Inventory of the existing residential building stock for the purpose of environmental benchmarking

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Abstract. The current renovation rate in Belgium is less than 1% and should be increased to 2.5% to reach the European targets to reduce the GHG emissions by 2050. There is a need to rapidly increase the renovation rate and at the same time guarantee that these renovations reduce the environmental impact on our planet. In order to define environmental benchmarks for existing buildings and their renovation targets, a better understanding of the existing building stock is needed. In this paper, the approach used to model the existing building stock is presented for the specific case of Leuven. The methodological steps, challenges and data gaps are presented in detail. The proposed building stock model uses GIS data in order to gain insights in the geospatial distribution of the impacts of the stock. These spatial maps moreover allow to clearly visualise the impacts which can improve communication and contribute to policy actions.

1. Introduction  
The construction sector is responsible for 30% of the resources used in Europe as well as for 40% of the energy used and 36% of greenhouse gas (GHG) emissions.[1] According to the European Commission, cities are responsible for the largest share of most environmental impacts, but provide also major opportunities for improvement.[2] Cities hence play a crucial role in the aim to move towards a more sustainable built environment.[3] The European Union targets to reduce the GHG emissions by 2050 with 80% to 95% compared to 1990.[4] Likewise, Flanders wants to evolve to low carbon, sustainable, reliable and affordable energy sources to achieve this European target.[5] The building sector has in many aspects already moved forward to a sustainable transition path as innovative products and new skills have been developed and the energy performance of new buildings has improved to a great extent. Nevertheless, the existing building stock in Europe, and likewise in Flanders, is still using a lot of energy and the refurbishment rate is too low to be able to reach the GHG emission reduction goals. Belgium aims at increasing the current (2016) annual renovation rate of less than 1% to 2.5%[6] through the ‘Renovatiepact’. The Renovatiepact consists of various actions: increasing the renovation level of each building, gathering energy related information of each building and formulating renovation recommendations for each building. It is clear that a building-specific approach needs to be followed, mostly because of the highly privatized and hence very diverse building stock of Belgium.

This paper presents a methodology for a part of the inventory of the existing residential building stock in order to model its environmental impacts. The inventory focuses both on the geometry and energy performance of the buildings in order to have insights in the operational energy use of the buildings and to have all data required for a life cycle assessment of the buildings and renovation
interventions. This forms the base of defining environmental benchmarks for the renovation of residential buildings in future research.

Building stock modelling typically uses either a top-down or bottom-up approach. In top-down methods the complete building stock is described at an aggregated level based on input-output modelling (urban metabolism). Bottom-up methods start with a set of individual stock components, buildings or building elements for example, and upscale these components to the complete stock level.[7] In this research the bottom-up approach will be used because this approach allows to identify the root causes of phenomena at stock level. So, this inventory consists of a detailed inventory at the individual building level which is then scaled up to the city level.

The methodology is elaborated for the city of Leuven which is selected as a case study due to its experience in carbon footprinting[8] and hence there is a relatively good data availability.[2] Leuven moreover has its own ambitious target to renovate 1000 buildings each year by 2030.[9] Which makes it an interesting case study. Finally, the carbon footprint of Leuven was previously calculated through a top-down approach[8] which will allow to (partially) validate our proposed bottom-up model. Although the research focuses on Leuven, the method is also applicable to other cities.

2. Methodology

2.1. Bottom-up approach

Two building stock aggregation models can be used in bottom-up approaches: the archetype and the building-by-building approach. The archetype approach uses reference buildings according to the characteristics of the building stock and represents the full stock based on these reference buildings. The building-by-building approach consists of modelling each building of the stock or a sample of the building stock in case of large building stocks (e.g. national level).[7]

For the goals of our study, the inventory of the existing building stock should be as detailed as possible in order to define an accurate environmental benchmark for the renovation of existing buildings. For this reason, the building-by-building approach is preferred over the archetype approach. Nevertheless, lacking building-by-building data are filled with proxy data from archetypes.

