Development of environmental benchmarks for the Belgian residential building stock

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Abstract. Over recent years Belgium has made meaningful effort in adopting Life Cycle Assessment (LCA) in building practice to improve building environmental performance. Today, architects can compare the environmental performance of different building designs with an online calculation tool that incorporates the national LCA method. However, they are still lacking environmental benchmarks to position themselves within current building practice. Furthermore, such benchmarks play an important role in the development of environmental targets in building regulation. In this research, benchmarks are defined for new residential buildings in Belgium. A bottom-up approach is followed consisting of a statistical analysis of reference buildings to define limit, reference and best practice values. The buildings are based on four representative typologies for Belgium, ranging from detached houses to apartments. Different variants are assessed including various energy performance levels and construction types (solid versus timber). The buildings’ life cycle impacts are calculated including the embodied (material) and operational (energy) impacts. Results are reported both for an aggregated environmental single-score and for Global Warming Potential (GWP). The calculated reference values for life cycle and embodied GWP (20 and 7 kgCO₂eq/m²·year) are comparable to existing benchmarks in the literature. The results further highlight that building compactness provides the largest impact reduction, followed by construction type. Finally, limitations are discussed and recommendations are formulated for developing future benchmarks.

Keywords: Residential buildings, Life Cycle Assessment, bottom-up benchmarks, embodied impacts, operational impacts

1. Introduction

1.1. Relevance of environmental benchmarks for buildings

Building construction and operation are responsible for significant amounts of energy and resource consumption, resulting in high quantities of greenhouse gas (GHG) emissions and overall pollution of
land, air and water. In 2020 the building sector was responsible for 36% of global final energy use and 37% of energy-related carbon dioxide (CO₂) emissions [1]. Global awareness of these major impacts has led to the development of reduction targets and legislation to limit buildings’ impacts.

Building energy efficiency is high on the agenda in many countries worldwide [1]. Although it is positive that countries aim to reduce their building operational impacts, the impact of construction materials is currently under-addressed [1]. It appears that while buildings have become more energy efficient and operational impacts have decreased, the embodied impacts and GHG emissions, i.e. related to building materials, have increased both in relative and absolute terms [1–9]. Hence, it is essential that building environmental impacts are considered from a full life cycle perspective.

The Life Cycle Assessment (LCA) methodology enables the assessment of a building’s environmental impact across its full life and it is increasingly integrated in building practice. In the context of Belgium, a national LCA method (Environmental profile of buildings) was developed to harmonise the environmental impact assessment of building elements and buildings as a whole [10]. The method is in line with the current European LCA standards and methods EN 15804+A2 and EN 15978 [11,12] and is adapted to the Belgian context in terms of data and scenarios. Building on this LCA method, a web-based calculation tool called TOTEM (Tool to Optimize the Total Environmental impact of Materials) was launched in 2018 [13]. The tool enables the evaluation of the environmental performance of different building designs, but lacks reference values to benchmark the environmental performance in a broader context. Such benchmarks would not only allow building professionals to position themselves in the market, but are also essential to support policy makers in defining national targets for buildings and setting up environmental regulations.

1.2. Existing benchmarks in building practice

As mentioned, the measures to reduce building environmental impact have mainly aimed at improving building energy efficiency. In fact, among these measures are several types of operational energy use benchmarks. In Europe, the Energy Performance of Buildings Directive (EPBD) requires all EU Member States to implement energy benchmarks in their national regulation [14]. In contrast, benchmarks focusing on full life cycle impacts are only recently emerging.

Over the past years, several life cycle and/or embodied benchmarking systems have emerged in Europe. Generally, these systems have a strong emphasis on GHG emissions. As of 2022, France implemented mandatory CO₂eq limit values for both embodied and operational impacts of buildings [15]. Denmark developed voluntary sustainability classes [16] and defined gradually strengthening life cycle CO₂eq limit values that will be enforced in 2023 [17]. Norway, Sweden and Finland are developing similar strategies [18,19].

