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Life cycle assessment benchmarks for Danish office buildings

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ABSTRACT Life cycle assessment (LCA) benchmarking of buildings is highly relevant in certain contexts of building sector practice, for instance in certification schemes or regulation. This study aims at developing a preliminary set of LCA reference values to serve as benchmarks for the Danish construction sector. We analyze the embodied impacts set against the operational impacts of 16 office buildings. We discuss the different approaches to derivation of life cycle benchmarks and identify critical points of attention for the future work with derivation of benchmarks for Danish buildings.

1 INTRODUCTION

1.1 Benchmarking environmental performance

Following an increased focus on life cycle impacts of buildings, a range of LCA standardization measures have been put into action, notably within the auspices of the CEN/TC 350 concerning sustainability of construction work. This has facilitated common terminology and methodological awareness in the building LCA practice.

Nonetheless, comparisons of different LCA studies are still challenged by great diversity in parameters affecting results, e.g. the use of databases for LCA calculations or the normalization references used to evaluate the environmental performance of a building (Rasmussen et al. 2018). LCA based studies of buildings can be compared horizontally and/or evaluated against pre-set values of results only if the studies use same functional equivalent and setting of methodological parameters (Lützkendorf, Balouktsi, et al. 2012). The pre-set values of results are often in the form of guiding benchmarks of one kind or another.

One basic use of benchmarks is to evaluate results against a predefined level of performance which can be set from diverse sources as listed in Table 1.

From literature, there are several examples of statistical derivation of benchmarks for different building types based on reference values of existing constructions or defined “typical” building variations. Lasvaux et al. (2017) used a sample of 40 different low-energy individual houses to derive guidance values for new constructions.

They found that results varied by an order of two when taking into account the differences in design, energy performance and climatic conditions. The OPEN HOUSE project elaborated further on the differences in design and local conditions and proposed a methodology to benchmark buildings at national or regional European scale (Gantner et al. 2013).

A statistical analysis of embodied carbon of 1007 cases of buildings with different levels of system boundaries regarding inventory and life cycle stages was carried out by Simonen et al. (2017). Results showed for instance that embodied impacts from cradle-to-construction (LCA module A) commonly ranged between 200 and 500 kg CO₂-equivalent/m² for commercial office buildings.

König and Christofaro (2012) developed a set of reference, target and limit values for multi-family dwellings based on statistical results from a range of theoretical variations of residential blocks.

Wittstock et al (2010) described the derivation of LCA benchmarks for the German DGNB certification system which uses a fixed, statistically based value for the building’s life cycle stages (including production, maintenance and end-of-life), and a variable value for the energy demand, based on the German implementation of the Energy Performance of Buildings Directive (EPBD). Same benchmarks for embodied impacts have been applied within the Austrian ÖGNI’s
certification system and operational impacts are then benchmarked according to the Austrian implementation of the EPBD (Neururer et al. 2016).

1.2 Encouraging environmental building design

The use of benchmarks as a design parameter can lead to environmentally optimized design. Russel-Smith et al. (2015) investigated the results of building design teams working with sustainability targets that were either qualitative (“green building”) or quantitative (national target values for GWP, ODP and energy and water consumption). They concluded that when a quantitative target was in place, the building designs had lower environmental impacts than if there was no target.

In this sense, the benchmark values cannot just reflect the business-as-usual building practice but must aim higher to achieve a more sustainable building design by use of target values. Target values are seen developed from statistical analyses (König & De Cristofaro 2012), but also value-based from specific areas of focus. For instance, Brejnrod et al. (2017) used the planet’s carrying capacity as target values for a range of environmental categories and investigated the exceedance of the planetary carrying capacity that can be allocated to a Danish person’s housing demands. They found that prevalent building practice utilizes more than 1500% of the climate change carrying capacity.

Zimmermann et al. (2005) analyzed permissible impacts of buildings in terms of energy demand and pollutant loads, embodied as well as operational. Evaluation of construction practices were framed with critical pollutant loads as defined in Ecological scarcity method, Greenhouse gas emissions loads as described in the IPCC 3rd assessment report and demands of 2000-Watt society.

1.3 The need for national benchmarks

In a Danish context, benchmarks are first and foremost relevant in the context of building certification within the Danish adaptation of DGNB. The certification system was chosen in 2010 for adaptation by the Danish Green Building Council, which represents a large group of actors and companies from the national building sector (Birgisdóttir & Hansen 2011).