For the inventory of the building stock, data about the geometry, the location, the function and the energy performance are needed. The search for this data for each building of the building stock of the city of Leuven revealed that most of the data is directly available or can be derived in a sufficiently accurate way. Publically available Geographic Information System (GIS) data from Flanders[10] include the following information required for the stock model: ground floor area of each building, perimeter of each building and ridge hedge of each building. In addition, for the specific case of Leuven, more extended GIS data are available: construction year, building type, roof type, function of the building, number of floors and number of residential units. Energy consumption data (electricity and gas) are available from the energy distribution network operator (Fluvius) at street level together with the number of gas connection points per street. An overview of the available data is provided in table 1, indicating also which data are not directly available but can be derived from the other data. An important data gap for each of the buildings in the building stock is the thermal insulation level of the building envelope. For this data gap, proxies from the archetypes will be used in a next step of the research. The archetypes are defined based on the reference buildings of the IEE-Tabula project. In the subsequent sections the inventory of the various data is described in more detail.
Table 1 Overview of the sources of the data inventory.

| Data                        | Available? | Data Source                          | Discussed in section |
|-----------------------------|------------|--------------------------------------|----------------------|
| Geospatial information      | yes        | dataset Leuven/Flanders             | 2.2                  |
| Ground floor surface        | yes        | dataset Flanders                    | 2.3                  |
| Perimeter                   | yes        | dataset Flanders                    | 2.3                  |
| Wall surfaces               | can be derived | dataset Flanders            | 2.3                  |
| Window surfaces             | no         | -                                   | -                    |
| Ridge height                | yes        | dataset Flanders                    | 2.3                  |
| Roof type                   | partial    | dataset Leuven                      | 2.7.1                |
| Building typology           | can be derived | dataset Leuven            | 2.5                  |
| Construction year           | partial    | dataset Leuven                      | 2.7.2                |
| Energy consumption (at street level) | yes | Fluvius (energy network operator) | 2.4                  |
| Function                    | yes        | dataset Leuven                      | 2.3                  |
| Number of floors            | yes        | dataset Leuven                      | 2.3                  |
| Number of residential units | yes        | dataset Leuven                      | 2.3                  |
| U-values                    | no         | IEE-Tabula project                 | 3                    |

2.2. GIS
The building stock model developed for the city of Leuven is based on GIS data in order to gain insight in the geospatial distribution of the buildings and their current energy performance and environmental impact. Such geospatial inventory data have various benefits: these allow to identify priority neighbourhoods for renovation, allow to define archetypes for environmental benchmarking of existing buildings, allow to visualise results in a clear way and allow to model effects of future scenarios.[7] Mapping the energy consumption or life cycle environmental impact of buildings results in clear visualisations can be very helpful for public administrators regarding their policy plans[11] and to improve the communication and strengthen their decisions according to their policy.

The building-by-building data in our GIS stock model are a result of the combination of the GIS data from Flanders and the GIS data from Leuven. The building datasets of Flanders include the address and geometry data while the building datasets of Leuven contain the construction year, roof type and building function(s). The combination of these data are presented in the sections 2.3 to 2.7.

2.3. Data collection
The geometric data needed for each building in the stock model is partly provided by the open data of the Flemish region, and partly by the city of Leuven (not publicly available). The datasets from Leuven and the Flemish region are GIS data. With these data the building stock can be modelled regarding the area of the ground floor, the perimeter of the building, the building height, address, the number of floors, the number of residential units, the construction year, the building function and the roof type. These data is mostly available for 96,7% to 100% of the buildings, except for the number of residential units where the data availability is only 22% and for the construction year with an availability of 60%. This means that for 13,619 buildings the construction year is lacking. In section 2.7 it is described how these lacking data are filled. The area of the walls are unknown, but based on the perimeter of the building, the roof type and the building height, estimations can be made. In future, the assumptions can be replaced by real data when these become available in the GIS datasets of the city or region, or may be filled with real building-by-building data based on measurements of specific projects.

2.4. Energy consumption at street level
With the Fluvius data regarding gas consumption per street and number of gas connections per street, the gas consumption of each building in the stock can be estimated. A first estimate of the average gas consumption per square meter floor area of the residential building stock in 2017 is calculated and presented in figure 1. This average is calculated by dividing the total gas energy consumption of a street by the total area of the buildings of that street. This calculation does not take the energy performance of the buildings into account, so these values are street averages, not building specific values. In future the
allocation per building can be improved when the insulation of the buildings is known. This first estimate however already reveals where the largest energy consumers are located and hence allows to identify the energy problematic neighbourhoods of a city.

![Figure 1](image1.png)

**Figure 1** Overview of the average gross gas energy consumption of the residential buildings of each street per square meter in 2017 in Leuven (kWh/(m²·year))

2.5. **Building typology**

The GIS data obtained from Leuven do not provide information about the building type. It is hence not clear if a building is a detached building, terraced building, semi-detached building or apartment. This information is however important to calculate the surface of the building envelope and the related energy transmission losses, since the energy transfer is different for separating walls and exterior walls.

