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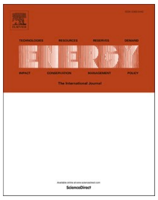

A comparative life cycle assessment of building sustainability across typical European building geometries

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ABSTRACT

In recent years, significant progress has been made in the sustainability assessment of building materials and buildings. The introduction of Environmental Product Declarations (EPDs), the development of Level(s), and the release of relevant series of standards have helped to improve the sustainability of buildings. However, a research question that remains unresolved is the lack of information related to the comparison of the sustainability performance of building units across Europe and the significance of conducting such research. This study addressed this question by implementing a comparative whole-building Life Cycle Assessment (LCA) across buildings in Europe. The study emphasizes the necessity of considering typical building geometries and thermal performance of buildings across Europe and introduces six typical building geometries for three different European clusters (northern-western, central-eastern, southern cluster). The results of this study revealed that the sustainability performance of buildings is not similar across the EU and that cost-optimal minimum thermal performance requirements for building structures have a significant impact on their environmental performance. Particularly, single-family houses in Central and Eastern Europe are responsible for 324.42 $kgCO_2e/m^2$. Contrary to this, Northern and Western European single-family buildings have the lowest environmental impact with 268.97 $kgCO_2e/m^2$. Multifamily houses in Southern Europe are responsible for 321.82 $kgCO_2e/m^2$, in Northern and Western Europe the environmental impact is 275.37 $kgCO_2e/m^2$. The outcome of this study is significant for the scientific community involved in assessing the sustainability of buildings in Europe, as it provides valuable insights into their environmental performance, considering the energy efficiency and sustainability aspects of buildings. The study's findings should be considered when setting minimum LCA-related requirements, in view of the provisions of the new EU policies expressed in the Energy Performance of Buildings Directive (EPBD) recast for defining the Global Warming Potential (GWP) of new buildings.

1. Introduction

Research and development activities, as well as new methods and practices related to evaluating the sustainability performance of buildings are constantly increasing [1]. These are directly related to the need to promote sustainable practices in the building sector, reducing its overall environmental impact [2]. The development in this field includes both research activities and the demonstration of new market solutions, including materials [3], future trends of construction practices [4] with the aim to reduce buildings carbon footprint, as well as building services solutions, and integrated building systems [5] aiming to achieve energy savings and increase sustainability performance. Recent research activities also take into account a holistic approach to effective renovation involving building systems [6]. In this context, various standardised procedures are continuously being developed and adopted to assess the sustainability of buildings or their components in a generally acceptable way.

Research work related to the assessment of proposed concepts and solutions by definition includes the demonstration of the solution in real life or simulated conditions by use of a case study. It is also common

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practice, in several standards relating to practices and data in the field of building energy assessment, to include examples of typical buildings [7,8]. In both cases, however, what is lacking are commonly accepted building geometries, which can be used as subjects to demonstrate these principles. Inevitably, the use of reference building geometries for the demonstration of new principles is only related to advantageous features, which can be summarized as follows:

1. It allows the comparative assessment on a common basis of different principles for similar topics
2. It saves time and effort to identify and simulate the geometry of a building required as case studies
3. It establishes a consensus among researchers and the standardization community on typical building geometries.

This study is addressing the main research questions and objectives that are listed below:

- Can European building stock be generalised to enhance comparative research for the sustainability assessment? The research is focussing to assess if it is feasible to develop a representative residential building models of the European building stock. These typical geometries should lead to more effective and comprehensive benchmarking studies to assess the sustainability of buildings.
- How does the sustainability performance of buildings vary across European regions and what is the significance of such benchmarking? The study aims to highlight the diversity of sustainability performance in Europe and the importance of analysing and addressing these differences.
- What impact the thermal requirements of typical geometries have on the sustainability performance of buildings? Researchers aims to assess the potential trends in thermal requirements and embodied carbon emissions within the building sector.

Considering the identified need, motivation and research questions, the aim of this study is to define and introduce representative geometries of residential buildings across Europe, to carry out a comparative life-cycle assessment covering the whole life-cycle of buildings, as well as to assess the impact of minimum thermal requirements on sustainability performance.

This study provides standardised geometries for residential buildings on a European scale, thus facilitating comparative life cycle assessments across different building clusters. The novelty of the study lies in the comparative assessment of thermal requirements and their impact on the environmental impact, providing a new perspective on the carbon footprint of the building sector. The study also provides a reference point for sustainable building practices to support comparable future research on energy-efficient and sustainable solutions. The results provide a valuable reference point for policy makers and industry helping to align energy efficiency requirements with sustainability objectives, ensuring long-term relevance and applicability.

2. Theoretical background

2.1. The need for a consensus on typical building geometries

Understanding the typology of geometry in existing buildings can be beneficial for the preliminary design of major renovation projects. This aspect is linked to Macro-objective 2, indicator 2.3 of the Level(s) framework. It also supports the assessment of the opportunities for dismantling, reuse and recycling, linked to Macro-objective 2, indicator 2.4 [9].

Given the Macro-objective 1 of the Level(s) framework to reduce life-cycle carbon emissions (indicator 1.2), interest in building LCA research and the drive to reduce embodied carbon has been growing rapidly over the last decade [1]. In addition, research and development in the field of energy assessment has developed rapidly in recent decades [10]. The need to reduce energy consumption in the building sector (Macro-objective 1, indicator 1.1), as well as the challenges related to the digitalisation of energy assessment in this sector, are driving the development of this field. Considering research of both fields, it is a common practice to support the research conducted with the use of use cases, mainly utilizing mock or real buildings.

Regarding the types of buildings, studies usually focus on residential (Single-family detached, bungalows, apartments) [11], large multi-family (apartments and flats) [12], public, commercial (offices, retail buildings, shopping centres, hotels) and industrial buildings [13]. All studies in the field introduce a building unit, describe it, and simulate its geometry from scratch, to demonstrate the topic discussed. In those cases, where this validation is verified by field measurements, this practice is appropriate. However, in most cases, where no field measurements are available, it is evident that there is no measure of comparison between the results arising from different geometries. It is also important that main research findings of novel building design, materials, energy efficiency improvement, etc. can be replicated. When typical geometries are used for these studies, the reproducibility of the findings would be increased, as no reference is made to a specific building and its characteristics. If we group research in this field into two distinct categories, building envelope and building systems, the main achievements of research in this field can be described as follows:

Related to building shell:

1. Novel building materials, related to circular economy practices, as well as advanced thermal insulating properties of materials [14];
2. Environmental design practices for bioclimatic design [15];
3. Digitization of the assessment of buildings with the use of numerical methods and finite elements, as well as the use of Building Information Modelling (BIM) practices [16].
4. Environmental assessment of the building shell, using life cycle approaches [17];

Related to building systems:

1. Advanced building automation and control systems [18];
2. Advanced practices to assess indoor thermal comfort conditions and energy assessment of the whole building, for enhanced thermal comfort conditions [19];
3. Smart and nearly zero energy buildings [20];
4. Building integration of renewable energy technologies [21];
5. Energy audit-related studies [22].

However, a comprehensive assessment of a building requires detailed information on its specific geometric characteristics and building materials, which can be addressed in subsequent stages. Beyond the scope of the Level(s) framework, typical building geometry is useful in cases where novel concepts or standardized methodologies need to be demonstrated or for the approximate forecasting of LCA or energy related output.