The LCA reference values of the DGNB certification were originally adopted from the German version. However, experience show that most certified projects obtain high levels of credit points, which may relate to inherent differences between the Danish and the German construction practice but also to methodological differences in the LCA practice.

Apart from the specific use in certifications, guiding values for LCA of buildings have been sought by frontrunning construction companies with environmental profiles. Additionally, political interest in developing a voluntarily based sustainability building class have also, in recent years, been communicated from the ministry.

1.4 Aim of research

This study aims at developing a preliminary set of LCA reference values to serve as benchmarks for the Danish construction sector. The study discusses the limitations of the statistical approach and identifies areas of focus for the future adjustment of the references.

2 METHOD

2.1 Study sample

Inventories and background details of 16 office buildings, constructed between 2013 and 2017, were obtained in spreadsheet formats from the Danish Green Building Council. Inventories were conformity checked and corrected for irregularities in reported material uses by cross checking with the background building documentation. All cases are supplied with district heating and comply with the three different energy consumption levels specified in the Danish building regulations (class 2010, 2015 and 2020) where building class 2020 sets the most ambitious target of energy consumption corresponding to a nearly zero energy building. Further details of the cases can be found in Table 2.

Benchmark values in this project are aimed at reflecting the construction practice for the 2015 energy class buildings. Two groups of analyses are therefore carried out in order to evaluate results; one including all buildings (16 cases) and another including only the 2015 class (8 cases).

2.2 LCA procedure and background

The information on material and energy consumptions of the 16 certified cases was used to construct new
building models in the LCAbyg tool (Danish Building Research Institute 2014) (Rasmussen & Birgisdóttir 2016).

The tool operates with a translated version of the Ökobau 2016 database and includes the EN 15978 life cycle modules of A1-A3 (raw material supply, transport, manufacturing, B4 (replacements), B6 (operational energy use) and C3-C4 (waste processing, disposal). Environmental impacts and resource uses are reported for global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP) with the CML characterization method and the primary energy uses, nonrenewable (PEnren) and total (of nonrenewable and renewable – PEtot), in line with EN 15978 / EN 15804.

Replacement scenarios are determined from the service life guidelines on building materials developed by Aagaard et al (Aagaard et al. 2013). Same guidelines estimate an 80-year’s service life of new office buildings.

The scope of the building inventory covers foundation, structure and surfaces as well as technical aggregates. Distribution systems are not included (ventilation ducts, pipes) nor are the uses of connective items (nails, screws, anchors and fittings).

The inventory for energy consumption is based on the cases’ reported numbers for expected energy demand (district heating and electricity) in the use phase. These numbers of expected energy demand are required as part of the building permit and the calculation of the numbers is performed in a standardized tool.

LCA data for the energy supply mix is based on the national Energy Agency’s scenarios for transitioning energy mixes of electricity and heating to fossil free sources by 2050. Modelling of the energy mixes are carried out with projected data points in 2015, 2020, 2025, 2030 and 2050 (COWI consulting 2016). Annual impacts from energy mixes after 2050 are calculated as the 2050 data points.

3 RESULTS AND DISCUSSION

3.1 Benchmarks of embodied impacts

Figures 1a-g illustrate box-plot distributions of all 16 buildings analyzed and allows for more detailed analysis of the contributing life cycle stages. The box-plots are elaborated for each impact category or resource use and show the distribution of results from the different life cycle stages included in the calculations. In these figures, the values for the calculated B6 are also included. In categories EP and AP, the B6 module, i.e. the operational impacts, is shown to be the module with highest contribution to the overall results. In the ODP category, the replacement module (B4) is the primary contributor to the results. This correlates to the use and replacements of cooling appliances. Initial embodied impacts of the building are the main contributors to overall results in the GWP, POCP and PEnren categories.

Table 3 shows an excerpt of descriptive statistics for the categories of embodied impacts and resource uses from the 2015-buildings sample. The variation coefficient for each category illuminates the extent of variability in relation to the calculated average. In the case of ODP the variability is notable, again reflecting differences in the inclusion of cooling appliances within the building cases. Hence, buildings with installed cooling appliances (service life 20 years) show very high results of ODP compared with buildings without cooling demands. Likewise, the POCP variability can be partly explained by differences in results from buildings with high levels of installed EPS insulation, generating high POCP results, against the buildings with low levels of installed EPS.