To define the building type for each of the buildings in the stock model, the following approach is used. For each GIS dataset (building), the GIS software allows to define if the building (polygon) is attached to one or more neighbouring buildings (polygons). These results are combined with the available information regarding the building function (apartments and single-family houses) and the information in the dataset regarding the fact if it is a main building or an annex building. Annex buildings (e.g. garages) have been excluded from the datasets in order to ensure that two buildings with two garages in between (figure 2) are considered as detached instead of terraced buildings.

![Figure 2](image2.png)

**Figure 2** By excluding annex buildings (e.g. garages) from the GIS data, the main buildings (dark grey) are classified as detached houses.
The distribution of derived building types for Leuven is visualised in figure 3. By visualising buildings with similar properties, it becomes clear that the majority of the residential buildings are terraced buildings (13,521 (42.3%)), and the minority are apartment buildings (2,142 (6.7%)). The detached and semi-detached buildings are respectively 7,564 (23.7%) and 8,743 (27.3%) buildings. Further, in the visualisation it becomes clear that almost half of the terraced houses and apartment buildings are situated inside the city centre of Leuven, for the (semi)-detached houses only 20% are situated inside the city centre. So the distributions inside and outside the city centre are clearly different.

2.6. Coupling of GIS datasets from different sources

The datasets provided by Leuven and by Flanders were not compatible. The FME (Feature Manipulation Engine) software is a platform for data integration specialised in spatial data and has been used to couple both GIS datasets in our study. The following matching procedure is used (figure 4): for each polygon the coordinates of a central point are defined. In the FME software, the coordinates of the central points of both datasets are matched and the datasets are combined based on these matching coordinates.
2.7. Data gaps

As mentioned in section 2.3, for some buildings the roof type and/or construction year is lacking in the GIS data from of Leuven. These data had to be filled in to make a complete building stock model. The data gaps are filled in based on statistical data regarding construction years and roof types of buildings in Leuven for which these data are known.

2.7.1. Roof types

Firstly, the buildings with undefined roof types are identified. Secondly, for each building type, the percentage of flat roofs and pitched roofs is calculated based on the dataset of Leuven. Thirdly, each building with an unknown roof type is assigned a roof type according to the percentages calculated. The unknown data of roof types are geospatially randomly allocated to the buildings belonging to the specific category.

Table 2 Distribution of the roof types and construction years of the detached buildings in Leuven.

| Construction year | Total known | % Total known | % Distribution of known | Distribution of unknown |
|-------------------|-------------|---------------|-------------------------|-------------------------|
| <1945             |             |               |                         |                         |
| Flat roof         | 57          | 21%           | 10%                     | 9%                      |
| Pitched roof      | 86          | 32%           | 10%                     | 39%                     |
| Total             | 143         | 53%           | 20%                     | 48%                     |
| 1946-1970         |             |               |                         |                         |
| Flat roof         | 248         | 62%           | 36%                     | 66%                     |
| Pitched roof      | 1720        | 38%           | 37%                     | 37%                     |
| Total             | 1968        | 100%          | 73%                     | 73%                     |
| 1971-1990         |             |               |                         |                         |
| Flat roof         | 87          | 18%           | 32%                     | 32%                     |
| Pitched roof      | 1501        | 32%           | 32%                     | 32%                     |
| Total             | 1588        | 100%          | 64%                     | 64%                     |
| 1991-2005         |             |               |                         |                         |
| Flat roof         | 65          | 14%           | 10%                     | 10%                     |
| Pitched roof      | 888         | 18%           | 15%                     | 15%                     |
| Total             | 953         | 100%          | 29%                     | 29%                     |
| 2006-2011         |             |               |                         |                         |
| Flat roof         | 28          | 6%            | 4%                      | 4%                      |
| Pitched roof      | 29          | 6%            | 1%                      | 1%                      |
| Total             | 57          | 100%          | 7%                      | 7%                      |
| >2012             |             |               |                         |                         |
| Flat roof         | 358         | 73%           | 8%                      | 8%                      |
| Pitched roof      | 1812        | 27%           | 1%                      | 1%                      |
| Total             | 2170        | 100%          | 8%                      | 8%                      |