2.2. The role of standardization for the assessment of the energy performance of buildings

To define requirements for the evaluation of overall building energy performance of buildings, the European Commission has developed a set

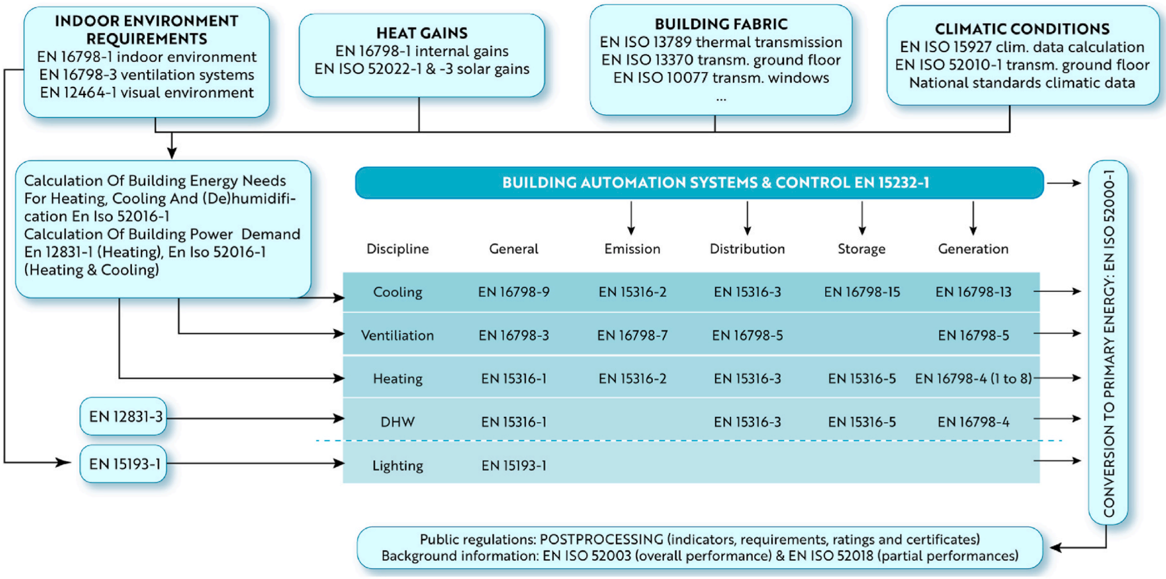

Fig. 1. Standard for overall EPB assessment by calculations.

of standards and technical reports that supports the Energy Performance of Buildings Directive (EPBD) [23]. EPBD promotes improvements in energy efficiency of European Union building stock [24], considering outdoor climate and local conditions, as well as indoor climate requirements and the cost effectiveness of the solutions [25]. In general, more than 60 standards related to building energy performance have been developed by the European Committee for Standardization (CEN). Fig. 1 presents the set of EPB standards which are directly related to assessing the energy performance by calculations, as well as preparation or post-processing procedures.

From the set of standards presented, a core chain that has the highest priority, is most closely related to the others and covers the main areas of energy assessment of buildings can be identified. The core consists of the following documents: EN ISO 52000–1:2017, EN ISO 52003–1:2017, EN ISO 52010–1:2017, EN ISO 52016–1:2017, EN ISO 52018–1:2017, EN 16798-1: 2019, EN 16798–7:2017, EN 16798-5-2:2018, ISO 52032–1:2022, EN 15316-4-2:2017.

The spine of standards provides a comprehensive and systematic framework, starting from the definition of the work sequence and the background of the procedures, including detailed calculations of climate data conversion. Energy needs for heating and cooling, DHW, ventilation, as well as requirements related to thermal energy balance and thermophysical properties of building elements are defined. Additionally, a description of the indicators, rating criteria and their interrelations is provided in the documentation. The standards referred to consider general and specific calculations, which apply to various building life cycle phases – it can be utilized for the assessment of new and existing buildings, as well as for buildings in a renovation phase, both for residential and non-residential buildings. Some of the already established regulations include guidelines and proposed verification procedures for defined calculation methods. The validation procedure for the methods or the calculations themselves allows for cross-checking with a test case, to assess the input data and the rationality of the solutions applied. Unfortunately, test cases are not widely included in the standards or appear very unspecific and not representative, since they deliver incomprehensive design rooms or spaces. Due to the recent lack of typical construction buildings in the standards and accompanying documentation, the application of the verification procedure is very limited. The use of typical building reference is neither reflected in the standards under the Energy Performance of Buildings Directive 2010/31/EU [26], nor in the Energy Efficiency Directive 2012/27/EU [27], which covers standard series that apply for the energy audits of buildings.

The use of typical buildings for the verification or assessment of the decision under consideration at the building level is expected to increase the rationality of the decision-making process, as the boundary conditions would be systematically defined. As in the test cases already presented in some of the standards, all of the building characteristics will be retrieved from EPB standards and accompanying documentation to present the most accurate and representative cases.

3. Materials and methods

The methodology employed in this study aims to address the identified problem of insufficient data to compare the sustainability performance of buildings in European Union (EU) Member States. Research workflow is presented in Fig. 2.

The following methods were used to achieve the objectives of this study:

- **EU building stock data collection -** In the initial phase, relevant data were collected, including historical records, EU statistics and relevant reports from authoritative sources such as the EU Building Stock Observatory [28], Level(s) framework [29], the European Building Performance Institute (BPIE) study "Europe's Buildings Under the Microscope" [30].These datasets formed the basis of our analysis.
- **Data analysis and classification -** Based on the insights of the BPIE study [30], the EU Member States have been divided into three different regions based on the main characteristics of the building stock. These factors included typical building geometry, thermal performance, built-up area per capita, age of the building stock,

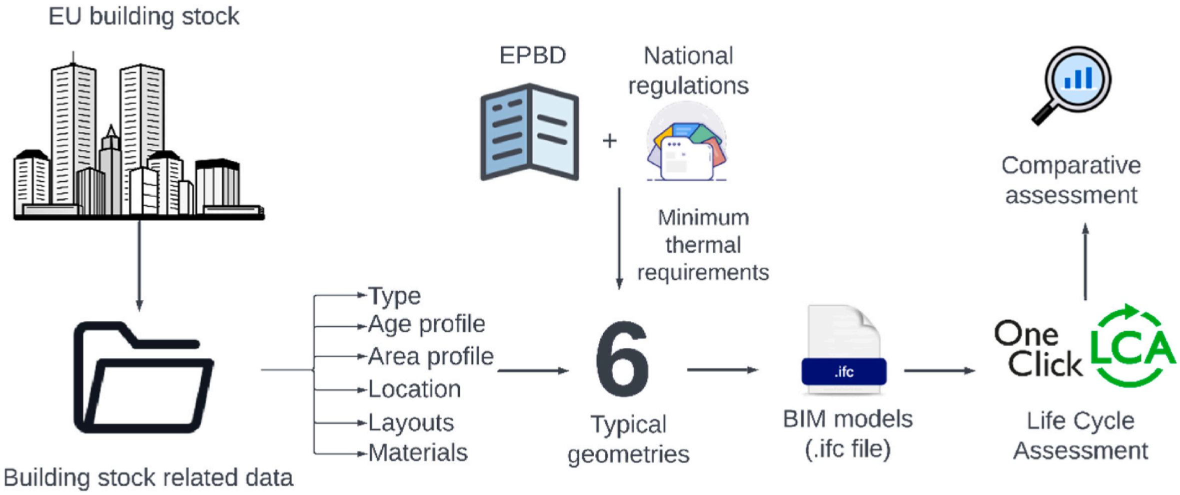

Fig. 2. Comparative whole building life cycle assessment workflow.

building systems and energy consumption patterns. This categorisation allowed a more detailed analysis of the sustainability indicators in each region.

- **Minimum thermal requirements –** In addition to assessing the geometric representativeness of a building, this study also aims to assess the impact of energy performance on the sustainability of buildings in the EU building sector. To assess the minimum thermal requirements for each EU MS the standards and technical reports underlying the Energy Performance of Buildings Directive (EPBD) [23] as well as national regulations were analysed. This phase allowed a detailed assessment of the different regulatory and operational standards in different countries.
- **Typical building geometries –** typical European residential building design practices were taken into account to ensure a representative building geometry. The building geometry is presented for a 3-person family house, taking into account that the average household in Europe currently consists of 2.6 persons [31]. The layout of the living spaces was defined by the most frequently used room types [32], their height and the layout determined by their orientation [33]. In addition, the unique characteristics of each cluster are taken into account, such as the varying ratio of housing to window area [30], based on the practice of using natural lighting. Accordingly, different roof types were considered. Based on the analysis and its results, BIM models of the proposed geometries of six representative buildings were created using Autodesk® Revit modelling software. The models developed include the thermal performance and building envelope material parameters for each cluster. A graphical representation of the workflow for defining the geometry of typical buildings is provided in Fig. 3
- **Comparative Life cycle assessment –** the research focused on performing a comparative whole building LCA for six typical building geometries in three European clusters: north-western, central-eastern, and southern regions. The experiment involves conducting empirical studies using LCA for six typical building geometries. The Ecoinvent database and the OneClickLCA software are used to perform the analysis**.** The IFC file was used to transfer the standardised primary building geometry and material data into the software. A detailed analysis and comparison of the results was carried out to provide meaningful insights regarding buildings environmental impacts.

The actions described above have helped to fill data gaps in the EU building stock for the sustainability analysis, as well as to provide valuable insights for the generalised environmental impact assessment of existing buildings. In addition, the results provide a basis for future comparative studies on energy efficiency and sustainability assessment.

