one overarching dataset. Harmonising data structures and content, particularly within CES, could therefore enhance data availability and consistency across Member States, thereby facilitating more robust analyses and policy-making efforts.

4. Conclusions

The analysis carried out in this work highlights the primary need to improve the collection of reliable statistical data in future European and national surveys, in order to improve the quantity and quality of the available information and facilitate future assessments of the environmental impact of the building stock. In particular, it is necessary to improve the granularity of information relative to building geometry and building element characteristics. A more detailed approach to information gathering is essential, and can be achieved through the inclusion, at the national and regional level, of survey questions involving both experts, such as designers and builders, and building users. Increased data granularity would make it possible to model highly detailed archetypes, scalable to the entire building stock and useful for scenario definition. The CES could be a good means for such streamlined data gathering and repository in the EU, but clear EU Guidelines would be needed to ensure consistency and transparency. Not only guidelines on archetype definition, but also on reporting the archetype data would be a great step forward to bolster EU building stock modelling and related EU policy support.

It is also necessary to collect more detailed information on non-residential buildings, in order to define archetypes for the enormous variety of buildings which fall under this classification. Indeed, there is a disequilibrium between the amount of available information pertaining to the residential and non-residential sectors: additional focus is required to even out the differences, and data gathering activities aimed at collecting new, reliable and easily accessible datasets should be promoted at both the MS and EU levels.

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