Although several European countries have developed regulations or guidelines that address embodied carbon emissions of buildings, a comprehensive policy at EU-level is currently lacking. Recently, the importance of addressing whole-life carbon (WLC) emissions at the EU-level has also been highlighted. The European Commission specifically states in its Renovation Wave strategy that it aims to reduce carbon emissions over the building’s full life cycle [20]. This full life cycle approach to energy renovations is required to ensure that emissions are not shifted from operational to embodied stages. The current updating of EU policy and legislation regarding building performance is considered as an opportunity to integrate WLC in a common framework. Such EU-level framework will be beneficial for comparability and monitoring of the overall progress across the different Member States [21].

The problem is that too strong a focus on carbon emission reduction diverts attention from other environmental impacts. To avoid this burden shifting, it is suggested that benchmarks should consider multiple impact indicators [22]. However, such systems are currently less prevalent [23]. For example, the Netherlands are the only country with a mandatory limit value for an aggregated environmental score, which includes eleven impact indicators expressed as one environmental cost [24]. Other benchmarking systems that consider multiple indicators are found in certification systems such as DGNB [25], BREEAM [26], LEED [27] and Active House [28].
1.3. Methodological aspects to developing benchmarks for buildings

Based on the benchmark aim and the data source, there exist two methodological approaches to derive benchmarks. The first approach is a top-down approach which defines long-term target values for buildings with the aim of fulfilling global environmental goals or policy targets. The second one is a bottom-up approach and is currently most prevalent in building practice. Bottom-up benchmarks are considered achievable with current construction practice and are derived from a statistical analysis of the building stock, by evaluating either representative real buildings or generic archetypes [23].

The benchmarks derived with these approaches can be categorised into four types depending on their performance level [29]: limit, reference, best practice and target values. Target values are usually derived top-down, e.g. from policy targets or theoretical optima, and are considered as values to be reached in the long-term. Limit, reference and best-practice values are generally derived with the bottom-up approach and are considered feasible in the short-term. Limit values define the lowest acceptable performance in current practice. Reference values correspond to the state-of-the-art. Best practice values are in theory achievable with current technology and are obtained from experimental or demonstration projects.

Although target values are most useful to set policy targets for efficient impact reduction, they might not be achievable for every building project today [30]. Contrarily, the bottom-up benchmarks will not cause significant impact reduction, but can serve as a baseline for more ambitious benchmarks and support setting a strengthening path in time to reach target values in a feasible way over a longer period [30]. Therefore, it is recommended to combine both short-term and long-term benchmarks [23].

1.4. Objectives

This study aims to define environmental benchmarks that are representative for new Belgian buildings and serve as a reference for building stakeholders. Specifically, a bottom-up approach is used to derive benchmarks that can be achieved in current building practice. The focus is on residential buildings as these represent 83% of the current Belgian building stock [31]. The benchmarks are derived from different types of real residential buildings ranging from detached houses to apartments. For each building, different construction types and energy performance levels are evaluated. A statistical analysis is performed to derive limit (90th percentile), reference (median) and best practice (10th percentile) values for the set of building variants. As a validation step, the obtained preliminary set of benchmark values is compared to existing benchmarks in the literature. A top-down calculation is anticipated in future research.

2. Methods

2.1. LCA methodology

2.1.1. Goal and scope. To cover the diversity of the Belgian residential building stock, four types of representative buildings are selected: detached, semi-detached, terraced and apartment. The building models include the following building elements, according to the BB/SfB classification [32]: (13.)+ Floors on grade, (21.)+ External walls, (22.1)+ Load-bearing internal walls, (22.3)+ Non-load-bearing internal walls, (22.8)+ Party walls, (23.)+ Storey floors, (27.)+ Roofs, (31.) Windows and external doors, and (32.) Internal doors.