4. Results and analysis

4.1. Typical buildings characteristics and geometry

According to data from the EU Building Stock Observatory [28], the built-up area within the European Union (EU) was estimated to be approximately 33.65 billion m2 in 2020, with an annual growth rate of approximately 1 %. A study released by the Building Performance Institute Europe (BPIE), titled "Europe's Buildings Under the Microscope" [30], classifies Member States (MS) of the European Union (EU) into three distinct regions based on their building stock characteristics:

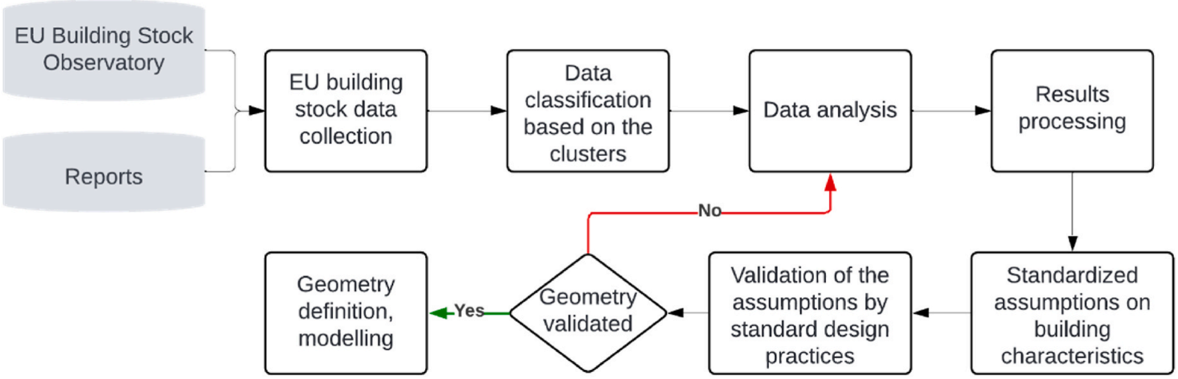

Fig. 3. Workflow for defining the geometry of typical buildings.

Table 1
EU MSs clusters of buildings with population.

Cluster	Countries	Population
Northern and western Europe	AT, BE, CH, DE, DK, FI, FR, IE, LU, NL, NO, SE	220 MM
Central and Eastern Europe	BG, CZ, EE, HU, LT, LV, PL, RO, SI, SK	100 MM
Southern Europe	CY, GR, ES, IT, MT, PT	130 MM

Table 2
Floor space of residential buildings per capita.

Cluster	Single family houses	Multifamily houses
Northern and western Europe	41 m^2	31 m^2
Central and Eastern Europe	26 m^2	20 m^2
Southern Europe	50 m^2	36 m^2

- Northern and Western Europe, which accounts for 45 % of the European building stock.
- Central and Eastern Europe, comprising approximately 17 % of the total built-up area.
- Southern Europe, with approximately 38 % of the overall floor space.

This classification is performed based on the criteria such as built area per capita, the age of the building stock, as well as other relevant aspects such as building systems and energy consumption patterns. The countries and their populations that make up each cluster are presented in Table 1.

According to the Directorate-General for Energy of the European Commission and its Building Stock Observatory [34], residential buildings occupy the largest area of the built-up area in Europe, with 75 % of the total building stock, of which approximately 65 % relates to single family houses and 35 % to apartments. Table 2 shows the area occupied per inhabitant for single and multi-family houses in the three clusters of Europe examined.

Another important classification criterion is the age of the building, as it is most likely to be linked to the energy consumption of non-renovated buildings. Taking this factor into account, the European building stock can also be divided into three categories according to the year of construction:

- Old buildings that have been built before 1960
- Modern buildings, built from 1960 to 1990
- Contemporary buildings built after 1990

In relation to the three age periods of the buildings, the distribution of the European building stock is summarized in Table 3.

The principles of the geometry of typical buildings are introduced and detailed in the following section. In particular, six typical geometries of residential buildings are presented in this study. Some of the characteristics of the proposed typical building geometries are the following:

- The geometries result as the combination of the three EU MSs clusters and the single and multi-family houses.
- The building geometries are delivered for a 3-member family house, based on the fact that the average household in Europe currently consists of 2.6 persons [31];
- The typical buildings consist of a vestibule, a living room, a kitchen, two bedrooms, a toilet, a bathroom, and corridors, connecting the spaces;
- Single-story buildings are considered, with typical zone height of 3 m for single-family houses and 2.7 m for multifamily houses;
- The roof in single family houses in the northern and western, as well as in the central and eastern European clusters is inclined, whereas in the southern cluster, flat roof is considered. Loft spaces are not considered for sloping roofs;
- The relation between the building shell and the window area was considered based on previous studies as 80/20 for the northern and western, as well as for the central and eastern European clusters, and 70/30 for the southern cluster. Openings in southern Europe are larger, to allow natural light and better ventilation, due to the prolonged duration of sunshine and the sea breeze that occurs in the Mediterranean basin [30]. These values can differ for office and commercial buildings, where glazed areas play a more significant role [35].

Table 3
Age profile of residential building stock for different clusters.

Cluster	Northern and western Europe	Central and eastern Europe	Southern Europe
Old buildings	19 %	17 %	14 %
Modern buildings	39 %	48 %	49 %
Contemporary buildings	42 %	35 %	37 %

Regardless of the surface and age of residential buildings in Europe, they have specific uses. Specifically, the minimum uses found in residential buildings are the following [32]:

- Entrance - building vestibule;
- Living room;
- Kitchen;
- Bedroom;
- Toilet – bathroom;
- Corridors.

In Europe and thus in the northern hemisphere, environmental design practices, where urban planning allows for, place main uses to the south of the building, or southeast and southwest, and ancillary uses to the north. In that sense, as a rule, the living rooms and bedrooms are located in the southern part of the building, while auxiliary functions such as the toilet, kitchen, entrance, or corridors are located in the northern part of the building [33].

Based on the statistics of the European building stock provided in Section 4.1, the main building shell related information of proposed typical geometries is presented in Table 4. The information in this table is derived from a detailed analysis of the European building stock and its main characteristics, which are described above in this section. In addition, based on the known characteristics of the housing stock in each region, standardised assumptions have been applied to define typical building sizes, typical roof structures and the building envelope to window ratio.

The proposed geometries and internal layouts of these buildings are shown in Annex 1 and the IFC files of the buildings have been uploaded to the supplementary dataset.

Table 4
Main characteristics of the residential building shell in different clusters.

Cluster	Single family houses	Multifamily houses	Single family houses roof	Building Shell to Windows Areas
Northern and western Europe	120 m^2	90 m^2	Sloped	85/15 %
Central and eastern Europe	75 m^2	60 m^2	Sloped	85/15 %
Southern Europe	150 m^2	110 m^2	Flat	80/20 %

Table 5
Average thermal transmittance values in different clusters [W/(m2·K)].

Cluster	External walls	Floor on ground	Roof	External doors	Windows
Northern and western Europe	0,26	0,22	0,18	1,47	1,42
Central and Eastern Europe	0,24	0,29	0,18	1,53	1,18
Southern Europe	0,39	0,53	0,33	2,27	2,27
All EU MSs	0,31	0,38	0,24	1,88	1,72

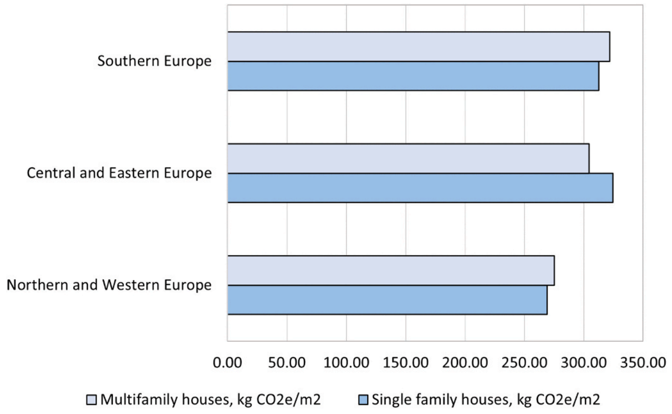

Fig. 4. Comparison of typical buildings GWP for different clusters and building types.

