Environmental assessment at the urban level combining LCA-GIS methodologies: a case study of energy retrofits in the Barcelona metropolitan area

Sergio García-Pérez[1], Jorge Sierra-Pérez[2,3], Jesús Boschmonart-Rives[3, 4]

[1] U.P. Arquitectura, Escuela de Ingeniería y Arquitectura, Universidad de Zaragoza, Spain

[2] Centro Universitario de la Defensa de Zaragoza - Spain

[3] Sostenipra (ICTA – IRTA - Inèdit Innovació SL) 2014 SGR 1412. Instituto de Ciencia y Tecnología Ambiental (ICTA), Unidad de excelencia «María de Maeztu» (MDM-2015-0552), Universidad Autónoma de Barcelona (UAB), Spain

[4] Department of Environmental, Biological and Chemical Engineering (XBR), Universitat Autónoma de Barcelona (UAB), 08193, Cerdanyola del Vallès, Bellaterra, Barcelona, Spain

Abstract

This study proposes a combined life cycle assessment (LCA) and Geographical Information Systems (GIS) methodology to develop complex LCA inventories for multiple applications. The study focusses on the environmental implications of buildings retrofits, especially in the European context, where the building sector is one of the largest energy consumers. In this context, a new and holistic perspective is needed that expands from the building scale to the urban scale.

The combination of LCA and GIS methods includes the development of an urban characterization model based on bottom-up methodologies. The environmental implications associated with increasing the thermal insulation of existing buildings to the current standard are determined based on LCA methods. In this step, common construction systems for building retrofits are used, and insulation materials are compared. Then, absolute and relative extrapolations are performed considering different urban morphologies.

The results confirm the importance of the energy retrofitting of residential buildings in large functional urban areas such as the Barcelona metropolitan area, which is examined as a case study. The LCA results indicate that the selection of proper construction systems and thermal insulation materials is important to the environmental performance of building retrofits, and these selections can lead to CO_2 emission differences of up 16% in the region. The relative extrapolation results indicate significant environmental differences between urban morphologies. The LCA results show the potential strategic impacts of the inclusion of LCA methods in retrofit policies at the urban scale.

Highlights

- A bottom-up methodology is presented to measure and map the environmental implications of retrofit scenarios for residential buildings at the urban scale based on a combined LCA-GIS method.
- The study compares different construction systems and insulation materials, and significant differences are observed between retrofit scenarios.
- The method is applied to the Barcelona metropolitan area, Spain, considering the urban morphology as an aggregate method.
- The results show the potential strategic impacts of the inclusion of LCA approaches in retrofit policies at the urban scale.

Keywords

Energy efficiency, building retrofit, urban characterization model, bottom-up methodology, urban morphology, cork

1. Introduction

Currently, cities are responsible for 75% of global energy consumption and greenhouse gas emissions [1], and recent studies have indicated that the population of cities will grow by up to 66% by 2050 [2]. Therefore, it is clear that the transformation to a low carbon economy offers an important opportunity for change in cities and their urban functional areas, where the building stock plays an essential role in energy consumption [3]. Moreover, more than 40% of total energy consumption is attributed to buildings in the EU [4] due to facilities and construction work. In this sense, the building sector represents one of the most significant challenges according to the European Union Framework Programme for Research and Innovation – Horizon 2020 [5].

European Union Directive 2012/27/EU [6] recognizes the retrofitting of old building stock as an energy efficiency strategy to reduce energy consumption in the EU. In this regard, increasing the level of insulation in buildings is one of the most effective passive solutions in retrofitting [7]. Previous studies have noted the importance of introducing a comprehensive perspective to retrofit solutions based on life cycle assessment (LCA) methods due to the related environmental implications of the embodied energy of materials and processes [8,9]. Recent studies have focused on comparisons between different alternatives for building design and the selection of construction systems and building materials [10–14]. In this regard, the selection of building materials has received increased interest in the environmental field and has an important influence on the energy and environmental performance of buildings during both the construction phase [14–16] and the building use phase [17,18]. These environmental evaluations, according to an LCA framework, have focused on the building level, and this focus is necessary for extending environmental research to the urban scale. Lotteau et al. [19] conducted a recent LCA review at the urban level and analysed buildings, open spaces, networks and mobility at the neighbourhood scale from a holistic perspective. However, assessments of building retrofits at the urban scale or large scales has been less common in LCA frameworks due to methodological barriers and data availability problems [20].

In this sense, the building stock aggregation model has been identified as an appropriate methodology for quantifying operational energy use at the urban level. Moreover, the environmental performance throughout several stages of the building life cycle can be assessed using LCA methodologies [21] that have been developed to support decisions regarding building stock retrofits for sustainable urban planning. According to the Swan and Ugursal classification [22], bottom-up models can be useful for developing building stock aggregation models, in which the definition of a minimum unit is required according to data availability and extrapolation methods.

In the context of segregation models, several bottom-up studies have used archetype techniques in which the building stock is classified according to variables such as the age of construction, size, and house type [21]. After these variables are defined, a representative building is selected for each archetype, and the results are extrapolated for similar buildings. This technique has been previously applied to estimate energy performance at the urban scale [23–27].

Tools such as Geographical Information Systems (GIS) facilitate the use of information associated with individual buildings and permit building-by-building analyses. GIS are based on the combination of spatial data with several attributes and have been demonstrated as effective interdisciplinary tools [28]. Batty and Xie [29] indicated that GIS technology provides the basic framework for processing large volumes of spatial data, obtaining georeferenced information, and producing visual and easily updatable results; therefore, these systems are ideal for creating models that incorporate the attributes of individual buildings [20,30–34].

According to the extrapolation methods, the building-by-building approach considers the minimum unit in the data, an individual building. In this approach, multiple forms of data can be aggregated according to different criteria. This method provides flexibility and adaptability in the building-by-building approach and allows cross-comparisons with other studies and datasets. Various aggregation methods have been researched in recent studies. These studies highlight the use of administrative criteria, such as municipalities [35] or census sections [36], instead of physical criteria. Thus, urban morphology information can be incorporated into aggregation methods because it is directly related to the physical form of cities and their spatial configurations [37,38].

Therefore, bottom-up techniques based on building-by-building methods represent potential methods of characterizing buildings according to geospatial building stock models [34]. Considering the objective of this approach, the evaluation performance of building retrofits at the urban scale is assessed using a novel LCA-GIS approach that focuses on small-sized cities [20]. Moreover, the data available for the development of the geospatial model differ in different contexts; therefore, a methodological adaptation to each situation is needed.

The presented methodology combines LCA and GIS methods for retrofits at the urban scale and extends the scope of previous methodologies to functional urban areas. Focusing on a Spanish dataset, the residential building stock of the "*area metropolitana de Barcelona"* (Barcelona metropolitan area, AMB) is assessed. This area is home to more than 3 million inhabitants [39]. The specific objectives are as follows: to develop an urban bottom-up characterization from a building-by-building approach in which the results are georeferenced, visually displayed and easily updated and to apply this method to the Spanish dataset; to identify the environmental implications of both typical construction systems used in retrofitting and urban morphologies; and to provide a scientific basis for policymakers to propose future strategies in the field of building retrofits.

2. Materials and Methods

This section is presented based on the three main steps of the proposed methodology (Figure 1): (i) envelope surface characterization to obtain qualitative and quantitative envelope surface data, (ii) LCA to obtain the environmental implications of 1 m^2 of a declared unit, and (iii) the extrapolation of results.

<FIGURE 1>

2.1 Envelope surface characterization at the urban scale

Urban characterization includes three main steps: a data collection process that defines open source data for our case study (Spain) and standardization criteria; a qualitative characterization that defines the year of construction and urban morphology variables; and a quantitative characterization to develop a geospatial model and obtain a geometric characterization.

2.1.1 *Data collection process*

Since the promulgation of the 2003/98/CE European Commission Directive [40], which regulates the reuse of public information, governments have worked towards the creation of public databases that are useful to citizens, companies and research institutes. Data are crucial to developing a bottom-up approach. Moreover, each country regulates and establishes particular conditions. In this context, this study uses Spanish dataset sources. Recently, some authors have performed studies to assess the data structure and investigated the possibility of reusing the Spanish cadastral dataset, which is the main public administration dataset of building stock information in Spain. Among these studies, Mora-García et al. [41] described a methodology in which urban-scale cadastral data were reused in urban analysis cases.

2.1.2 *Qualitative characterization*

The envelope surface of residential buildings can be characterized from a qualitative approach considering two main factors: the year of construction and the urban morphology. Sufficient urban scale information regarding thermal regulation and morphological features should be available (Table 1).

<Table 1>

A recent study conducted by the Spanish Institute for Diversification and Energy Savings (IDAE) [42] defined three main classes of residential buildings from an energy perspective considering the year of construction: (i) buildings built before 1981, when compulsory thermal insulation regulations did not exist; (ii) buildings built between 1981 and 2007, when the first regulations determining minimum thermal insulation demands were established for the first time [43]; and (iii) buildings built between 2008 and 2014, when the Spanish Technical Building Code, which increased the minimum requirements, was implemented [44]. A new class must be considered based on the IDAE methodology: (iv) buildings built after 2015, when the most recent regulations, which enforce the latest European Union directives, were established [45].