2.1.2. LCA modelling approach. To be in line with the Belgian context, the modelling of the buildings and the life cycle impact assessment are performed with the Belgian TOTEM tool. The modelling in TOTEM has a hierarchical structure: buildings consist of multiple building elements (e.g. floors, walls, windows); building elements consist of different components (e.g. masonry, insulation); and components consist of different materials, for which the background data are based on the ecoinvent database (version 3.6 at the time of writing) [33].
2.1.3. Functional unit. The functional unit (FU) is one square metre of gross floor area of a building, as this is the unit in which TOTEM results are expressed. Also, most of the currently existing benchmarks are expressed in m² floor area, although the definition of floor area can vary [23].

2.1.4. Reference study period. The reference study period is 60 years, as defined in the TOTEM tool. Although the average life span of buildings in Belgium is usually longer than 60 years, it is assumed that after 60 years most buildings undergo a thorough renovation leading to the demolition of many of the original materials [10].

2.1.5. System boundaries. The LCA is a cradle-to-grave assessment and includes stages both related to embodied and operational impacts. Specifically, all life cycle modules as defined in EN 15978 [11] are considered, with the exception of modules B1 (use), B3 (repair), B5 (refurbishment), B7 (operational water use), and D (benefits and loads beyond the system boundary).

2.1.6. Life cycle impact assessment. The LCA results are obtained by translating the life cycle inventory data to specific environmental impacts. The impacts are expressed in terms of the environmental indicators recommended by EN 15804+A2 [12]. Next to the individual impact indicators, TOTEM includes the calculation of an aggregated score expressed in millipoints per functional unit (mPt/FU). The aggregated score is obtained by the normalization and weighting of the individual impact indicators following the weighting approach developed in the context of the European Product Environmental Footprint (PEF) [34]. In this study, the benchmark values are calculated for the aggregated PEF score in order to cover a wide range of impact indicators. Furthermore, the results are reported separately for the global warming potential (GWP) indicator, which is relevant in the context of climate change policies.

Concerning GWP, biogenic carbon flows are assessed based on the so-called ‘-1/+1’ approach, as recommended by EN 15804+A2 [12]. In this approach, the uptake of biogenic CO₂ during biomass growth is reported as a negative emission (-1) in the production stage while the release is reported as a positive emission (+1) in the end-of-life stage [35].

2.2. Reference buildings

The reference buildings used in this study are based on cases from the SuFiQuaD (Sustainability, Financial and Quality evaluation of Dwelling Types) research project [36]. In this project, 16 dwellings representative for the Belgian residential building stock were defined. The dwellings are subdivided into four types (i.e. detached, semi-detached, terraced and apartment) and four construction periods (<1945, 1945-1970, 1971-1990 and 1991-2001) [36]. For this preliminary benchmark study, the geometry of the dwellings from the latest period, i.e. 1991-2001 are selected as representative geometries for new residential buildings. Table 1 shows the floor area and the quantities (e.g. m² or piece) of building elements for each dwelling. Note that for the apartment the quantities are reported for one housing unit instead of the whole building, shared spaces being allocated to the different housing units.

For the materialisation three different variants were assessed: one baseline materialisation representative for current Belgian construction practice and two variants in which either the construction type or the energy performance level is altered. The baseline materialisation comprises a solid construction of which the external building elements’ U-values are line with the maximum values from the Belgian EPB regulation of 2022 [37]. The first variant includes the same construction type as the baseline (i.e solid) but with a more ambitious energy performance level. Specifically, the external building elements are modelled so that their U-values are in line with the values recommended by the Belgian Passive House Platform [38]. For the second variant the same energy performance level as the baseline (i.e. EPB2022) is considered, but the construction type is changed to a timber frame construction. Applied to the four dwellings, this gives the 12 dwelling variants presented in Table 2.
Table 1. Dwelling characteristics.