As the minimum requirements for the thermal transmittance of building elements are considered, it is important to note that these values can vary considerably between EU MSs, as they differ according to local legislation and climatic conditions. For vertical external elements, the values range from 0,10 to 0,70 W/(m2·K), for floors on the ground from 0,10 to 1,20 W/(m2·K). For roof systems, the requirements range from 0.08 to 0,50 W/(m2·K), and for windows and doors from 0,60 to 3,20 W/(m2·K). A detailed list of minimum thermal transmittance values requirements for each country is given in Annex 2. Categorized values for each cluster are presented in Table 5. These values for each cluster are obtained by calculating the average of the minimum thermal requirements for new and existing (if applicable) buildings in all countries of the specific cluster.

4.2. Sustainability performance of buildings across Europe

The study carried out a comparative whole building life cycle assessment of six representative buildings in three different European clusters: the Northern and Western, Central and Eastern, Southern. To achieve this, the commercial software tool OneClickLCA, which uses the comprehensive Ecoinvent database, was used to perform the LCA analysis.

The analysis conducted aligns with the defined Level(s) framework, taking into account factors related to the building, such as type of use, location, structural elements, materials used. With regard to materials, the assessment takes into account life cycle inventory data, including the mass of material resources used, as well as other critical resources such as energy, fuel, water and direct emissions during different life cycle stages. The comprehensive assessment provides valuable insights and data for an in-depth understanding of the sustainability performance of a building across different European clusters.

Table 6
Numbering of building types.

Building type	Cluster	Building use type	Area
Type 1	Northern and Western Europe	Single family house	120 m^2
Type 2	Central and Eastern Europe	Single family house	75 m^2
Type 3	Southern Europe	Single family house	150 m^2
Type 4	Northern and Western Europe	Multi-family house	90 m^2
Type 5	Central and Eastern Europe	Multi-family house	60 m^2
Type 6	Southern Europe	Multi-family house	110 m^2

Fig. 4 present generic comparison of representative European single and multi-family buildings environmental impact across different clusters. In order to compare the environmental impact of different building sizes, the analysis went beyond an absolute assessment of the global warming potential (GWP). Instead, the aim was to provide a benchmarking by estimating the GWP per square meter. Regional comparisons show evident parallels between Southern Europe and Central and Eastern Europe clusters, with relatively similar environmental impacts per square metre in both regions. However, given the similar building structures and materials used in the context of both single-family and multi-family houses in the same cluster, some differences in environmental impacts emerge. In particular, while in Southern Europe there is a slight difference of 2.84 % between the impact of single-family houses and multi-family houses, in Central and Eastern Europe the difference is higher with the value at 6.53 %. This difference is caused by factors such as the ratio of the building frame to openings and the internal layout of the building, which, while having a small influence, also account for the observed differences in environmental performance. In Northern and Western Europe, due to construction practices and materials used, single and multi-family houses have the lowest GWP compared to other clusters. In Northern and Western Europe, the environmental impact per square metre differs by 2.84 % between single-family and multi-family dwellings, which may be due to the reasons mentioned above.

Table 6 provides additional information on how buildings are numbered and will be used as a reference for this research as well as future work.

The following figure (Fig. 5), graphically illustrates the environmental impact of building materials at different stages of their life cycle. A comprehensive results table is provided in supplementary dataset. It is evident, that for all building types product stage (A1-A3) is the most responsible for the carbon footprint, varying from the lowest impact at 233.55 $kgCO_2e/m^2$ for building Type 1 to 270.91 $kgCO_2e/m^2$ for Type 6. The construction/installation process (A5) is the second highest environmental impact factor, ranging from 19.29 $kgCO_2e/m^2$ for Type 1 to 28.45 $kgCO_2e/m^2$ for Type 6. The lowest impacts for all building structures and materials are in the transport to site (A4) and end-of-life phases (C1–C4), which take into account deconstruction, transport, waste treatment and disposal. As presented in Fig. 5, buildings in Northern and Western Europe, as well as in the Central and Eastern European clusters, show the same behaviour between the different life cycle phases. For Southern Europe, it is clear that even in phases A1-A3 the impact per square metre is not the highest, the impact of the construction/installation process appears to be the highest compared to the other clusters. This difference is related to the building envelope and the materials used for the roof. As the typical roof structure of a Southern European building is considered as a flat roof, it requires a higher amount of concrete than the other buildings and this has a significant

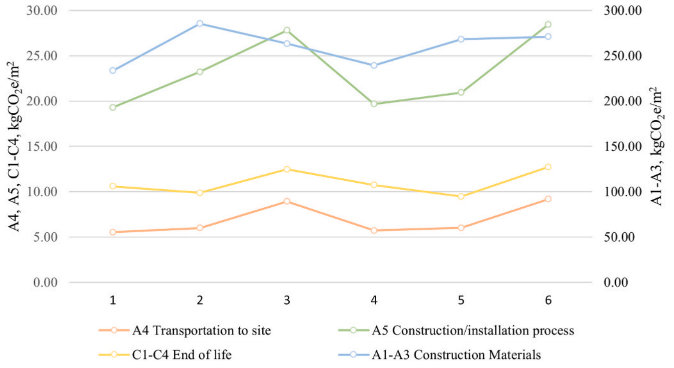

Fig. 5. GWP during all life cycle stages of a building.

impact on the results of phase A5.

The main findings of the comparative assessment can be summarized as follows:

1. **The importance of building type –** Even if the type of building does not have a significant impact on the environmental performance in the comparative assessment, the findings suggest that the difference can range from 2.32 % to 6.53 %. This difference can arise from the different functions of the buildings and the layout of their rooms. In addition, the ratio of building envelope to openings and the number of such units can increase the difference in performance between single-family and multi-family buildings.
2. **The importance of building materials –** A comprehensive whole building life cycle assessment takes into account all building components and materials, including but not limited to all layers of layered structures such as walls, floors, roofs and similar. In addition, homogeneous building elements such as monolithic structure, reinforcement rebar, door and window frames, glazing, and other components are evaluated. The findings of the study justifies the importance of building materials in assessing environmental impacts. The apparent trends and the direct correlation between the impact of the product (A1-A3) and its construction/installation process (A5) suggest that more environmentally friendly materials will have a lower impact during the installation process. A list of building materials with the corresponding environmental impacts for each building type can be found in the supplementary data set of this study.
3. **The importance of regional context –** The geographical location of a building affects its sustainability performance not only due to environmental conditions, but also due to regional practices and preferences, which can lead to different environmental impacts, making it necessary to develop region-specific sustainability strategies. The regional strategy also plays an important role in sustainability performance of materials or products, as the assessment also takes into account the energy sources used in the production phase (A1-A3).

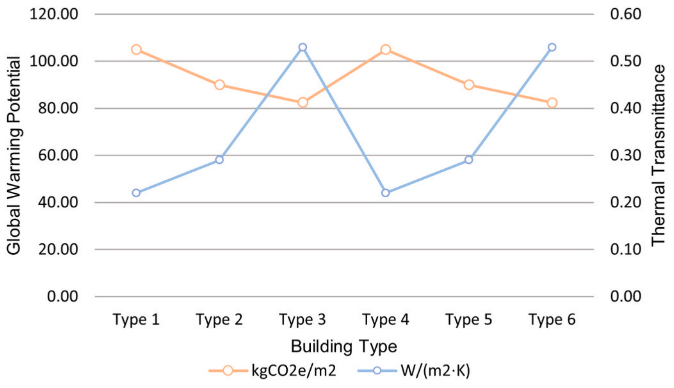

Fig. 6. Comparison of floor on ground minimum thermal requirements to GWP of the structure.

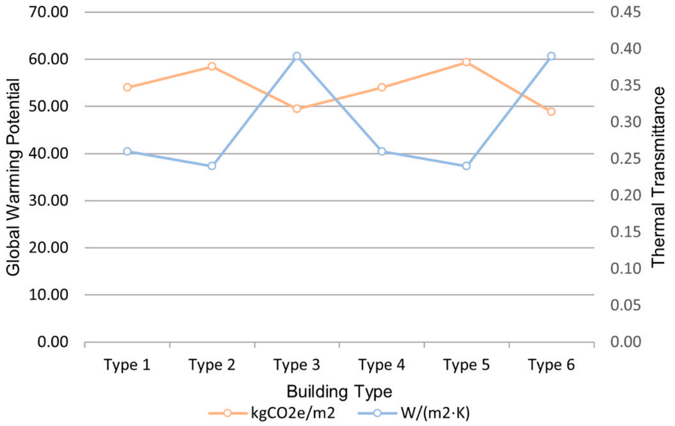

Fig. 7. Comparison of external walls minimum thermal requirements to GWP of the structure.