2.7.2. Construction years

Using a similar approach, the unknown construction years are defined. Of the 7,564 detached buildings, the construction year is unknown for 2,210 buildings (41%) (see table 2 for the detached houses). Firstly, the buildings with an unknown construction year are identified (2,210). Secondly, table 2 is set up for each of the building types, in this table all the buildings with a known construction year (5,354) are counted according to their construction year and roof type. For example, of all the 7,564 detached houses, 67 have flat roofs and are built before 1945. This means that for the period before 1945, only 12.41% of the detached houses have flat roofs. In a next step is defined how many detached houses are constructed in each construction period, for instance 10% of the detached houses is built before 1945. With these numbers, the distribution of the known construction years can be calculated according to their roof type. For example, 19% of the detached houses with pitched roofs are built in 1991-2005. When these percentages are multiplied with the number of buildings with an unknown construction year, the number of buildings for each construction period are known. So, table 2 shows that 183 buildings with an unknown construction year and a pitched roof have been assigned the construction period ‘before 1945’. This allocation of construction years is done in a geospatial random way. These construction periods are in accordance with the construction period of the IEE-Tabula project: before 1945, 1946-1970, 1971-1990, 1991-2005, 2006-2011 and after 2012.\(^{[12]}\)
3. Conclusions and future outlook

The building stock model developed in our study combines a building-by-building and an archetype approach to make a model that includes all data needed to model the energy performance, material amounts and environmental impact of the buildings, with information on their geospatial location. The geometric data of all buildings in the stock is mainly based on building-by-building data, either directly retrieved from GIS datasets from the city or the region or calculated based on other data from the GIS datasets. For the buildings where geometric information is lacking, statistical data were used to fill the data gaps. The FME software is used to couple the various GIS data sources.

Although the research focuses on the city of Leuven, the used approach to model building stocks is also applicable to other cities. The method proposed can however only be used if GIS data of (part of) a city are available. GIS data of building stocks are available for a growing number of Flemish cities and it is expected that in the near future the majority of the cities will have such GIS model.[13] In Flanders these data are combined in the GRB-tool (Grootschalig Referentie Bestand) and are publically available. The European Commission furthermore aims to create a European spatial data infrastructure with the tool INSPIRE (Infrastructure for Spatial Information in the European Community) to provide public sector data in a practical way.[14,15]

In a next step of the research, the geometry characteristics will be combined with energy performance characteristics. When the U-values of the construction elements are known, the energy losses of the buildings can be estimated, environmental benchmarks defined and renovation strategies proposed. Furthermore, this will allow to identify the main drivers of the total energy consumption of the building stock and consequently efficiently reduce the energy use of the building stock. The collection of the U-values is less obvious because of privacy issues. These data are not available for the various buildings in the stock and hence a building-by-building approach is not possible. The archetype approach will be used differentiating in U-value for the various elements of the building envelope per construction period, roof type and building type. Based on the statistical distribution of the building types and construction periods of each building in the stock, the representative values of the archetypes can be linked to the buildings in the stock. And based on these proposed U-values, the energy consumption can be calculated at the level of a building or for the whole building stock. Further investigation is needed on how renovations in the past can be included in the model. Potentially, the gas consumption at street level and at municipality level might be used to validate the estimated U-values and to correct these based on statistical data on renovation measures have already been done in the past. For the U-values of representative buildings, the IEE-Tabula project might be helpful. In the Tabula project, U-values are defined for different construction periods and building types.[12] Combining the U-values and the corresponding energy consumption with the geometric building stock model, will result in a complete building stock model including spatial data (SBSM – Spatial Building Stock Modelling) where hotspots and improvement potentials can be defined for each neighbourhood of the model.[17]

The building stock model that is under development will allow to identify how future renovation measures will allow to reduce the energy consumption of the stock and its implications regarding the life cycle environmental impact of each building in the stock as well as for the stock as a whole. As the geometry of the building stock and the construction period of the buildings are collected, an inventory of the materials in the building stock can also be made and consequently the environmental impact of the stock can be assessed. In Europe, life cycle assessment (LCA) is more and more integrated in building practice to reduce the environmental impact of buildings.[17,18] As LCA is mostly used in comparative studies, benchmarks should be defined so that targets can be set to support policy making and tracking of the achievement of policy goals. In order to allow for defining such environmental benchmarks for existing buildings and their renovation, this paper presents how an inventory of the current building stock can be made that will allow to gain insight in their environmental impact.
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