|                      | Detached | Semi-detached | Terraced | Apartment |
|----------------------|----------|---------------|----------|-----------|
| Gross floor area [m²]| 123      | 144           | 200      | 143       |
| (13.)+ Floor on grade [m²] | 81      | 86            | 80       | 36        |
| (21.1)+ External wall [m²]| 103     | 104           | 87       | 74        |
| (22.1)+ Load-bearing internal wall [m²] | 53     | 42            | 38       | 44        |
| (22.3)+ Non-load-bearing internal wall [m²] | 86     | 48            | 69       | 78        |
| (22.8)+ Party wall [m²] | 0       | 65            | 126      | 12        |
| (23.1)+ Story floor [m²] | 78      | 60            | 61       | 151       |
| (23.2)+ Attic floor [m²] | 0      | 0             | 61       | 0         |
| (27.1)+ Flat roof [m²] | 0       | 23            | 16       | 40        |
| (27.2)+ Pitched roof [m²] | 81     | 64            | 64       | 0         |
| (31.1)+ Windows [m²] | 23      | 16            | 17       | 39        |
| (31.1)+ External doors [piece] | 1      | 2             | 1        | 0         |
| (31.1)+ Garage doors [piece] | 1     | 1             | 1        | 0         |
| (32.1)+ Internal doors [piece] | 9      | 7             | 8        | 7         |

Table 2. Overview of the 12 dwelling variants obtained by applying the three materialisation variants to the four dwelling types.

|                      | Solid construction | Timber construction |
|----------------------|--------------------|---------------------|
|                      | EPB                | Passive standard    |
|                      | EPB                | EPB                 |
| Detached house       | Detached_Solid_EPB | Detached_Solid_Passive |
|                      |                    | Detached_Timber_EPB |
| Semi-detached house  | Semidetached_Solid_EPB | Semidetached_Solid_Passive |
|                      | Semidetached_Timber_EPB |
| Terraced house       | Terraced_Solid_EPB | Terraced_Solid_Passive |
|                      | Terraced_Timber_EPB |
| Apartment            | Apartment_Solid_EPB | Apartment_Solid_Passive |
|                      | Apartment_Timber_EPB |

For the three materialisation variants, typical building elements from the TOTEM library are selected. Table 3 presents a simplified description of the composition of the building elements used in these variants. Table 4 shows the U-values of the external building elements selected in TOTEM.

Table 3. Description of the building elements’ compositions for solid and timber construction.

|                      | Solid construction | Timber construction |
|----------------------|--------------------|---------------------|
|                      | EPB                | Passive standard    |
|                      | EPB                | EPB                 |
| Walls                | Hollow brick walls | Hollow brick walls  |
| Floors and roofs     | Hollow concrete slab | Hollow concrete slab |
|                      | Joist and cross beams |
| Windows              | PVC frame, double glazing | PVC frame, triple glazing |
|                      | Wooden frame, double glazing |
### Table 4. U-value [W/m²K] of the different building elements applied.

|                | Solid construction | Timber construction |
|----------------|--------------------|---------------------|
|                | EPB                | Passive standard    | EPB     |
| External walls | 0.24               | 0.15                | 0.21    |
| Floor on grade | 0.24               | 0.15                | 0.20    |
| Roof - flat    | 0.22               | 0.14                | 0.22    |
| Roof - pitched | 0.24               | 0.17                | 0.24    |
| Windows        | 1.59               | 1.19                | 1.56    |
| External walls | 0.24               | 0.15                | 0.21    |
| Floor on grade | 0.24               | 0.15                | 0.20    |
| External doors |                    | 1.26                |         |
| Garage doors   |                    | 1.38                |         |

The impact of operational energy use in TOTEM is estimated based on the Equivalent Heating Degree Days (EHDD) method, taking into account both transmission and ventilation losses [10]. For the ventilation losses, a ventilation system without heat recovery and a default air infiltration rate of 12 m³/h.m² are assumed. Furthermore, the environmental impact of the heat production is calculated considering a condensing gas boiler with an efficiency of 102%. As the parameters used for the energy calculations cannot be adapted in the current version of TOTEM, all the variants were simulated using this default scenario. However, note that this default scenario is not representative for a passive house, which is likely to be equipped with a heat pump for heat production, entails a ventilation system with heat recovery, and is required to be more airtight.