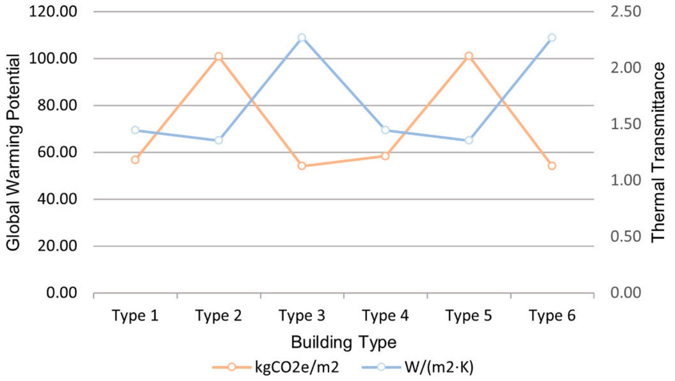

Fig. 8. Comparison of facade openings minimum thermal requirements to GWP of the elements.

4.3. *Comparison of environmental impacts of buildings with different thermal performance requirements*

The study also conducted a comparative assessment of the environmental impact of building partitions, considering the minimum thermal performance requirements for specific building elements. Graphical

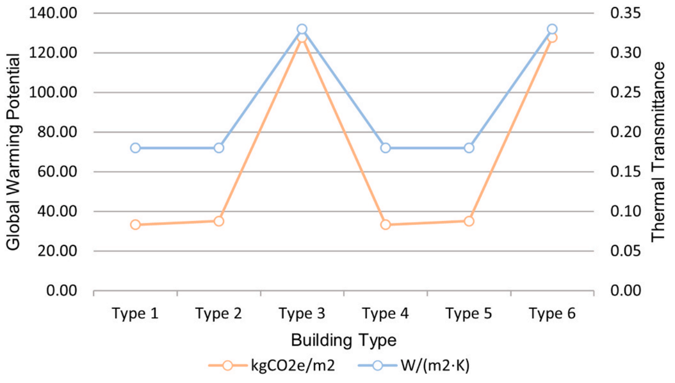

Fig. 9. Comparison of roof minimum thermal requirements to GWP of the structure.

representations of the results are provided in Figs. 6 - 9. As depicted in Figs. 6 and 7, the data reveals a trend toward higher environmental impact being associated with lower thermal transmittance and vice versa. Therefore, in this particular dataset, it is reasonable to highlight a potential inverse correlation between these two variables. As construction materials account for an average of 86.3 % of the assessed building's GWP, the correlation of these variables can be linked to the amount of insulation materials used in partitions. However, the dependency may vary depending on regional aspects and the sustainability of the insulation materials used.

In contrast to the continuous dependence of the sustainability of floors on the ground and external walls on the thermal transmittance of the partition, the assessment of façade openings gives slightly different results. Although, the same thermal performance and sustainability dependency can be observed, the results are more dispersive. Fig. 8 shows that the environmental impact of the thermal performance of partitions in different European clusters varies significantly depending on the region. As presented, façade openings in Northern and Western Europe with the thermal transmittance value of 1.45 W/(m^2·K) will have almost the same GWP as the opening in Southern Europe with the thermal transmittance value of 2.27 W/(m^2·K). The results emphasize the importance of taking into account regional markets, materials and their sustainability practices when designing or renovating buildings.

As far as roofs are considered (see Fig. 9), Northern and Western, Central and Eastern Europe shows similar trends, specifically in this case, minimal energy efficiency requirements are similar in both clusters and environmental impact results are respectively equal. Significantly different results are obtained in Southern Europe cluster. Even minimal thermal performance requirement of the roof for this cluster is 83.35 % lower than for the others, GWP per square meter is on average 81.05 % higher. Such significant differences are resulted by regional construction practices and requirements. As in Southern Europe cluster flat roofs are dominant, installation of such structures requires higher amounts of less sustainable materials. As well as presented previously, installation process itself results in higher environmental impact.

The overall comparative assessment of the environmental impact of building envelopes against the minimum thermal performance requirements in the European housing clusters indicates a consistent trend in most cases—higher environmental impacts are associated with lower thermal transmittance of the building envelope. However, the assessment of the impact of roofs in Southern Europe reveals that the higher use of less sustainable materials can significantly affect the correlation between thermal properties and environmental impact. This finding underscores the need for a holistic approach when considering the design or renovation of buildings.

5. Conclusion

In conclusion, this study has addressed a critical research question regarding the comparative sustainability performance of building units across Europe. In order to fill the gap in the lack of generally accepted and analysed building geometries that could be used as subjects to demonstrate the main findings and principles of the research topic, the authors have proposed six representative buildings of European housing clusters. In Northern and Western Europe, a 120 m^2 building is proposed to represent a single-family house, in Central and Eastern Europe a 75 m^2 building, and in Southern Europe a 150 m^2 typical building. For the multi-family houses in Northern and Western Europe 90 m^2 area is considered as a typical dwelling, respectively 60 m^2 in Central and Eastern Europe and 110 m^2 in Southern Europe.

Through LCA analysis of typical geometry buildings, it became evident that sustainability performance varies significantly across the EU and building types. Comprehensive whole building life cycle assessment revealed that single-family houses have the highest carbon footprint in Central and Eastern Europe with 324.42 kgCO$_2$e/m^2, while Northern and Western European buildings have the lowest environmental footprint with 268.97 kgCO$_2$e/m^2. As far as multi-family houses are concerned, buildings in Southern Europe are responsible for the highest environmental impact of such type, with 321.82 kgCO$_2$e/m^2. While the lowest impact is in Northern and Western Europe - 275.37 kgCO$_2$e/m^2. In addition, the study also identifies trends in sustainability performance in relation to building types, building materials used and the regional context that influences the environmental impact of residential buildings.

Additionally, the study revealed the substantial influence of cost-optimal minimum thermal performance requirements on building sustainability. It is evident that the thermal performance requirements of the building envelope have a strong influence on the carbon emission footprint of a building, research reveals the trends that lower thermal transmittance values influence to higher the environmental impact of the building. More specifically, the environmental impact of external walls increases by up to 18.18 %, of floors on the ground by up to 27.23 %, and of façade openings by up to 86.54 %, when taking into account the thermal performance requirements of Southern Europe, which are the lowest, with Central and Eastern Europe, where thermal performance requirements are the highest. However, it is also shown that even with low thermal performance requirements, the GWP per square metre of a building can be higher if less sustainable materials are used in the construction. More specifically, this trend is observed when assessing the impact of a typical roof structure, where the environmental impact of a typical roof of a Southern European building is up to 263.95 % higher compared to other clusters, despite the fact that the thermal requirements are 83.33 % lower.

In summary, this study contributes to advancing the understanding of building sustainability in Europe, highlighting the importance of standardized benchmarks, minimum performance requirements, and innovative assessment methods. It underscores the necessity of considering building geometries and thermal performance to comprehensively assess and improve the sustainability of buildings across the EU.

The study's findings also highlight the importance of incorporating the geometry of typical buildings into EPBD assessment practices to reflect the different climatic conditions and construction practices in Europe. As all building characteristics related to energy performance requirements are derived from EPB standards and supporting documents, typical buildings could potentially serve as a test case and are expected to increase the rationality of the decision-making process as boundary conditions are systematically defined. This approach promotes standardised but adaptable methodologies that directly contributes to achieving the energy efficiency objectives of the EPBD.

The development of typical building geometries reflecting the different European clusters and their cost-optimal minimum thermal performance requirements potentially allows for a range of comparative assessment studies. Using the same building geometry for diverse studies provides pathway to the research community to deliver comparable results. Future work related to the six typical building geometries provided could potentially focused but not limited to research concerning new sustainable building materials and their impact on thermal performance. Also, authors believe that complex studies related to building energy assessment, indoor environmental comfort assessment and the development of innovative solutions can be conducted, taking into account the regional differences in Europe. However, it should be considered that the typical building geometries and characteristics presented are generalised and based on classification and standard design practice. The results should be considered as a comparative tool for residential buildings and should not be applied to very specific design or other building types.

CRediT authorship contribution statement

Paulius Spudys: Writing – original draft, Formal analysis. **Iryna Osadcha:** Resources, Investigation. **Lina Morkunaite:** Methodology, Investigation. **Fallon Clare Manhanga:** Software, Methodology. **Phoebe Zoe Georgali:** Visualization, Methodology, Formal analysis. **Egle Klumbyte:** Software, Resources. **Andrius Jurelionis:** Writing – review & editing, Software, Data curation. **Agis Papadopoulos:** Supervision, Resources. **Paris Fokaides:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Paris Fokaides reports financial support was provided by Kaunas University of Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data are available in a shared link, given int he publication.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.131693.