Urban morphology characterization allows for the aggregation of building information based on the physical characteristics of the urban fabric where buildings are located [38]. Moreover, this information allows to discern between residential buildings, included in residential morphologies, and other uses such us amenities or tertiary uses. At this level, two different datasets could be considered. On one hand, cadastral data include 4 categories: (Ca) slab, (Cb) perimeter block, (Cc) detached house and (Cd) terraced house. This information, which is automatically generated considering both the number of dwellings on a property and the relative positions of these buildings with respect to other buildings [46], is available for almost all Spanish territories, except Basque country. Although this dataset includes three-dimensional information on each building [47], it is not currently possible to obtain large quantities of three-dimensional building data. On the other hand, the AMB dataset provides abundant information for urban morphology characterization. Data are obtained from metropolitan planning [48] and produced by technicians through on-site visits. Table 2 shows a correlation scheme of these two datasets. Finally, the AMB dataset is considered because of its detailed characterization and the associated acquisition methodology. At this level, 4 main categories and 14 subcategories are defined (Figure 2):

<Table 2>

- (S) Slab: multi-family residential areas characterized by a non-street-based layout. These areas include (S1) grouped slab, which represents canonical functionalist urbanism, such as post-war mass housing estates; (S2) aligned slab, which is directly related to the street axis; and (S3) disaggregated slab, if none of the situations above apply.
- (P) Perimeter block: multi-family residential areas characterized by street-based layouts as grids. These areas include (P1) axial, in which blocks are adapted to rigid axes; (P2) irregular, where blocks are not adjusted to a rigid grid; (P3) regular, in which blocks are arranged according to homogeneous criteria grids; and (P4) Cerdà, designed by Idelfonso Cerdà and characterized by a grid of 113x113 m blocks located in Barcelona.
- (H) Historical: multi-family residential areas with historical street-based layouts. These areas include (H1) historical old town, the traditional urban morphology in which plots have a small façade length and narrow streets, and (H2) historical suburban growth, with clear narrow and large plots aligned along the axis with free space at the back of plots.
- (SF) Single family: (SF1) terraced, in which single buildings are joined by common sidewalls; (SF2) irregular, in which single-family houses are organized without clear patterns; (SF3) mixed; (SF4) regular, characterized by single-family houses organized around clear street axes and geometries; and (SF5), rustic, the main characteristic of which is that single-family houses are organized inside a rustic plot.

<Figure 2>

2.1.3 *Quantitative characterization*

The envelope surface is characterized from a quantitative approach by developing a geospatial model using the GIS software QGIS [49], cadastral vector cartography information from the Spanish Government [50] and the associated alphanumeric dataset [51]. For each real building, the model simulates another simplified building with the same three basic characteristics: gross living area, coverage and height of living index [37,52,53]. The calculation of each variable is defined as follows:

- Gross living area (G.L.A., m^2) is defined as the total living space of a building, including all space that has heating, lighting, and ventilation. It is calculated considering the use data for each part of the building, obtaining the residential percentage of each building. Hence, using the gross floor area (G.F.A.), which is defined as the total building area, including external walls, it is possible to exclude some non-living building areas, such as garages and storage, where thermal regulations do not demand special thermal requirements.

- Coverage (C, m^2) is defined as the amount of surface area overlaid by a building. It is calculated in QGIS considering the area of each building polygon.
- The height of living index (H, m) is defined as the relation between G.L.A. and C. Once these values are calculated, this study considers 3 metres as the average height of each floor [42]. Based on this assumption, it is possible to obtain the average height of each living area in each building.

After the main characteristics have been defined, the geospatial model can be obtained considering 4 phases (Figure 3). Table 3 contains the main assumptions considered in this study.

- First, real building data are obtained from QGIS, including the coverage and the perimeter of each building. The cadastral alphanumeric dataset provides G.F.A. (m^2) values.
- Second, the living area and building data are obtained. G.L.A. is calculated from the G.F.A., excluding non-living areas.
- Third, the real geometry is simplified to obtain a simplified G.L.A. for the building. In this step, the study idealises a building with the same C and H.
- Finally, considering hollow surfaces [54], a simplified net building living area is obtained.

<Table 3> <Figure 3>

After the simplified net model has been established, the net living envelope surface can be obtained considering the external perimeter of the building and H. These values, which are given in m^2, are considered in defining the retrofit surface in this study.

2.2 Life cycle assessment

This portion of the methods is based on the methodology presented by Sierra-Pérez et al. [14] for the quantification of environmental impacts during the construction of different façades based on LCA. The environmental implications of the retrofitting of façades and roofs are assessed for the envelope determined in the quantitative characterization. The environmental impacts of the façade retrofits are obtained from Sierra-Pérez et al. [14]. The impacts of roof retrofits are quantified for the first time in this study.

2.2.1 *Boundaries and limits*

This research is based on a cradle-to-site approach. In this approach, the environmental impact analysis includes the production (extraction and processing of raw materials, transport to manufacturers and manufacturing), distribution to the building site and the installation in the building processes according to the European normative EN 15804:2014 [55]. The use, maintenance and end-of-use phases have been excluded from the study because this study aims to evaluate the combination of LCA and GIS methods through the assessment of environmental implications in updating the energy efficiency of urban areas. Therefore, the different influences of both factors during the use of buildings and the different possibilities for construction materials at the end-of-life of buildings can be complex to address.

Simapro 7.3 software [56] and the *Ecoinvent 3.1* database [57] are used to develop the inventory data according to an attributional approach. The main impact category assessed is the global warming potential (GWP) due to its relevance in the environmental field. Moreover, as in the case of cork as a forest-based material, carbon storage must be taken into account; therefore, the GWP results, including those for biogenic carbon, are provided. Additionally, as noted above, the embodied energy (EE) is included due to its increasing importance in determining the building energy demand.

2.2.2 *Declared unit*

A declared unit (DU) is established according to the environmental product declaration (EDP) for construction products EN 15804:2014 [55] to compare the environmental impacts of construction solutions based on the different insulation materials. In this study, the DU is the production, transport, and installation of the quantity of materials required to construct 1 m^2 of the selected construction systems, where the amount of insulation required is variable depending on the geographic location, construction system, and thermal insulation material. However, in a retrofit scenario, the year of construction must be included as a variable because the transmittance values of existing buildings influence the results.

Geographic location

The definition of environmental impact is related to geographic location and climate conditions. The Spanish Technical Building Code [45] includes 6 different climate zones in Spain. However, in this case study, the climate variable is constant because all of the Barcelona metropolitan area is included in the same climate zone, "C" in this case.

Construction system

This section explains the selected construction systems, façades and roofs most commonly used in Spain for retrofitting. The development of these systems is based on the Spanish catalogue of construction elements [58,59]. According to the established DU and the building technical considerations, the supplementary data indicate the materials and energy content for 1 m^2 of the various façades and roof systems. Figure 4 shows the selected façade systems: ventilated façades, external thermal insulation composite systems (ETICS) and internal insulation façades. These façade construction systems are not invasive and permit retrofitting without having to interrupt the use of the building. An increase in thermal insulation is guaranteed with these three options, whereas only a ventilated façade and ETICS eliminate thermal bridges. Although internal insulated façades are appropriate for specific retrofits, recent studies have suggested that this construction system could modify the current living conditions and reduce the floor area [60]. Detailed façade construction system descriptions were given by Sierra-Pérez et al. [14].

<Figure 4>

As Figure 5 shows, the roof systems selected include a flat roof, sloping roof and sloping ventilated roof. These construction systems are not invasive and permit retrofitting without having to interrupt the use of the building. Thus, the expenses associated with temporary relocation are reduced, and the quality of life of residents is improved during the installation. Additionally, an increase in thermal insulation is guaranteed.

<Figure 5>

Thermal insulation

Two types of thermal insulation have been included, expanded polystyrene (EPS), which is one of the most common non-renewable insulation materials in Europe [15,61], and cork, a natural and renewable insulation material that is concentrated in the Iberian Peninsula [62]. The objective of this comparison is to identify the environmental implications of selecting insulation materials with different origins in retrofitting actions.

It is important to note that cork is a forest-based material that is extracted from the outer bark of the cork oak. The carbon fixed by the tree is transferred to the cork material, meaning that this material has the potential to mitigate climate change by storing carbon for long periods [63–65]. In the context of this study, from a cradle-to-grave approach, the biogenic carbon remains in the product, so there is no emission of biogenic carbon.

Year of construction

According to a recent study conducted by the IDAE, the year of construction is useful for defining transmittance values in the Spanish context [42]. It is possible to estimate the transmittance values by considering the year of construction and the construction system variables. Table 4 shows these values for climate zone “C”.

Second, the study defines an objective value of transmittance towards which the building stock should tend. To define this objective, the latest version of the Spanish Technical Building Code is considered [45]. As Table 4 shows, this document defines U=0.29 (W/m K) as the maximum value of façade transmittance in climate zone “C”, and that for roofs is U=0.23 (W/m K).

<Table 4>

Inventory data

After the geographic location, construction system, thermal insulation material and year of construction are defined, as given in Table 5 and Table 6, it is possible to calculate the quantity of materials required to construct 1 m^2 of the selected construction system and define the DU, which includes the production, transport, and installation phases. The inventory data for the production of materials used in the construction and installation of the roofs and the transport of these materials to the building location were collected from different sources. The supplementary data section contains the specific data for each process and the reference from which the data were collected. In the case of façades, all the information was taken from Sierra-Pérez et al. [14]. The main assumptions for the LCA are described in Table 3.

<Table 5> <Table 6>

2.3 Extrapolation

After the envelope surface is characterized at the urban scale (m^2), the LCA is developed to obtain the impact per m^2 of the DU. Therefore, it is possible to extrapolate both results at the urban level and determine the associated environmental effects at the urban scale. The results are presented directly and through scenarios to fully understand the scope of these impacts.

Direct extrapolation is performed considering urban morphologies. On one hand, absolute extrapolation is useful for measuring the extent of the LCA at the urban scale, where the total environmental impacts of retrofits can exhibit significant differences between construction systems. On the other hand, relative extrapolation shows the relations between environmental impacts and urban morphologies.