Figure 2 displays the difference between the two groups of analysis, the all-buildings and the 2015-buildings. Differences between the two groups of analyses may point to categories in which further adjustments of the benchmarks must be considered. Naturally, these adjustments are only possible at a later stage, and based on a larger sample of buildings within both groups. The POCP is notably lower in the 2015-building’s group and thus needs further attention in the certifications to come. The differences between remaining categories from the two groups are within a 5% difference, indicating that the all-buildings group and the 2015-buildings group correspond acceptably in the benchmarked values.

3.2 Considerations about operational benchmarks

The calculated average energy demand from the analyzed office buildings is 31.1 kWh/m²(heated floor area)/y covering heating and electricity demand.

By regulation, some buildings are allowed an additional supplementary demand and this supplement is not included in the averages. The supplement is assigned for buildings with e.g. extended in-use hours, extra lighting and/or ventilation demand and extra floor height. Hence, the actual energy demand is in fact, for many of the case buildings, higher than the calculated average demand.

Furthermore, the average value represents only the demand from decentralized production (district heating and electricity) and thus excludes the on-site energy production. On-site technologies represented in the cases are limited to PVs and heat pumps. The on-site production supply, on average, 6.1 kWh/m²(heated floor area)/y for one building.

The calculated average demand is not detailed enough for a benchmark on which to base LCA results as it does not differentiate between the contributing demands of electricity and heating respectively. When differentiating between average electricity and heating demand, potential LCA benchmarks presented in Table 4 is obtained.
Figure 1a–g. Box-plot distributions (all 16 buildings) of contributing life cycle stages to impacts results.
Table 3. Statistical benchmarks of embodied impacts and resource uses from the sample of 2015-buildings.

<table>
<thead>
<tr>
<th>Embodied impacts (modules A1-A3, B4, C3-C4)</th>
<th>GWP kg CO₂-eq/m²/y</th>
<th>ODP kg C₂H₄-eq/m²/y</th>
<th>POCP kg SO₂-eq/m²/y</th>
<th>AP kg PO₄-eq/m²/y</th>
<th>EP kg PO₄-eq/m²/y</th>
<th>PEnren kWh/m²/y</th>
<th>PEtot kWh/m²/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>5.3</td>
<td>5.5E-08</td>
<td>2.6E-03</td>
<td>1.3E-02</td>
<td>1.7E-03</td>
<td>14.8</td>
<td>19.2</td>
</tr>
<tr>
<td>Variance</td>
<td>1.6</td>
<td>3.2E-15</td>
<td>8.1E-07</td>
<td>1.2E-05</td>
<td>1.4E-07</td>
<td>16.9</td>
<td>24.9</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.3</td>
<td>5.7E-08</td>
<td>9.0E-04</td>
<td>3.5E-03</td>
<td>3.8E-04</td>
<td>4.1</td>
<td>5.0</td>
</tr>
<tr>
<td>Variation coefficient</td>
<td>24%</td>
<td>103%</td>
<td>35%</td>
<td>27%</td>
<td>22%</td>
<td>28%</td>
<td>26%</td>
</tr>
</tbody>
</table>

Figure 2. Difference between the all-buildings group and the 2015-buildings group.

Overall statistical benchmarks for a building’s life cycle in a Danish context could be generated from the average values for electricity, heating and building presented in Table 3 and Table 4. The overall benchmark would thus be based on fixed benchmarks for each of the three constituting components (i.e. electricity, heating, embodied) illustrated as type 1 in Figure 3.

The statistically derived benchmarks for the energy use (Table 4) are, however, not flexible enough to incorporate existing regulation on energy use in buildings. In the Danish energy regulation from the EPBD, electricity- and heating demands from a building are confined as one total energy demand. This allows for flexibility in the energy design of the building, because the sizes of the two demands (in kWh/m² (heated floor area)/y) are flexible as long as the total energy demand stays within a limit defined from regulation. This corresponds to type 2 in Figure 3.