Annexes

Annex 1. Typical buildings layouts

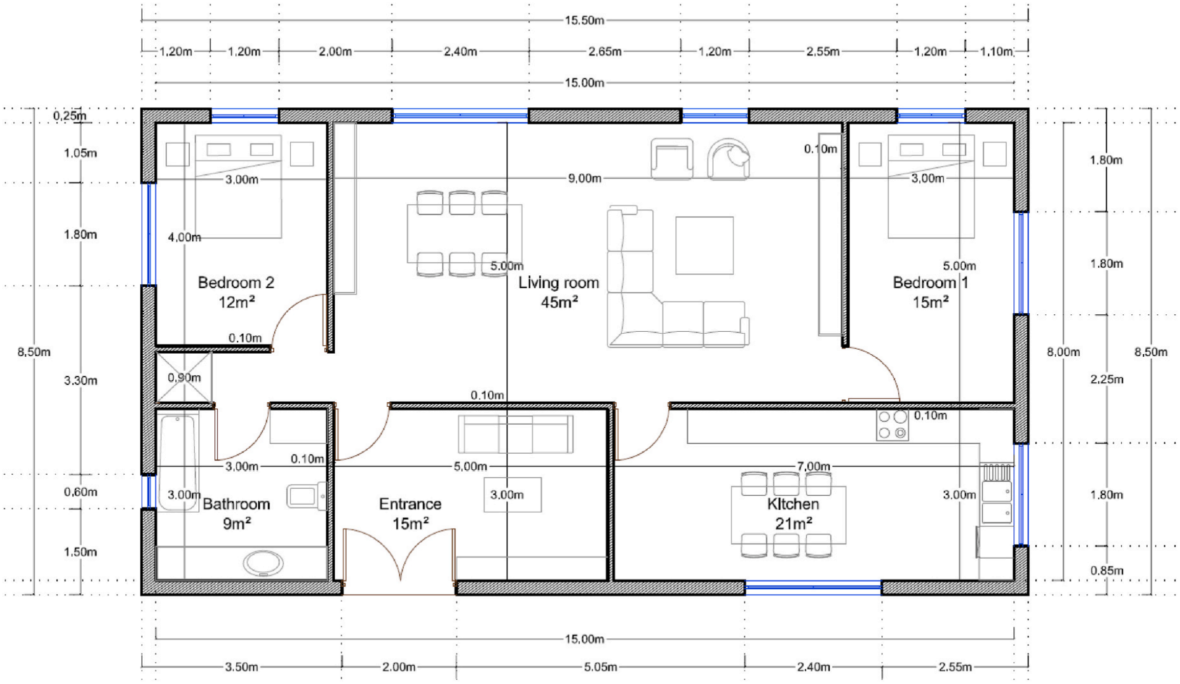

Fig. 10. Building Type 1 - Northern and Western Europe, Single family houses, 120 m2.

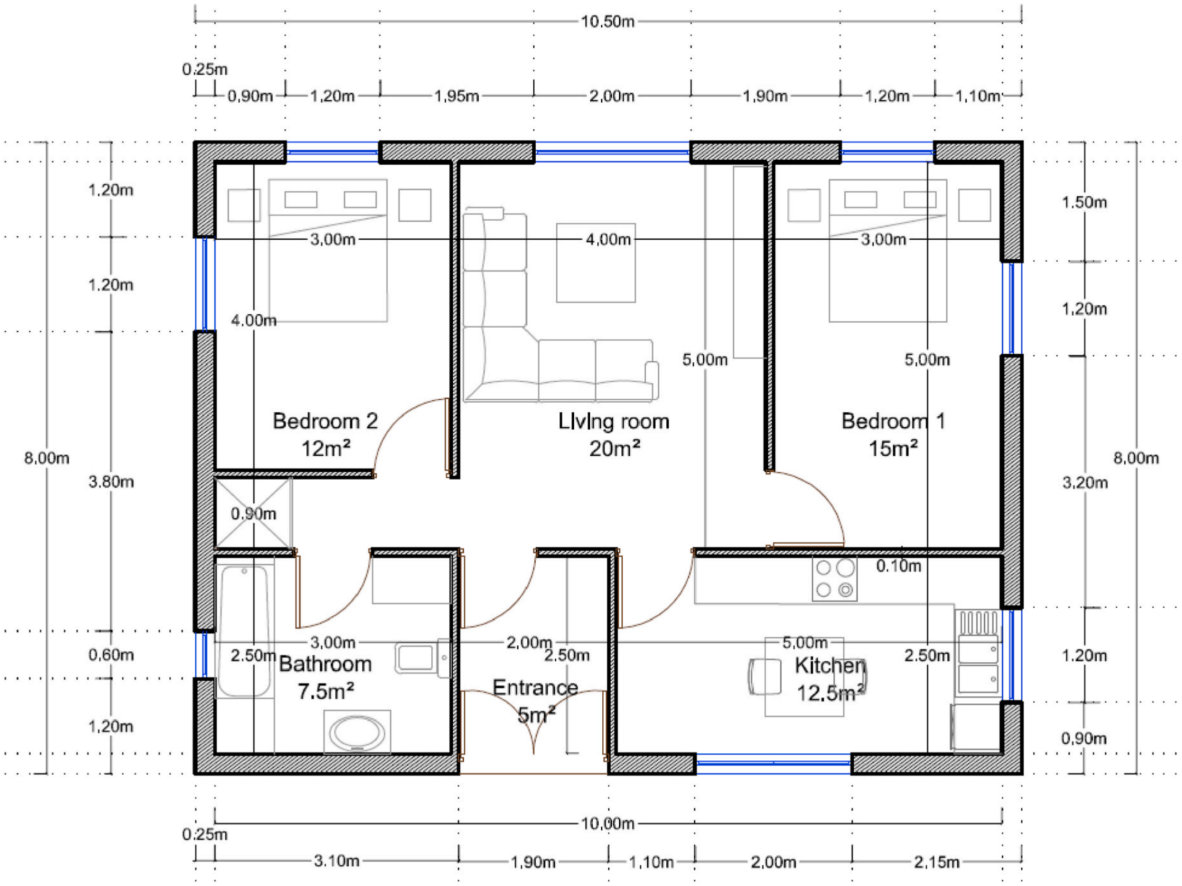

Fig. 11. Building Type 2 – Central and Eastern Europe, Single family houses, 75 m2.