### 3. Results

#### 3.1. Full life cycle aggregated environmental score

Figure 1 shows the embodied and operational impacts of the modelled dwellings for the aggregated environmental score. The results are expressed in mPt per m² of gross floor area, and grouped per construction type and energy performance level. The results show that the building type has a high influence on the total impact of the dwellings, i.e. more compact dwellings have overall lower impacts. The impact of terraced houses is 32-34% lower than for detached houses. The semi-detached houses have 12-14% less impact than the detached houses. Though the apartments are the most compact, their impact is 10-15% higher than that of the terraced houses. This is because the impact of the shared spaces in the apartment block is allocated to the various apartment units, but the floor area of these spaces is not considered for the calculation of the gross floor area of the housing unit.

Looking at the influence of the energy performance level, the life cycle impact of the solid passive variants is only 1-4% smaller than the solid EPB variants. Nevertheless, there is a shift in share of embodied versus operational impacts. Whereas for the solid EPB variants the embodied impacts account for 51% to 56% of the total impact, this becomes 55% to 61% for the solid passive variants. However, note that the operational impacts are assumed to be overestimated due to the limitations of the operational energy modelling.

Larger differences are observed when changing the construction type from solid to timber. Specifically, the timber EPB buildings show a reduction in impacts of 14-20% compared to the solid EPB buildings, and 13-17% compared to the solid passive buildings. Relatively, the embodied impact of timber buildings represents a lower share of the total, i.e. 44-48%.
Figure 1. Embodied and operational impacts of the 12 dwelling variants for the aggregated score.

3.2. Environmental impact indicators

Figure 2 presents the contribution of the different impact indicators to the aggregated single-score of the modelled dwellings. For all variants, GWP is responsible for the highest share of impacts, ranging from 36% to 40%. This highlights the relevance of the definition of individual benchmarks for GWP. After GWP, the most important contributors are depletion of abiotic resources (27-30%) and particulate matter emissions (5-18%). Also worth noting is the increase in land use related impacts for the dwellings with timber construction. Whereas for solid construction land use represents no more than 1% of the impacts, for timber construction the contribution is 5-6%.

Figure 2. Contribution of the different impact indicators to the aggregated score of the 12 dwelling variants.

3.3. Global warming potential

Figure 3 presents the GWP results, again subdivided into embodied and operational impacts. In this case, the operational impact dominates the life cycle GWP. The share of the operational impact is around 64-68% for solid EPB, 58-63% for solid passive, and 71-75% for timber EPB.

Just as the aggregated score of the terraced houses was around 32-34% lower compared to the detached houses (figure 1), for GWP there is a reduction of 33-36%. Both for the aggregated score and GWP the highest reduction from detached to terraced (i.e. 34% and 36%, respectively) is achieved among the timber variants. Similarly, the reduction in GWP from solid EPB to solid passive is 4-6% and from solid EPB to timber EPB is 11-14%, and just as for the aggregated score, the highest reduction (i.e. 6% to solid passive and 14% to timber EPB) is obtained among the apartment buildings.
3.4. **Limit, reference and best-practice values**

A preliminary set of benchmark values can be calculated based on the statistical analysis of the LCA results. In this study, limit, reference and best practice values are derived based on the 90th percentile, median value and 10th percentile, respectively. Table 5 presents the benchmark values that are obtained for the aggregated score and for GWP. Besides benchmarks for the full life cycle impact, guiding values for embodied and operational impact are calculated as well. While for the aggregated score the values for embodied and operational are quite close, for GWP the values for the operational impact are much higher than for the embodied impact.

For the aggregated score, the reduction from limit to best practice value is 45% for the embodied impact, 38% for the operational impact, and 36% for the total impact. For GWP these reductions are 44%, 38% and 33%, respectively.