Relative extrapolation is directly connected to the relation between the envelope surface and urban morphologies. Therefore, this study calculates not only the relative environmental impacts for each urban morphology divided by the total number of dwellings but also the previously considered relations between the envelope surface and urban morphologies.

3. Results and Discussion

3.1 Urban characterization of the Barcelona metropolitan area

As urban characterization of AMB shows that more than 69.7% of the envelope surfaces of dwellings were built before 1981 (without any thermal regulation), and the other 27.4% were built between 1981 and 2007 (the first period of thermal regulation), indicating that up to 2.9% of the envelope surfaces of dwellings were built between 2008 and the implementation of the Spanish Technical Building Code. The data obtained are similar to those in related studies using different methodologies [36] and exhibit some small differences because the data used here are more current. Moreover, if location is considered (Figure 6-7), older dwellings are mainly located in the Barcelona municipality and small metropolitan centres, whereas newer buildings are further away from the urban centre. The urban morphology distribution exhibits a characteristic pattern where multi-family units are located in central areas. The growth of single-family urban morphologies mainly occurred in the outskirts of urban areas from 1981-2007. Moreover, the new multi-family buildings were built during the past few decades, and most were constructed along the inner peripheries of metropolitan centres. Detailed results obtained with the bottom-up building-by-building approach can be viewed in the Supplementary Material. These results focus on the relevance of energy retrofits in this scenario and the determination of the environmental implications of such retrofits at the urban scale.

<Figure 6> <Figure 7>

3.2 LCA by type of construction system

The analysis of the environmental implications of building retrofits in the Barcelona metropolitan area is conducted following the methodology proposed by Sierra-Pérez et al. [14]. In the case of the LCA results for façade and roof retrofits obtained in this study, the presented results are original. In this paper, the results for roof construction systems are presented with the results for façades to provide a comparative perspective on both types of systems.

The previous section presents the results by the construction system type, year of construction and type of insulation material installed. The type of construction system is relevant considering the LCA approach. In the case of façades, ETICS has a lower environmental impact in all categories than ventilated façades (VFs) or internal insulated façades (IIFs). However, in the case of roof retrofits, flat roofs (FR) have lower environmental impacts than sloping roofs (SRs) and sloping ventilated roofs (SVRs) for both the GWP and EE. However, considering the GWP and including biogenic carbon, SR and SVR have lower environmental impacts because these construction systems include natural materials, such as wood, that store carbon during their growth.

Another variable to consider is the year of construction. As Figure 8 shows, the newer a building is, the less impact the system will have, which is logical. As Table 4 indicates, the values of the estimated transmittance generally decreased when insulation regulations were implemented.

<Figure 8>

Moreover, the selection of thermal insulation materials is also relevant, and the results allow for the identification of different key factors. On one hand, the use of natural thermal insulation materials does not necessary imply a low environmental impact due to the low level of technological development in the manufacturing processes of cork boards [66]. Considering the GWP and EE, Figure 8 shows that the use of cork increases the environmental impact compared to EPS in all construction systems. On the other hand, if the GWP results include biogenic carbon, the use of cork reduces the environmental impact of all construction systems. Thus, according to Sierra-Pérez et al. [66], biogenic carbon is one of the greatest advantages of natural materials and can help mitigate the GWP increase caused by building retrofits.

3.3 Absolute extrapolation

From an absolute approach, the environmental impact results by type of construction system and year of construction are compared to the urban characterization results, and the different types of insulation material are assessed. The results of the geospatial analysis reflect the quantitative impacts (Table 7) of retrofits and the spatial distribution of these impacts (Figure 9).

Table 7 shows the environmental implications of different retrofit scenarios for twelve construction systems (six façades and six roofs) in terms of the GWP, GWP biogenic and EE. Based on the GWP results, the differences between the absolute impacts of constructed façade systems reaches $1.85x10^9$ kg CO_2 eq. ETICS with EPS is the most recommended system, and internal insulation with cork is the least recommended, with a relative difference of up to 182% between these systems. In the case of roof construction systems, the highest difference is $3.24x10^9$ kg CO_2 eq., with a relative difference of 471% between the most recommended solution (FR with EPS) and the least recommended solution (SR with cork).

However, if the ability of cork oak to fix CO_2 is considered, i.e., biogenic carbon is transferred to the material, the difference between the most recommended façade system (ETICS with cork) and the least recommended system (IIF with EPS) is $1.7x10^9$ kg CO_2 eq., and the relative difference is 277%. In the case of roofing solutions, the difference is even larger between the most (FR with EPS) and least (SR with cork) recommended systems at $1.99x10^9$ kg CO_2 eq.

Similar results are obtained for the GWP, and the results suggest that cork is not as competitive as EPS. In this case, a difference of up to $4.33x10^{10}$ kg CO_2 eq., or 218% in relative terms, is obtained between ETICS with EPS and VF with cork. In the case of roofs, this value is $1.21x10^{11}$ kg CO_2 eq., or 607% in relative terms.

The results show the importance, especially the environmental importance, of considering LCA approaches in retrofit policies at territorial scales. The absolute differences in the data reflect the significance of these approaches. For instance, considering the GWP, the difference between the most and least recommended retrofit option (up to $5.10x10^9$ kg CO_2 eq.) represent savings of up to 16% of the CO_2 production in the energy sector of Catalonia (Spain) in 2012 [67].

<Table 7>

The proposed methodology allows for georeferencing environmental impacts, as shown in Figure 9. As an example, the figure indicates the most recommended combination of construction systems considering the GWP and biogenic GWP. The GWP map, which represents a combination of ETICS and FR, both with EPS, exhibits a concentration of impacts around multi-family morphologies. The main reason for this distribution pattern is that the larger the envelope surface an urban morphology has, the greater the GWP impact a retrofit will have. The areas with less impacts in absolute terms are single-family morphologies, which are located on the outskirts of metropolitan areas. However, considering the biogenic GWP based on the combination of ETCIS and SR with cork, the results exhibit some differences. In this case, the greater the envelope surface a morphology has, the more recommended a construction system will be. The distribution of impacts shows that the inner-city areas, which have more multi-family buildings, exhibit less concentrated biogenic GWP impacts than outskirt areas. The generated maps are presented in the Supplementary Material. These metropolitan maps allow for the georeferencing of critical retrofit areas based on the impact scenario considered.

<Figure 9>

3.4 Relative extrapolation

From a relative approach, the relationship between urban forms and their retrofitting impacts has been obtained. These results are presented based on the relationship between the envelope surface and number of dwellings (Figure 10) and based on georeferenced data (Figure 11).

When the relationship between the envelope surface and the number of dwellings is analysed, significant differences between urban morphologies are identified (Figure 10). Morphologies corresponding to multi-family residential areas, which represent more than 80% of the envelope surface, have average values of approximately 67 m^2/dwelling. Among these dwellings, the more representative morphologies, S1, P2, P3 and H2, exhibit values ranging from 57 m^2/dwelling to 73 m^2/dwelling. In contrast, the morphologies of single-family dwellings have an average value of 260 m^2/dwelling. Although the relative difference is high, the total surface area represented by these morphologies does not exceed 19%. Undoubtedly, the results show that morphology is a key factor in characterizing the building stock, with relative differences reaching 574%. Notably, the more intense and compact an urban form is, the smaller the envelope surface per dwelling will be, and the fewer environmental impacts the retrofit will generate.

<Figure 10>

Focusing on Figure 11, which represents the most recommended scenario considering the GWP and biogenic GWP, it can be noted that the relative results differ from the distribution of impacts according to the geospatial model. First, considering the GWP, the combination of ETICS and FR with EPS is shown. The map illustrates, in general terms, the smallest impacts on multi-family morphologies. However, in detail, we can observe some multi-family buildings that, individually, have high impacts. Influenced by the number of dwellings in these buildings, the methodology is able to describe the behaviour of each building in a unique way. Considering the biogenic GWP, the more recommended combination is ETICS with an SR with cork. Conversely, in Figure 9, a lower biogenic impact is exhibited by those morphologies that encompass more surface per dwelling, such as single-family dwellings or isolated multi-family buildings that have fewer dwellings. The metropolitan area maps are presented in the Supplementary Material. These maps display the impact distribution, which is closely related to the urban morphologies. In general, the distribution of most multi-family morphologies close to the inner city and metropolitan centres and the single-family morphologies around them determine the distribution of impacts for each scenario. Moreover, each single building can be analysed based on the building-by-building approach.

<Figure 11>

The proposed methodology permits the fast and reliable compilation and quantification of retrofit data. Compared with previous studies, this study uses the Spanish open dataset. Second, using cadastral data allows for a detailed description of the G.L.A. instead of making assumptions, as in previous studies. Third, different construction systems have been considered in this study. Finally, considering urban morphologies in an aggregated context reveals significant patterns. It is convenient to note that this methodology can be useful in political decision making regarding retrofits and urban regeneration strategies. Moreover, impact maps facilitate not only the measurement of retrofit impacts but also the determination of the distribution of these impacts across the city. Illustrating the results using maps allows for the geolocalization of critical areas at the urban level. In fact, this presentation can help in the decision-making process by cross-referencing these results with other data and adding nuance during decision making in the prioritization of building stock retrofits. For instance, the results could be combined with other multidisciplinary approaches, such as urban vulnerability criteria [68], energy poverty [69,70], and other environmental criteria [71].