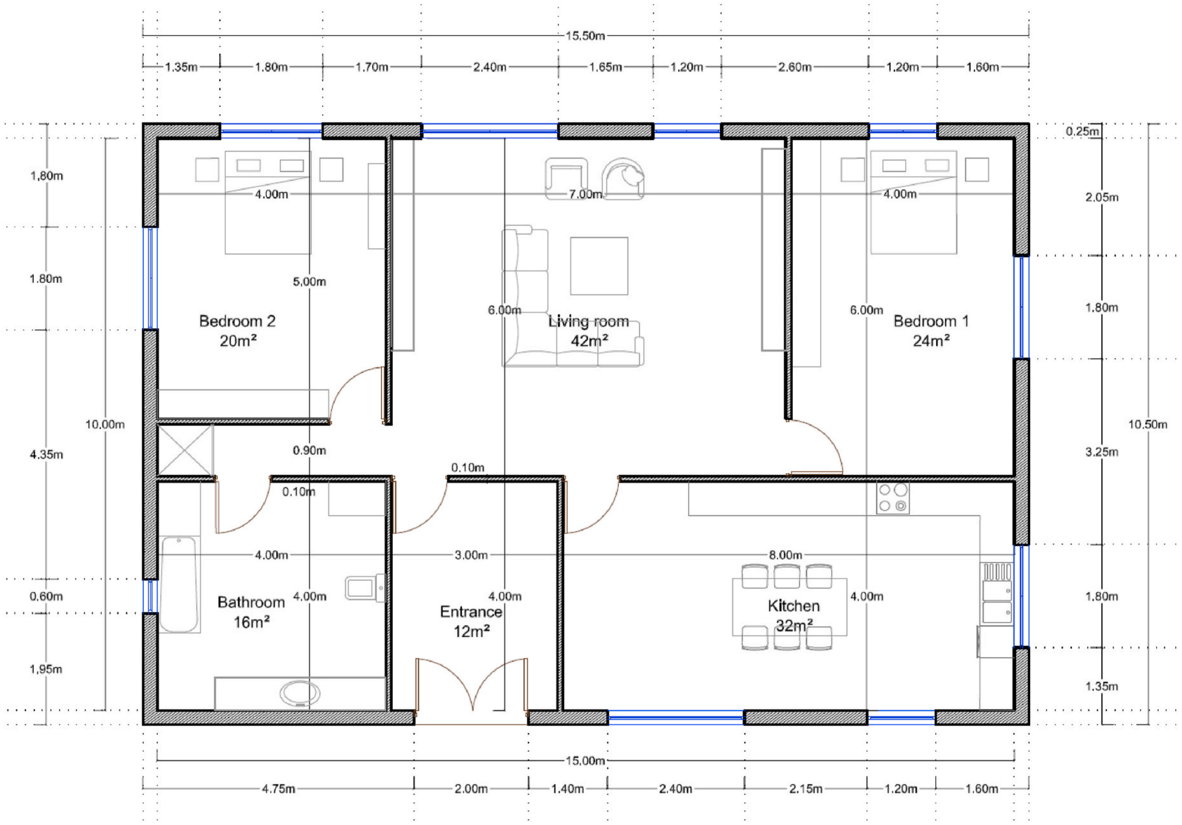

Fig. 12. Building Type 3 - Southern Europe, Single family houses, 150 m2.

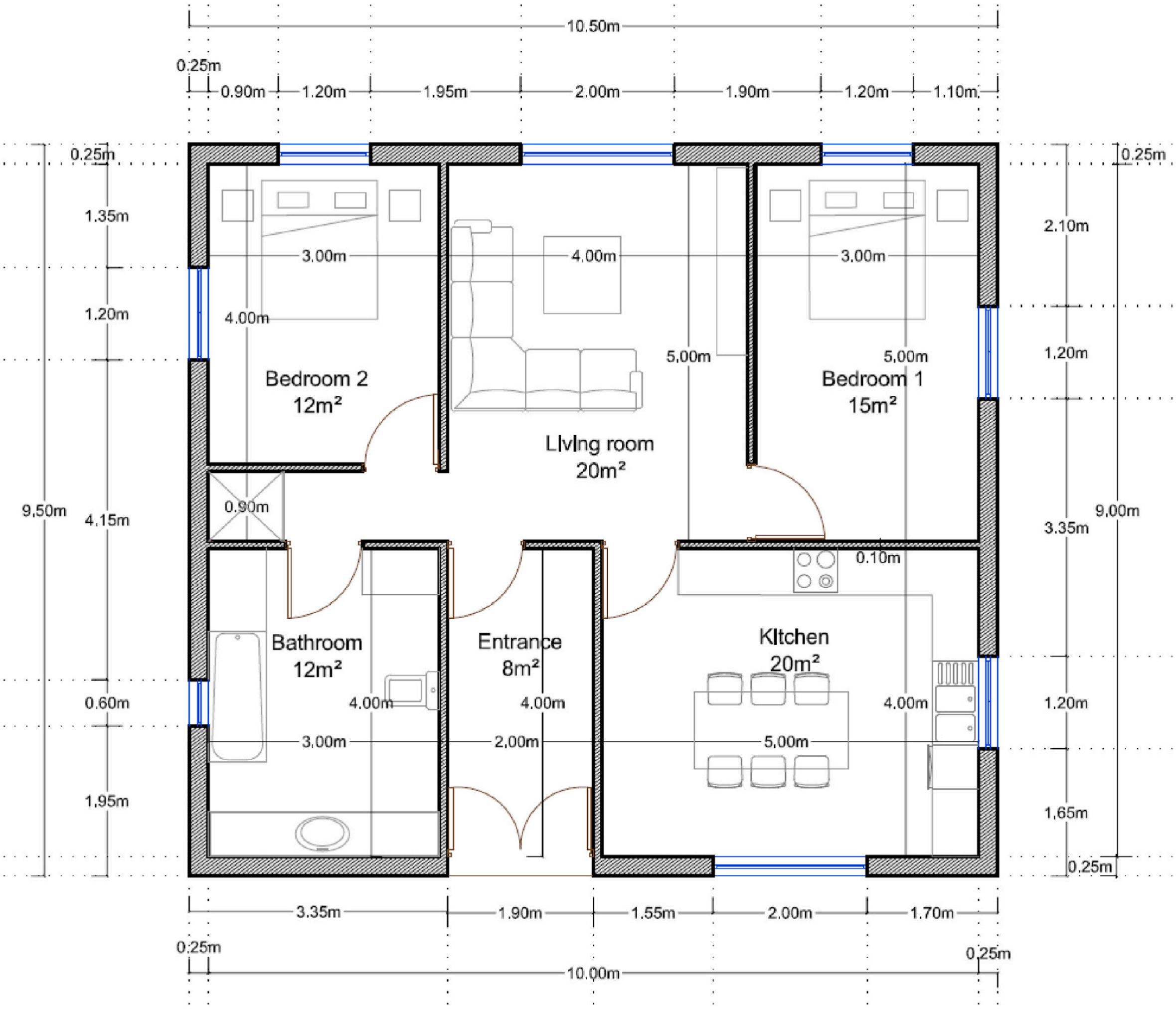

Fig. 13. Building Type 4 – Northern and Western Europe, Multi-family houses, 90 m2.

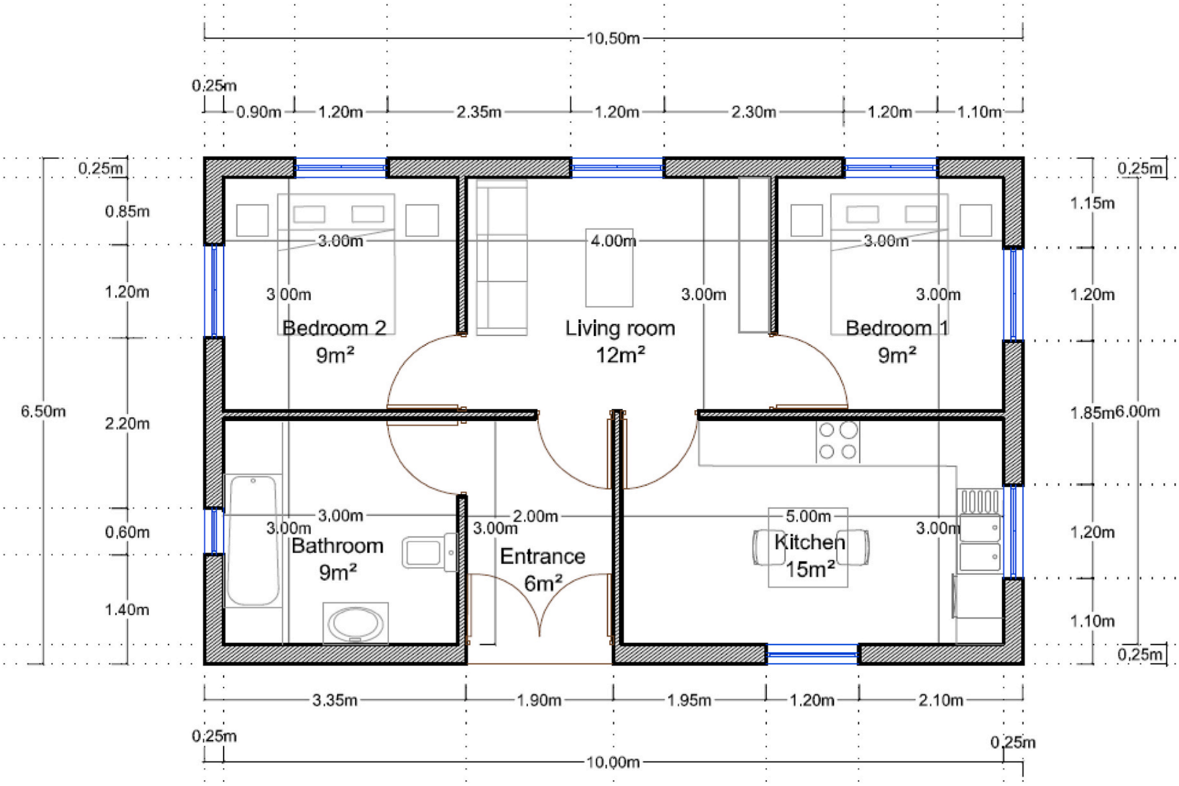

Fig. 14. Building Type 5 – Central and Eastern Europe, Multi-family houses, 60 m2.