**Table 5.** Benchmark values for the aggregated environmental score and global warming potential, for the embodied, operational and full life cycle impacts.

|                           | Aggregated score [mPt/m²GFA] | Global warming potential [kgCO₂eq/m²GFA] |
|---------------------------|-----------------------------|---------------------------------------|
|                           | Embodied | Operational | Full life cycle | Embodied | Operational | Full life cycle |
| Best practice             | 31       | 31          | 67             | 279      | 639         | 991           |
| Reference                 | 45       | 39          | 82             | 415      | 794         | 1206          |
| Limit                     | 56       | 50          | 104            | 497      | 1024        | 1469          |

4. **Discussion**

4.1. **Comparison with existing benchmarks**

As a validation step, the obtained benchmark values for GWP are compared with values reported in the literature review of Trigaux et al [23]. In this review benchmark values from regulations, labelling systems, sustainability rating tools and research studies have been collected and statistically analysed.

Figure 4 shows where the calculated reference values for the embodied and full life cycle GWP respectively are positioned among these existing benchmarks. For the comparison the reference values from Table 4 are divided by the reference service life of 60 years, resulting in about 7 kg CO₂eq/m²-year for the embodied impact and 20 kgCO₂eq/m²-year for the full life cycle impact. These results are of the same order of magnitude as the median values for residential buildings reported by Trigaux et al, i.e. 5.7 and 13.3 kg CO₂eq/m²-year for the embodied and full life cycle impact, respectively.
Figure 4. Comparison of the GWP reference values obtained in this study with benchmark values reported by Trigaux et al [23].

4.2. Limitations of the study and recommendations

The current study presents a number of limitations which should be tackled in future research. First, the number of cases is limited to four building geometries representative for one construction period (i.e. 1991-2001). Further steps will include a more extended library of representative buildings in order to better capture the diversity of the building stock. Moreover, the study was limited to the assessment of new buildings. However, benchmarks should also take into account the refurbishments of existing buildings as these represent an even larger share of the building stock. Second, the number of variants, in terms of construction types and energy performance levels should be increased to better analyse the potential environmental impact reductions. For example, a passive timber variant was not included, but is considered a relevant variant for current building practice. In addition, it is worth noting that only one solid and one timber variant were modelled, while it is known that the specific materialisation of the structure, insulation and finishes have a high influence on the total impact of an element. Third, the building elements applied are unaltered for the different building types, while in reality the build-ups of a single-family house might differ substantially from a large apartment block. Fourth, the scope is limited to space delimiting building elements (i.e. wall, floors, roofs and openings). Other building elements, such as stairs, foundations and technical services should be considered as these are influenced by architect and designer choices. Fifth, because energy calculation parameters cannot be changed in TOTEM, the energy performance of the passive buildings was not accurately modelled. Specifically, three issues are identified: (1) the ventilation system does not include heat recovery; (2) air infiltration is overestimated; and (3) a passive house is more likely equipped with a heat pump than with a condensing gas boiler. These features are expected to be introduced in future updates of the TOTEM tool.

Finally, a number of sensitivity analyses should be included in the benchmarking study. The influence of parameters such as the choice of the functional unit and reference study period should be investigated in further research.

5. Conclusion

In this study environmental benchmarks are derived from the analysis of reference residential buildings for the Belgian context. The reference buildings include four representative building typologies, ranging from detached houses to apartments. Different variants are assessed including various energy
performance levels and construction types. The LCA results are calculated based on the Belgian LCA tool TOTEM and reported for both an aggregated environmental score and the GWP.

The LCA results show first the high contribution of embodied impacts which represent a share of 51-61% of the life cycle impacts for the aggregated score. However, for the GWP indicator the operational impacts remain dominant, accounting for 58-71%.

Furthermore, the results show that the building type and thus building compactness provides the largest possible impact reduction (i.e. up to 34%). After that, the construction type or material choice can also induce a significant impact reduction of up to 20%. The energy performance level (EPB or passive standard) appears to have less influence on the life cycle impact, providing a reduction of up to 4% only. Nevertheless, it should be noted that a higher reduction might be obtained when the building model enables changing the energy calculation parameters.

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