3.5 Current methodological limitations

The methodological limitations and the model calibration of this study are reported in this section. In the development of the geospatial model, some geometrical aspects must be considered during the simplification processes of each building. It is important to note three main considerations that are unavoidable at the urban scale: 1) some complex buildings can be affected during the simplification process as a consequence of their complex geometry; 2) the average height is considered according to the Spanish context; and 3) the percentage of hollow areas is assumed considering a recent methodology proposed in the Spanish context. A sensitivity analysis has been carried out, in which the influence of both different average height and percentage of hollow areas has been studied. Results indicate a direct relation of both factors. The directly proportional relationship implies that, although there was a significant error assumed in the absolute quantification of the model, the relative location of the impacts in the geospatial model would be proportional. For this reason, the model could be useful for the detection of areas of interest.

Moreover, a comparison between real building and simplified model building has been carried out, considering one of the most representative archetypes of each urban morphology under study. The real buildings have been the main source to re-draw the envelope surface. Moreover, it is important to consider that the plan of the buildings have been obtained from the Cadastre source. Results present high correlation values (R^2=0.96), indicating the simplified geometry and the percentage of hollow areas is representative. However, the archetypes could introduce errors in a building-by-building approach. In order to understand better the influence and the limitations of the geospatial model future research could develop deeply comparisons between different methodological approaches.

In the qualitative characterization, the year of building construction is the primary variable. Recent studies [72] have noted some uncertainty in this variable. The error, quantified as 8%, must be assumed because the cadastral dataset is the only currently available source for Spain.

As qualitative data at building-by-building approach would be available in the Spanish context. This methodology could improve considering another variables such as use pattern of dwellings (main residence, holiday residence, etc.), or occupancy rate. At this point, it is interesting to check some experiences on the collection and accessibility of these data in other countries [73,74].

One of the limitations of this LCA study is the reliability of results because the majority of the data in the environmental database are not collected in Spain and the distance from the manufacturer to the building site could vary. Moreover, although the construction solutions studied are among the most common in Spain, the use of other systems could change the overall results.

4. Conclusions

The study investigates a possible application resulting from the combination of LCA and GIS and presents the potential applications for complex LCA inventories. The proposed GIS-based LCA methodology allows for the effective assessment of the environmental implications of thermal upgrades to buildings in a specific urban area based on an extensive and complete inventory. The considered case study, the Barcelona metropolitan area, is a functional area with a population of approximately 3 million inhabitants, and only 2.9% of the buildings meet the current Spanish Technical Code. Therefore, retrofitting buildings to increase the level of insulation is one of the most effective solutions for reducing building energy consumption.

First, this methodology allows for the characterization of the residential buildings stock from a bottom-up perspective with a building-by-building approach using a GIS methodology. The methods are based on open data to facilitate the updating of data and the reduction of the minimum data scale: the building scale. In addition, working at the building scale rather than census level or municipality level allows for the development of flexible aggregated models. Urban morphologies are considered in this case because they are directly related to the physical forms of cities and their spatial configurations. The patterns detected during the study confirm the relevance of this aggregation model.

Second, georeferencing the results and obtaining maps improves the communication with stakeholders and policy makers, helping them to localize the critical retrofit areas at the urban level. Whereas the quantification of environmental impacts shows the potential to introduce LCA frameworks in municipal policies, mapping helps to identify the most critical areas.

Third, this study facilitates the understanding of the environmental impacts of thermal retrofits to buildings at the urban scale. As the previous sections have shown, the magnitudes of the differences in the absolute extrapolation results indicate that the environmental implications of retrofits should be considered to minimize a variety of impacts at the urban scale.

Last, in this study, potential future research topics are identified. First, future studies should extend this LCA approach to other life cycle stages, such as the use and end-of-life stages. In addition, analysing the operative energy would be useful for understanding whether construction systems improve the environmental impacts during this stage. Second, it would be convenient to conduct an economic analysis of the chosen construction systems and compare the results at the urban scale. In addition, by relating these results to the generated impacts of retrofits, the broader concept of sustainability can be considered from a holistic perspective (environmental, economic, and social). Finally, in the assessment of retrofit scenarios, the data obtained could be cross-referenced with data from other studies related to urban vulnerability, energy poverty or other environmental indicators.

Acknowledgements

This work was supported by the Barcelona metropolitan area (AMB) in the framework of the "Support for climate change research in the AMB" grants in 2016.

References

[1] A. Gouldson, S. Colenbrander, A. Sudmant, E. Papargyropoulou, N. Kerr, F. McAnulla, S. Hall, Cities and climate change mitigation: Economic opportunities and governance challenges in Asia, Cities. 54 (2016) 11–19. doi:10.1016/j.cities.2015.10.010.

[2] UN - Population Division, World Population Prospects: The 2015 Revision, World Population 2015 Wallchart, 2015.

[3] P. Rode, R. Burdett, Cities: Investing in energy and resource efficiency., in: 2011: pp. 453–492.

[4] European Comission, Energy performance of Buildings Directive 2010/31/EU (EPDB), (2010).

[5] European Comission, Regulation of the European Parliament and of the council. Establishing Horizon 2020 - The Framework Programme for Research and Innovation, 1 (2011) 1–119.

[6] European Comission, Energy Efficiency Directive 2012/27/EU, (2012).

[7] L.F. Cabeza, A. Castell, M. Medrano, I. Martorell, G. Pérez, I. Fernández, Experimental study on the performance of insulation materials in Mediterranean construction, Energy Build. 42 (2010) 630–636. doi:10.1016/j.enbuild.2009.10.033.

[8] C. Thormark, A low energy building in a life cycle — its embodied energy , energy need for operation and recycling potential, Build. Environ. 37 (2002) 429–435.

[9] F. Pacheco-Torgal, J. Faria, S. Jalali, Embodied Energy versus Operational Energy. Showing the Shortcomings of the Energy Performance Building Directive (EPBD), Mater. Sci. Forum. (2012). doi:10.4028/www.scientific.net/MSF.730-732.587.

[10] I. Zabalza Bribián, A. Aranda Usón, S. Scarpellini, Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification, Build. Environ. 44 (2009) 2510–2520. doi:10.1016/j.buildenv.2009.05.001.

[11] S. González-García, R.G. Lozano, J.C. Estévez, R.C. Pascual, M.T. Moreira, X. Gabarrell, J.R. i Pons, G. Feijoo, Environmental assessment and improvement alternatives of a ventilated wooden wall from LCA and DfE perspective, Int. J. Life Cycle Assess. 17 (2012) 432–443. doi:10.1007/s11367-012-0384-0.

[12] H. Monteiro, F. Freire, Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods, Energy Build. 47 (2012) 572–583. doi:10.1016/j.enbuild.2011.12.032.

[13] H. Islam, M. Jollands, S. Setunge, I. Ahmed, N. Haque, Life cycle assessment and life cycle cost implications of wall assemblages designs, Energy Build. 84 (2014) 33–45. doi:10.1016/j.enbuild.2014.07.041.

[14] J. Sierra-Pérez, J. Boschmonart-Rives, X. Gabarrell, Environmental assessment of façade-building

systems and thermal insulation materials for different climatic conditions, J. Clean. Prod. 113 (2016) 102–113. doi:10.1016/j.jclepro.2015.11.090.

[15] A.M. Papadopoulos, E. Giama, Environmental performance evaluation of thermal insulation materials and its impact on the building, Build. Environ. 42 (2007) 2178–2187. doi:10.1016/j.buildenv.2006.04.012.

[16] N. Pargana, M.D. Pinheiro, J.D. Silvestre, J. de Brito, Comparative environmental life cycle assessment of thermal insulation materials of buildings, Energy Build. 82 (2014) 466–481. doi:10.1016/j.enbuild.2014.05.057.

[17] M. Beccali, M. Cellura, M. Fontana, S. Longo, M. Mistretta, Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits, Renew. Sustain. Energy Rev. 27 (2013) 283–293. doi:10.1016/j.rser.2013.05.040.

[18] B. Nicolae, B. George-Vlad, Life cycle analysis in refurbishment of the buildings as intervention practices in energy saving, Energy Build. 86 (2015) 74–85. doi:10.1016/j.enbuild.2014.10.021.

[19] M. Lotteau, P. Loubet, M. Pousse, E. Dufrasnes, G. Sonnemann, Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale, Build. Environ. 93 (2015) 165–178. doi:10.1016/j.buildenv.2015.06.029.

[20] A. Mastrucci, A. Marvuglia, E. Popovici, U. Leopold, E. Benetto, Geospatial characterization of building material stocks for the life cycle assessment of end-of-life scenarios at the urban scale, Resour. Conserv. Recycl. 123 (2017) 54–66. doi:10.1016/j.resconrec.2016.07.003.

[21] A. Mastrucci, A. Marvuglia, U. Leopold, E. Benetto, Life Cycle Assessment of building stocks from urban to transnational scales: A review, Renew. Sustain. Energy Rev. 74 (2017) 316–332. doi:10.1016/j.rser.2017.02.060.

[22] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: A review of modeling techniques, Renew. Sustain. Energy Rev. 13 (2009) 1819–1835. doi:10.1016/j.rser.2008.09.033.

[23] A. Mavrogianni, M. Davies, M. Kolokotroni, I. Hamilton, A GIS-based bottom-up space heating model of the London domestic stock, in: Elev. Int. IBPSA Conf., Glasgow, 2009: pp. 1061–1067.

[24] P. Caputo, G. Costa, S. Ferrari, A supporting method for defining energy strategies in the building sector at urban scale, Energy Policy. 55 (2013) 261–270. doi:10.1016/j.enpol.2012.12.006.

[25] M. Österbring, É. Mata, F. Jonsson, H. Wallbaum, A methodology for spatial modelling of energy and resource use of buildings in urbanized areas, in: World Sustain. Build. Conf. WSB14, Barcelona, 2014.

[26] I. Ballarini, S.P. Corgnati, V. Corrado, Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project, Energy Policy. 68 (2014) 273–284. doi:10.1016/j.enpol.2014.01.027.