The type 2 benchmarks thus fall in line with the current regulatory focus and is considered most convenient for practitioners in the building sector. Hence, benchmark LCA values of a given indicator, Bi, for the energy consumption are calculated based on the regulatory energy frame as follows:

\[
B_i = IP_{el} \times (10 + 350/A) \times (1 + D_{el}/Total_{el}) + IP_{h} \times (20 + 750/A) \times (1 + D_{h}/Total_{h})
\]

where \( IP = \) impact potentials from electricity- (el) and district heating production (h) for indicator \( i \); \( A = \) heated floor area; \( D_{el} = \) supplementary demand of energy allowed within the frame; and \( Total = \) total demand (including \( D_{el} \)) of electricity and heating respectively.

This benchmarking approach corresponds to the approaches applied in other EU countries where the EPBD implementation sets the limit for the energy demand (Neururer et al. 2016) (Wittstock et al. 2010).

If focus of regulation in the future is changed from energy design to life cycle design (i.e. taking the embodied impacts into account) a benchmark approach could be as outlined in type 3 of Figure 3. In this type, full flexibility of design is obtained by establishing one life cycle benchmark with flexible elements of both electricity-, heating- and embodied impacts.

Naturally, the embodied impacts of the building can also be broken down into individual benchmarks of the constituting components, i.e. production, replacement etc. In this way it would be possible to prioritize impact reductions at certain life cycle stages, for instance promoting design with low impacts in the production stage by putting a limit on the embodied impacts from the relevant modules. However, this modularization of benchmark values to account for, would also complicate the assessment of a building notably.

3.3 DK Benchmarks – points of attention

As noted in section 3.1, the sample of buildings used for embodied benchmarks is limited and display large variability in some of the categories, both in-between the 2015-buildings (ODP variability) and between the 2015- and the all-buildings group (POCP variability). Naturally, this must be kept in mind and analyzed further when larger samples of buildings exist.

Furthermore, for use in the Danish DGNB certification system, the derived benchmark values for embodied impacts are extrapolated to match the expected service life of the other use types within the certification system (see Table 5).

The extrapolation of benchmarks is a crude approach because the other building types display other characteristics than offices, e.g. by a higher number of load-bearing inner walls in residential blocks or by extra floor height in hospitals. Hence, future
Table 4. Operational impacts and resource uses from the sample of 2015-buildings. These statistically derived benchmarks are, however, not flexible enough for use in the overall benchmarking of buildings.

<table>
<thead>
<tr>
<th>Operational impacts (module B6)</th>
<th>GWP kg CO₂-eq/m²/y</th>
<th>ODP kg R11-eq/m²/y</th>
<th>POCP kg C₂H₆-eq/m²/y</th>
<th>AP kg SO₂-eq/m²/y</th>
<th>EP kg PO₄-eq/m²/y</th>
<th>PEren kWh/m²/y</th>
<th>PEtot kWh/m²/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity, average</td>
<td>0.7</td>
<td>2.6E-11</td>
<td>1.7E-03</td>
<td>7.3E-03</td>
<td>2.1E-03</td>
<td>2.4</td>
<td>15.2</td>
</tr>
<tr>
<td>District heating, average</td>
<td>1.2</td>
<td>9.0E-11</td>
<td>2.7E-04</td>
<td>3.9E-03</td>
<td>6.9E-04</td>
<td>3.0</td>
<td>6.8</td>
</tr>
<tr>
<td>Total</td>
<td>1.9</td>
<td>1.2E-10</td>
<td>2.0E-03</td>
<td>1.1E-02</td>
<td>2.8E-03</td>
<td>5.4</td>
<td>22.0</td>
</tr>
</tbody>
</table>

Limit and target values are necessary in the DGNB scheme to define credit points obtained within the LCA criteria. Each of these are set based on the experienced variability within the different impact categories and as such do not reflect any value-based targets.

4 CONCLUSION

The life cycle benchmarks established from current project are constituted by 2 components;
1) Statistically derived benchmarks of embodied impacts (Table 3)
2) Building specific benchmarks, based on regulation, for impacts from energy use (Eq. 1)

Further studies are important to improve the validity of benchmarks from larger samples of case studies and to monitor the ODP and POCP impact categories in which notable variabilities were detected.

The life cycle benchmarks reflect contemporary, industrial, building practice. The foremost aim of the benchmarks is thus to increase knowledge and aspire front-runners in the sector to push in a more environmentally friendly direction. However, some governmental or value-based targets may become more relevant when the construction sector has integrated the current benchmarks into practice.

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