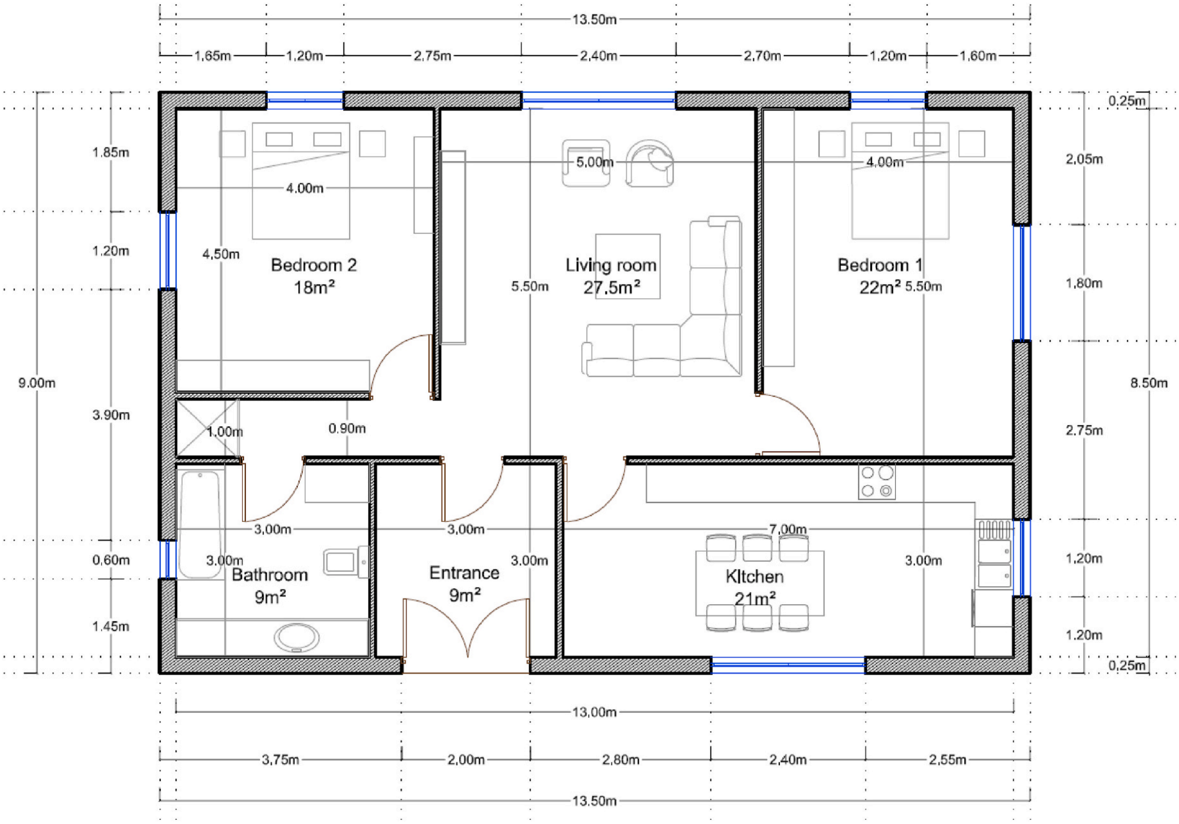

Fig. 15. Building Type 6 - Southern Europe, Multi-family houses, 110 m2.

Annex 2. Minimum thermal requirements of EU MSs

COUNTRY	BUILDING CONSTRUCTION STAGE	EXTERNAL WALLS	FLOOR ON GROUND	FLOOR ON GROUND	ROOF	EXTERNAL DOORS	WINDOWS
Austria	New	0,35	0,40	0,40	0,20	–	1,40
Belgium	New	0,24	0,30	0,30	0,24	2,00	–
Bulgaria	Reference value	0,28	0,40	0,40	0,40	2,20	–
Cyprus	New and existing	0,40	0,40	0,40	0,40	2,90	–
Croatia	New and existing	0,30	0,30	0,30	0,25	2,00	1,40
Czech	New and existing	0,30	0,60	0,60	0,30	1,80	1,80
Denmark	New	0,30	0,20	0,20	0,20	1,45	–
	Existing	0,20	0,12	0,12	0,15	1,65	–
Estonia	Existing, 25 % renovation	0,25	–	–	0,15	–	1,10
	Existing, 40 % renovation	0,15	–	–	0,11	–	1,10
Finland	New	0,17	0,16	0,16	0,09	1,00	1,00
France	Climatic zone H1 (existing)	0,35	–	–	0,22	–	1,90
	Climatic zone H2 (existing)	0,35	–	–	0,23	–	1,90
	Climatic zone H3 (existing)	0,45	–	–	0,23	–	1,90
Germany	New	0,28	0,28	0,28	0,20	1,80	1,30
Greece	Climatic zone A (new)	0,55	1,10	1,10	0,45	2,80	2,80
	Climatic zone B (new)	0,45	0,80	0,80	0,40	2,60	2,60
	Climatic zone C (new)	0,40	0,65	0,65	0,35	2,40	2,40
	Climatic zone D (new)	0,35	0,60	0,60	0,30	2,20	2,20
	Climatic zone A (existing)	0,60	1,20	1,20	0,50	3,20	3,20
	Climatic zone B (existing)	0,50	0,90	0,90	0,45	3,00	3,00
	Climatic zone C (existing)	0,45	0,75	0,75	0,40	2,80	2,80
	Climatic zone D (existing)	0,40	0,70	0,70	0,35	2,60	2,60
Hungary	New	0,24	0,26	0,26	0,17	–	1,15
Ireland	New, area-weighted	0,18	0,18	0,18	0,16	1,40	1,40
Italy	Climatic zone A, B (new)	0,43	0,40	0,40	0,35	3,00	3,00
	Climatic zone C (new)	0,34	0,38	0,38	0,33	2,20	2,20
	Climatic zone D (new)	0,29	0,29	0,29	0,26	1,80	1,80
	Climatic zone E (new)	0,26	0,26	0,26	0,22	1,40	1,40
	Climatic zone F (new)	0,24	0,24	0,24	0,20	1,10	1,10
	Climatic zone A, B (existing)	0,40	0,42	0,42	0,32	3,00	3,00
	Climatic zone C (existing)	0,36	0,38	0,38	0,32	2,00	2,00
	Climatic zone D (existing)	0,32	0,32	0,32	0,26	1,80	1,80
	Climatic zone E (existing)	0,28	0,29	0,29	0,24	1,40	1,40
	Climatic zone F (existing)	0,26	0,28	0,28	0,22	1,00	1,00
Latvia	New, existing	0,18	0,15	0,15	0,15	1,80	1,30
Lithuania	New	0,10	0,10	0,10	0,08	0,70	0,70
	Existing	0,20	0,25	0,25	0,16	1,60	1,60
Luxembourg	New	0,32	0,40	0,40	0,25	–	1,50
	New (Class A)	0,12	0,15	0,15	0,10	–	0,78
Netherlands	New, existing	0,22	0,29	0,29	0,16	2,20	2,20
Norway	New	0,18	0,10	0,10	0,13	0,80	0,80
	Existing	0,22	0,18	0,18	0,18	1,20	1,20
Poland	New	0,20	0,30	0,30	0,15	1,50	0,90
	Existing	0,23	0,30	0,30	0,18	1,50	1,10
Portugal	Lisbon (new)	0,50	0,40	0,40	0,40	–	2,80
	Braganca (new)	0,35	0,30	0,30	0,30	–	2,20
Romania	New, existing	0,56	0,22	0,22	–	–	–
Slovak Republic	New, existing	0,15	–	–	0,10	0,60	0,60
Slovenia	New, existing	0,28	0,35	0,35	0,20	1,60	1,30
Spain	Climatic zone A (new, renovated parts)	0,70	0,80	0,80	0,50	2,70	2,70
	Climatic zone B (new, renovated parts)	0,56	0,75	0,75	0,44	2,30	2,30
	Climatic zone C (new, renovated parts)	0,49	0,70	0,70	0,40	2,10	2,10
	Climatic zone D (new, renovated parts)	0,41	0,65	0,65	0,35	1,80	1,80
	Climatic zone E (new, renovated parts)	0,37	0,59	0,59	0,33	1,80	1,80
Sweden	New	Mean U value - 0,40					
	Existing	0,18	0,15	0,15	0,13	1,20	1,20

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