[27] P. Tuominen, R. Holopainen, L. Eskola, J. Jokisalo, M. Airaksinen, Calculation method and tool for assessing energy consumption in the building stock, Build. Environ. 75 (2014) 153–160. doi:10.1016/j.buildenv.2014.02.001.

[28] R.F. Tomlinson, Thinking about GIS: geographic information system planning for managers, ESRI Press, 2007.

[29] M. Batty, Y. Xie, Urban analysis in a GIS environment: population density modelling using, in: S. Fotheringham, P. Rogerson (Eds.), Spat. Anal. GIS, CRC Press, Hoboken, 2014: p. 189.

[30] D. Saner, N. Heeren, B. Jäggi, R.A. Waraich, S. Hellweg, Housing and Mobility Demands of Individual Households and their Life Cycle Assessment, Environ. Sci. Technol. 47 (2013) 5988–5997. doi:10.1021/es304084p.

[31] D. Saner, C. Vadenbo, B. Steubing, S. Hellweg, Regionalized LCA-Based Optimization of Building Energy Supply: Method and Case Study for a Swiss Municipality, Environ. Sci. Technol. 48 (2014) 7651–7659. doi:10.1021/es500151q.

[32] A. Mastrucci, E. Popovici, A. Marvuglia, L. De Sousa, E. Benetto, U. Leopold, GIS-based Life Cycle Assessment of urban building stocks retrofitting- a bottom-up framework applied to Luxembourg, in: Proc. EnviroInfo ICT Sustain. 2015, Atlantis Press, Paris, France, 2015: pp. 47–56.

doi:10.2991/ict4s-env-15.2015.6.

[33] S. García-Pérez, J. Sierra-Pérez, J. Boschmonart-Rives, G. Lladó Morales, A. Romero Calix, 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. 12 (2017) 294–303. doi:10.2495/SDP-V12-N2-294-303.

[34] A. Stephan, A. Athanassiadis, Quantifying and mapping embodied environmental requirements of urban building stocks, Build. Environ. 114 (2017) 187–202. doi:10.1016/j.buildenv.2016.11.043.

[35] Direcció de Serveis Ambientals de l'AMB, Anàlisis dels Teixits Urbans del L'AMB, AMB, Barcelona, 2015.

[36] Ministerio de Fomento, Atlas de la Edificación residencial en España, (2016). http://www.fomento.es/MFOM/LANG_CASTELLANO/DIRECCIONES_GENERALES/ARQ_VIVIENDA/SUELO_Y_POLITICAS/OBSERVATORIO/AtlEdiResEsp/ (accessed 10 July 2016).

[37] P. Rode, C. Keim, G. Robazza, P. Viejo, J. Schofield, Cities and Energy: Urban Morphology and Residential Heat-Energy Demand, SAGE Publications, London, 2014. doi:10.1068/b39065.

[38] V. Oliveira, Urban Morphology, Springer International Publishing, Cham, 2016. doi:10.1007/978-3-319-32083-0.

[39] Área Metropolitana de Barcelona, AMB - Datos abiertos, (2017). http://www.amb.cat/es/web/area-metropolitana/dades-obertes (accessed 8 September 2016).

[40] European Comission, Re-use of public sector information Directive 2003/98/EC, (2003).

[41] R.T. Mora-García, M.F. Céspedes-López, J.C. Pérez-Sánchez, V.R. Pérez-Sánchez, Reutilización de datos catastrales para estudios urbanos, in: J. de la Riva, P. Ibarra, R. Montorio, M. Rodrigues (Eds.), Análisis Espac. Y Represent. Geográfica Innovación Y Apl., Universidad de Zaragoza - AGE, 2015: pp. 295–304.

[42] IDAE, Guía IDAE: Manual de fundamentos técnicos de calificación energética de edificios existentes CE3X, Madrid, 2012.

[43] Ministerio de Obras Públicas y Urbanismo, Real Decreto 2429/79, de 6 de julio, por el que se aprueba la Norma Básica de la Edificación NBE-CT-79, sobre Condiciones Térmicas en los edificios, (1979).

[44] Ministerio de Vivienda, Documento Básico de Ahorro de Energía (DB-HE), (2006).

[45] Ministerio de Fomento, Documento Básico de Ahorro de Energía (DB-HE), (2013).

[46] Dirección General del Catastro, Catastro, (2017). http://elcatastro.blogspot.com.es/ (accessed 21 October 2017).

[47] J.M. Olivares García, Cartografía catastral en Google Earth, CT/Catastro. 58 (2006) 21–36.

[48] C. Crosas, ed., Metròpolis Barcelona, Área Metropolitana Barcelona, Barcelona, 2015.

[49] QGIS Development Team, QGIS Geographic Information System, Open Source Geospatial Found. Proj. (2015).

[50] Dirección General del Catastro, Modelo de datos de cartografía vectorial (formato shapefile), (2013).

[51] Dirección General del Catastro, Descarga y tratamiento de información alfanumérica en formato CAT. Manual del usuario., (2013) 25.

[52] M. Berghauser Pont, P. Haupt, Spacematrix: Space, Density and Urban Form, nai010 publishers, Rotterdam, 2010.

[53] A. Fernández Per, J. Mozas, A.S. Ollero, A. Deza, Why Density? Debunking the myth of the cubic watermelon, A+T architecture publishers, Vitoria - Gasteiz, 2015.

[54] B. Rodríguez-Soria, J. Domínguez-Hernández, J.M. Pérez-Bella, J.J. del Coz-Díaz, Quantitative analysis of the divergence in energy losses allowed through building envelopes, Renew. Sustain. Energy Rev. 49 (2015) 1000–1008. doi:10.1016/j.rser.2015.05.002.

[55] European Committee for Standardization, EN 15804:2012+A1, 2013. Sustainability of construction works - Environmental product declarations – Core rules for the product category of construction

products., (2014).

[56] PRé Consultants, Simapro 7.3.0, Amersfoort (Netherlands), 2010.

[57] Ecoinvent, ecoinvent database 3.1, Swiss Cent. Life Cycle Invent. (2009). http://www.ecoinvent.ch/.

[58] Ministerio de Vivienda, Instituto de Ciencias de la Construcción EduardoTorroja, CSIC, Catálogo de elementos constructivos del CTE, (2008) 141.

[59] Instituto de ciencias de la construcción Eduardo Torroja, Hyspalist, Catálogo de soluciones cerámicas para el cumplimiento del Código Técnico de la Edificación, Hyspalist, 2008.

[60] F. Daumal i Domenech, M. Monzón Chavarrías, B. López-Mesa, La necesidad de conciliar la normativa de habitabilidad con la rehabilitación acústica de la vivienda mínima, Inf. La Construcción. 70 (2018).

[61] F. Ardente, M. Beccali, M. Cellura, M. Mistretta, Building energy performance: A LCA case study of kenaf-fibres insulation board, Energy Build. 40 (2008) 1–10. doi:10.1016/j.enbuild.2006.12.009.

[62] J. Sierra-Pérez, J. Boschmonart-Rives, X. Gabarrell, Production and trade analysis in the Iberian cork sector: Economic characterization of a forest industry, Resour. Conserv. Recycl. 98 (2015) 55–66. doi:10.1016/j.resconrec.2015.02.011.

[63] L. Gil, C. Pereira, A fórmula da cortiça, Tecnol. E Vida. November (2007) 1–4.

[64] A.C. Dias, L. Arroja, A model for estimating carbon accumulation in cork products, For. Syst. 23 (2014) 236–246. doi:10.5424/fs/2014232-04100.

[65] European Committee for Standardization, UNE-EN 16449. Wood and wood-based products. Calculation of the biogenic carbon content of wood and conversion to carbon dioxide, 2014.

[66] J. Sierra-Pérez, J. Boschmonart-Rives, A.C. Dias, X. Gabarrell, Environmental implications of the use of agglomerated cork as thermal insulation in buildings, J. Clean. Prod. 126 (2016) 97–107. doi:10.1016/j.jclepro.2016.02.146.

[67] Oficina Catalana del Canvi Climàtic, Catalunya i els objectius de reducció d'emissions de gasos amb efecte d'hivernacle. Cinquè informe de progrés., Barcelona, 2014.

[68] Ministerio de Fomento, Atlas de la Vulnerabilidad Urbana en España 2001 y 2011. Metodología, contenidos y créditos, 2015.

[69] S. Pachauri, D. Spreng, Measuring and monitoring energy poverty, Energy Policy. 39 (2011) 7497–7504. doi:10.1016/j.enpol.2011.07.008.

[70] P. Nussbaumer, M. Bazilian, V. Modi, Measuring energy poverty: Focusing on what matters, Renew. Sustain. Energy Rev. 16 (2012) 231–243. doi:10.1016/j.rser.2011.07.150.

[71] M. Braulio-Gonzalo, M.D. Bovea, M.J. Ruá, Sustainability on the urban scale: Proposal of a structure of indicators for the Spanish context, Environ. Impact Assess. Rev. 53 (2015) 16–30. doi:10.1016/j.eiar.2015.03.002.

[72] Instituto Nacional de Estadística, Instituto Nacional de Estadística, (2016). http://www.ine.es/ (accessed 7 December 2016).

[73] NYC Mayor's Office of Sustainability, NYC Benchmarking Law, (2018). http://www.nyc.gov/html/gbee/html/plan/ll84.shtml (accessed 15 January 2018).

[74] Washington State Department of Enterprise Services, Energy Star Portfolio Manager, (2018). https://des.wa.gov/services/facilities-leasing/energy-program/energy-star-portfolio-manager (accessed 15 January 2018).

Tables

Figures

Supplementary Material

Supplementary table A: Inventory of the materials and energy per m^2 of the flat roof system considered for the declared unit.

Supplementary table B: Inventory of the materials and energy per m^2 of the sloping roof system considered for the declared unit .

Supplementary table C: Inventory of the materials and energy per m^2 of the sloping ventilated roof system considered for the declared unit.

Supplementary material D: Complete metropolitan maps

Supplementary material E: Online version of the absolute extrapolation map. The recommended GWP scenario (ETICS and FR with EPS).

Link: https://sgarciap.carto.com/builder/e589f24f-463c-4202-b660-a93aea244327/embed

Embed: <iframe width="100%" height="520" frameborder="0" src="https://sgarciap.carto.com/builder/e589f24f-463c-4202-b660-a93aea244327/embed" allowfullscreen webkitallowfullscreen mozallowfullscreen oallowfullscreen msallowfullscreen></iframe>

Table 1: Qualitative characterization of the envelope surface at

	Variable		Regulations	Source	Coverage
Year construction	(i) Built before 1981		-	Cadastre	National (Spain)
	(ii) Built between 1981 - 2007		NBE-CT-79 (Ministerio de Obras Públicas y Urbanismo 1979)		
	(iii) Built between 2008-2014		CTE-DB-HE (Ministerio de Vivienda 2006)		
	(iv) Built after 2015		CTE-DB-HE (Ministerio de Fomento 2013)		
Urban Morphology (as per Cadastre)	(Ca) Slab		RD 1020/1993 (BOE 1993)	Cadastre	
	(Cb) Perimeter block				
	(Cc) Detached house				
	(Cd) Terraced house				
Urban Morphology (as per Barcelona Metropolitan Area Master Plan)	(S) Slab	(S1) Grouped		Urban Master plan (Crosas 2015)	Specific urban area (Barcelona Metropolitan Area)
		(S2) Aligned			
		(S3) Disaggregated			
	(P) Perimeter block	(P1) Axial			
		(P2) Irregular			
		(P3) Regular			
		(P4) Cerdà			
	(H) Historical	(H1) Centre			
		(H2) Suburban			
	(SF) Single Family	(SF1) Row			
		(SF2) Irregular			
		(SF3) Mixed			
		(SF4) Regular			
		(SF5) Rustic			

Table 2: Relationships between urban morphology variables based

Source	Main categories		Sub categories	Main categories		Source
Cadastre	Multi-family	(Ca) Slab	(S1) Grouped	(S) Slab	Multi-family	AMB (Barcelona Metropolitan Area Master Plan)
			(S2) Aligned			
			(S3) Disaggregated			
		(Cb) Perimeter block	(P1) Axial	(P) Perimeter block		
			(P2) Irregular			
			(P3) Regular			
			(P4) Cerdà			
			(H1) Old town	(H) Historical		
			(H2) Suburban growth			
	Single-family	(Cd) Terraced house	(SF1) Terraced	(SF) Single-family	Single-family	
		(Cc) Detached house	(SF2) Irregular			
			(SF3) Mixed			
			(SF4) Regular			
	Rustic		(SF5) Rustic			

Table 3: Main assumptions of the study

GIS assumptions	Inventory data		Reference
Height between floors	3 metres		(IDAE 2012)
Hollows surface	Multi-family urban morphologies S1, S2, S3, P1, P2, P3, P4, H1, H2	30%	(Rodríguez-Soria et al. 2015)
	Single-family urban morphologies SF1	19%	
	Single-family urban morphologies SF3	18%	
	Single-family urban morphologies SF2, SF4, SF5	15%	
LCA assumptions			**Reference**
Transmittance values	See Table 4 in detail		(IDAE 2012)
The lifespan of buildings	50 years		(Monteiro & Freire 2012; Sharma et al. 2011; Sartori & Hestnes 2007)
The distance for transport from factory to the building location	100 km		(Sanjuan-Delmás et al. 2014; Zabalza Bribián et al. 2011; Oliver-Solà et al. 2009)

Table 4: Transmittance values for façades and roofs based on the

	Variable	U estimated (W/m²K)	U objective (W/m²K)
Façades	Built before 1981	3.00	0.29
	Built between 1981 - 2007	1.80	
	Built between 2008-2014	0.73	
Roofs	Built before 1981 – Flat	2.50	0.23
	Built before 1981 – Sloping	3.80	
	Built between 1981 - 2007	1.40	
	Built between 2008-2014	0.41	
Source		(IDAE 2012)	(Ministerio de Fomento 2013)

Table 5: Declared unit (kg) of each façade system required to pr

			Unit per m²					
Geographic location	U objective (W/m²K) (Climate zone "C")		0.29					
Year of construction	Period		before 1981		1981-2007		2008-2014	
	U estimated (W/m²K) (Climate zone "C")		3.00		1.80		0.73	
Thermal insulation type	Material		**EPS**	**Cork**	**EPS**	**Cork**	**EPS**	**Cork**
	Thermal conductivity (λ) (W/m K)		0.035	0.042	0.035	0.042	0.035	0.042
	Density (kg/m³)		35.00	171.00	35.00	171.00	35.00	171.00
Façade system	ETICS	U refurbishment (W/m² K)	0.33	0.33	0.35	0.35	0.49	0.49
		Thickness (m)	0.11	0.13	0.10	0.12	0.07	0.09
		Weight (Kg)	**3.75**	**22.00**	**3.48**	**20.41**	**2.48**	**14.56**
	Ventilated façade	U refurbishment (W/m² K)	0.34	0.34	0.36	0.36	0.51	0.51
		Thickness (m)	0.10	0.13	0.10	0.12	0.07	0.08
		Weight (Kg)	**3.66**	**21.44**	**3.38**	**19.84**	**2.39**	**13.99**
	Internal insulation façade	U refurbishment (W/m² K)	0.34	0.34	0.37	0.37	0.53	0,53
		Thickness (m)	0.10	0.12	0.09	0.11	0.07	0.08
		Weight (Kg)	**3.58**	**21.01**	**3.31**	**19.41**	**2.31**	**13.56**

Table 6: Declared unit (kg) of each roof system required to prov

			Unit per m²					
Geographic location	U objective (W/m²K) (Climate zone "C")		0.23					
Year of construction	Period		before 1981		1981-2007		2008-2014	
	U estimated (W/m²K) (Climate zone "C")		2.5 (Flat) / 3.80 (Sloping)		1.40		0.41	
Thermal insulation type	Material		**EPS**	**Cork**	**EPS**	**Cork**	**EPS**	**Cork**
	Thermal conductivity (λ) (W/m K)		0.035	0.042	0.035	0.042	0.035	0.042
	Density (kg/m³)		35.00	171.00	35.00	171.00	35.00	171.00
Roof system	Flat roof	U refurbishment (W/m² K)	0.26	0.26	0.28	0.28	0.54	0.54
		Thickness (m)	0.14	0.16	0.12	0.15	0.06	0.08
		Weight (Kg)	**4.75**	**27.82**	**4.36**	**25.57**	**2.25**	**13.18**
	Sloping roof	U refurbishment (W/m² K)	0.25	0.25	0.28	0.28	0.54	0.54
		Thickness (m)	0.14	0.17	0.13	0.15	0.06	0.08
		Weight (Kg)	**4.93**	**28.91**	**4.38**	**25.67**	**2.27**	**13.28**
	Sloping ventilated roof	U refurbishment (W/m² K)	0.26	0.26	0.29	0.29	0.58	0.58
		Thickness (m)	0.14	0.16	0.12	0.15	0.06	0.07
		Weight (Kg)	**4.80**	**28.12**	**4.24**	**24.88**	**2.13**	**12.49**

Table 7: Global environmental implications of improving the ener

		GWP (kg CO_2 eq.)		Biogenic GWP (kg CO_2 eq.)		EE (MJ)	
		EPS	Cork	EPS	Cork	EPS	Cork
Façade	ETICS	2.27E+09	3.80E+09	2.27E+09	9.58E+08	3.68E+10	5.65E+10
	VF	2.48E+09	3.97E+09	2.48E+09	1.20E+09	6.09E+10	8.01E+10
	IIF	2.65E+09	4.12E+09	2.65E+09	1.41E+09	4.87E+10	6.76E+10
Difference	Absolute	1.85E+09		1.70E+09		4.33E+10	
	Relative	182%		277%		218%	
Roof	FR	8.74E+08	2.00E+09	8.74E+08	-8.01E+07	2.40E+10	3.84E+10
	SR	2.96E+09	4.12E+09	-1.43E+08	-1.12E+09	9.98E+10	1.15E+11
	SVR	2.39E+09	3.51E+09	1.60E+08	-7.93E+08	1.31E+11	1.45E+11
Difference	Absolute	3.24E+09		1.99E+09		1.21E+11	
	Relative	471%		78%		607%	
				max		min	
Façade – roof Combination	Most recommended combination	3.14E+09	ETICS EPS - FR EPS	-1.62E+08	ETICS Cork - SR Cork	6.07E+10	ETICS EPS - FR EPS
	Least recommended combination	8.24E+09	IIF Cork - SR Cork	3.53E+09	IIF EPS - FR EPS	2.26E+11	VF Cork - SVR Cork
Difference	Absolute	5.10E+09		3.69E+09		1.65E+11	

Figure 1: Schematic diagram of the proposed methodology

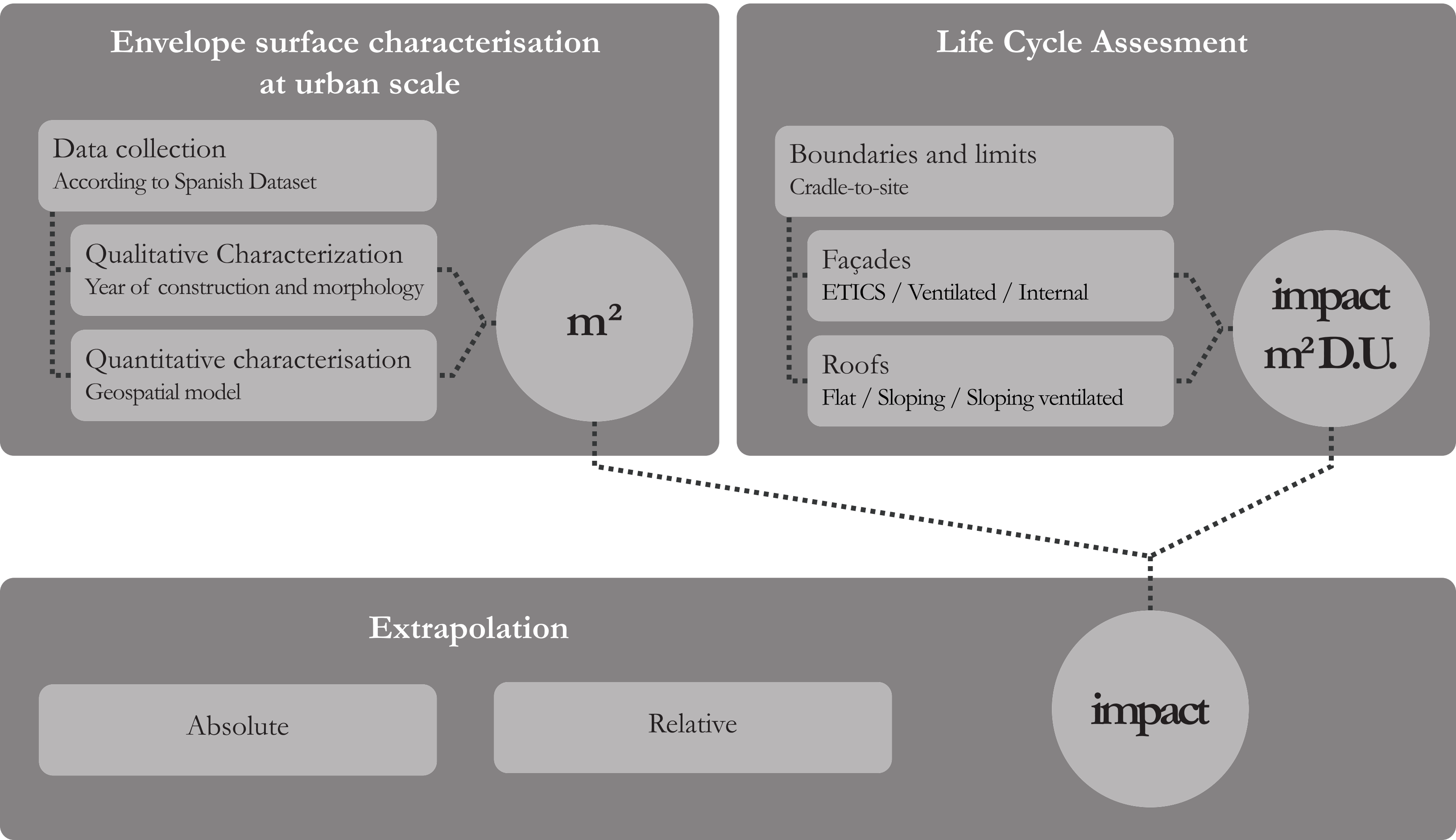


Figure 2: Existing urban morphologies in the Barcelona metropoli

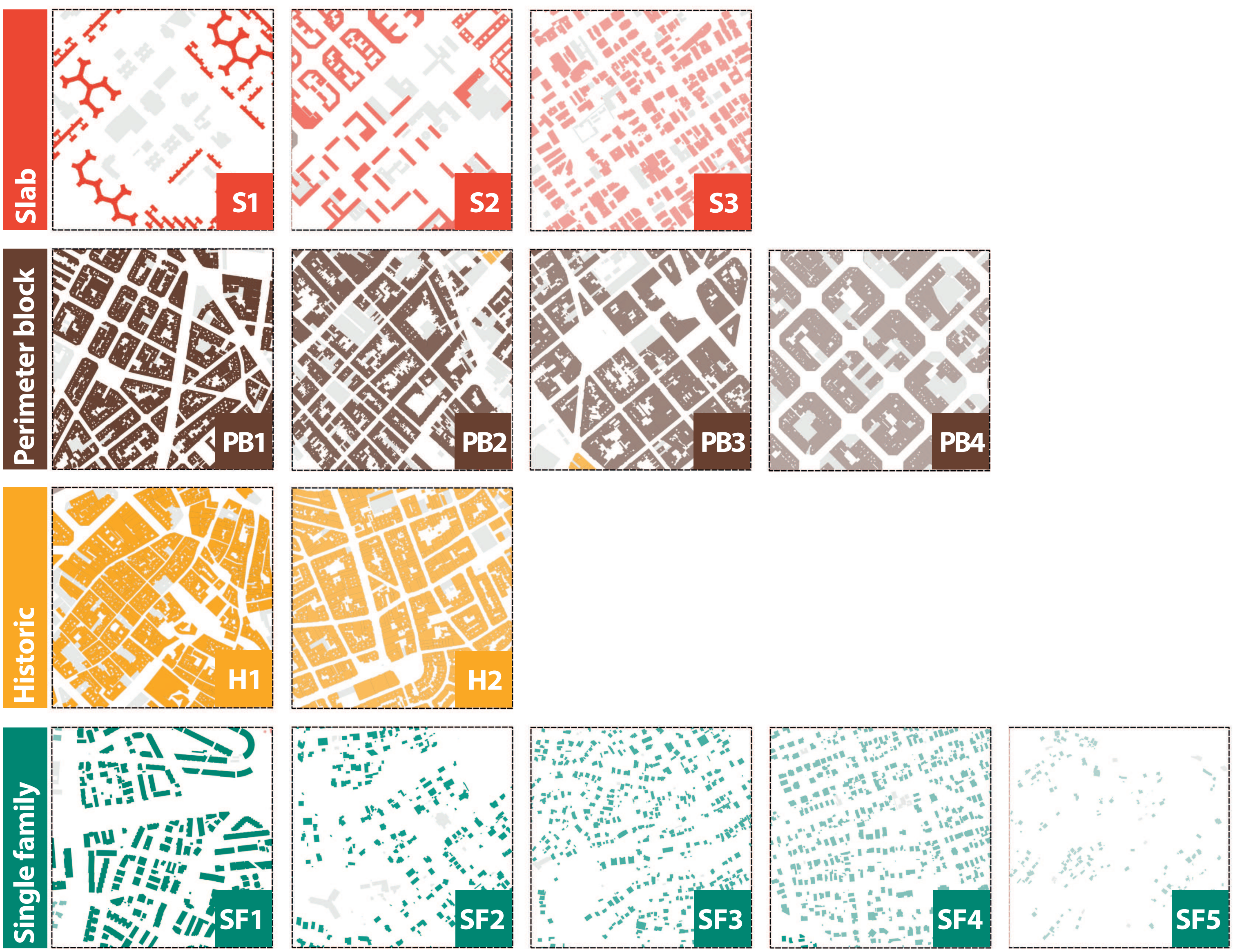
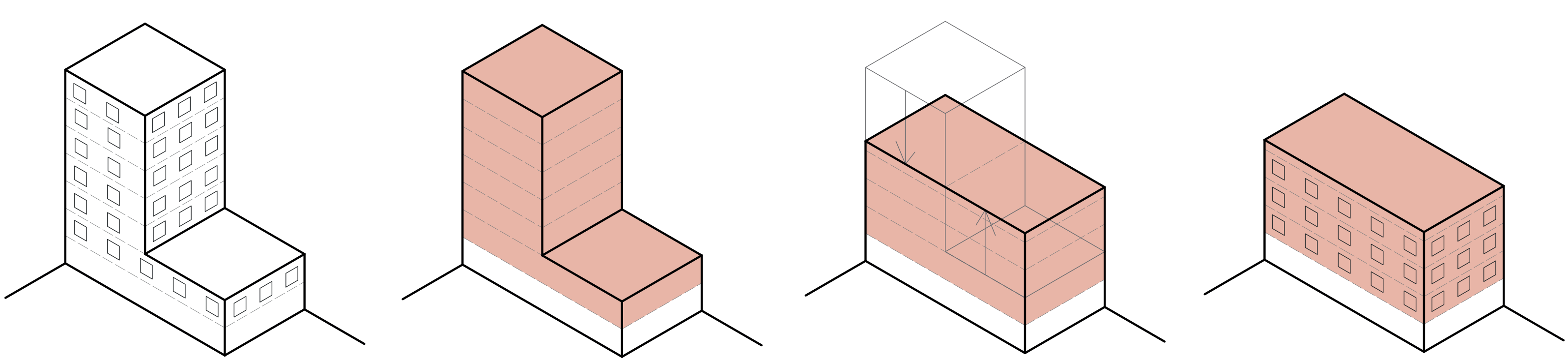


Figure 3: Schematic diagram of the process of obtaining the geos

Phase 1	Phase 2	Phase 3	Phase 4
Real building	**Gross living Building**	**Simplified gross living building**	**Simpflified net living building**



Gross floor area	Gross living area = G.L.A. m^2	Gross living area = G.L.A.’ m^2	Net living area = N.L.A.’ m^2
Coverage = C m^2	Coverage = C m^2	Coverage = C m^2	Coverage = C m^2
Height	Heated Height = H	Heated Height index = H’	Heated Height index = H’

Figure 8: Environmental results in terms of GWP, biogenic GWP an

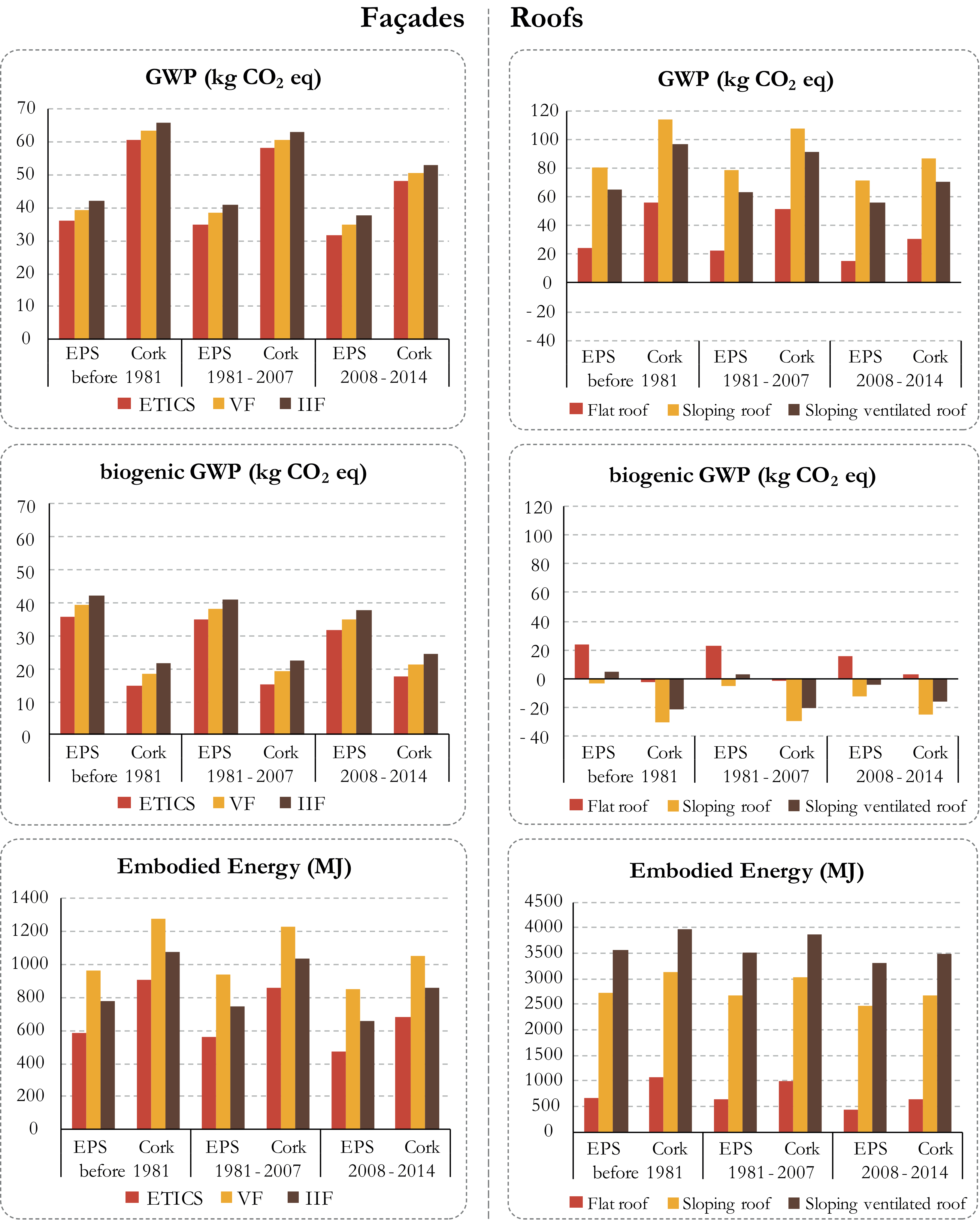


Figure 9: Absolute extrapolation maps. The recommended GWP scena

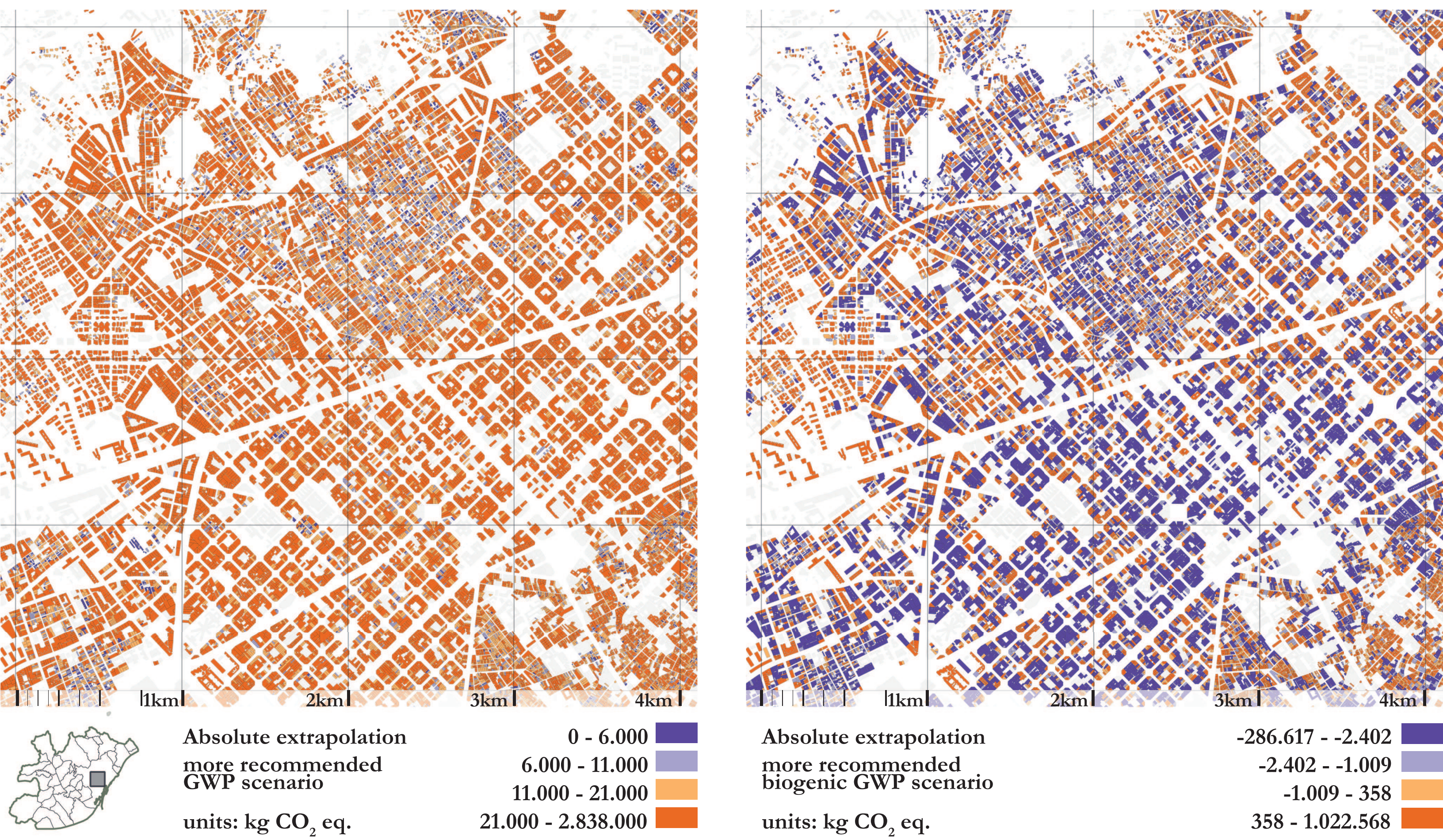


Figure 10: Relationship between the envelope surface and number

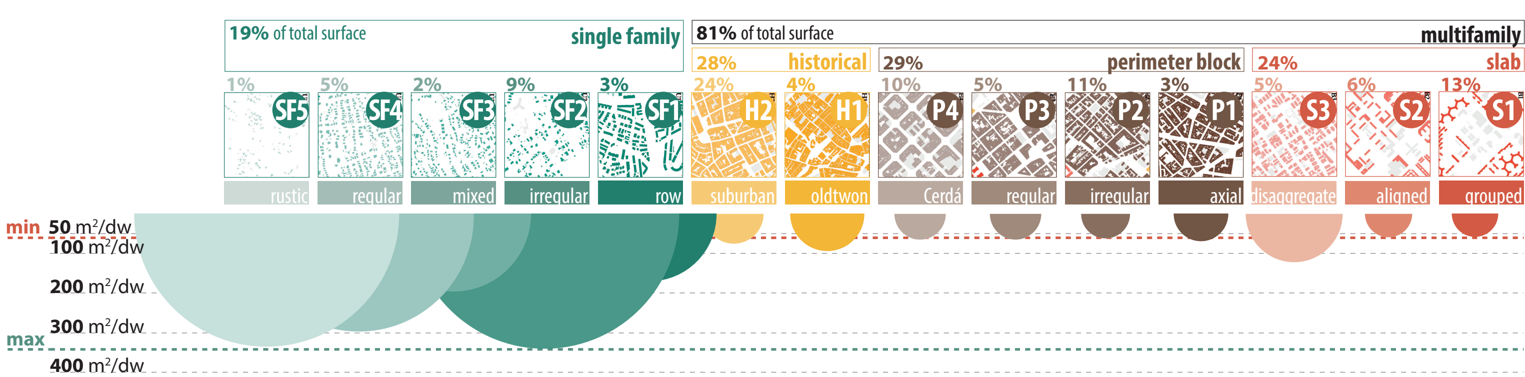


Figure 11: Relative extrapolation maps. The recommended GWP scen