Heuristic Urban-scale Life Cycle Assessment of Districts to Determine Their Carbon Footprints
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Abstract
The decarbonisation goals for the building sector require the large-scale determination of buildings’ carbon footprints. For this purpose, Life Cycle Assessment (LCA) is generally used as a methodology to determine the Global Warming Potential (GWP) of individual buildings and districts. LCA tends to be granular, requiring a large amount of data and time. This work introduces Teco, an enrichment framework for heuristically determining the carbon footprints of districts using City Geography Markup Language (CityGML) Level of Detail (LoD) 2 building models along with a few manual input parameters. In this paper, a use case demonstrates the necessity for refinements of available archetypes and user input for an accurate calculation of the GWP.

Key Innovations
• An extended data framework for Life Cycle Inventory (LCI) based on data in City Geography Markup Language (CityGML), combining materials with physical properties relevant for Building Energy Performance Simulation (BEPS) and Global Warming Potential (GWP) determination.
• Heuristic approach to determine district-scale Life Cycle Impact Assessment (LCIA) with fewer input parameters.
• Developed framework Teco, prospectively, provides an efficient method for district Life Cycle Assessment (LCA) by providing a Graphical User Interface (GUI) and an input functionality of publicly available CityGML building models.

Introduction
The ambitious climate-neutral goals defined by the Paris Agreement of 2015 (UNFCCC 2015) imply decarbonisation objectives for the building sector. This requires a detailed Life Cycle Assessment (LCA) and determination of carbon footprints of buildings on a large scale. LCA, however, tends to be highly granular, requiring large amounts of data and effort to determine the Life Cycle Inventory (LCI) of all materials and energy carriers. The Life Cycle Impact Assessment (LCIA) of the consequential environmental impacts requires additional data (Lotteau 2015). To determine the overall impact, methods have been developed to interconnect single building models described in various data formats with existing data sets of environmental indicators, e.g. OneClickLCA (One Click LCA Ltd 2021), BIM2LCA (Horn 2020), eLCA (Brockmann 2019).
Furthermore, Geographic Information System (GIS)-based approaches have been employed to determine the carbon footprints of districts. Bottom-up methods, such as (Ali 2021), include the enrichment of CityGML building models in Level of Detail 2 (LoD2) (Gröger 2012) with archetype-based data using different building typologies, as well as information retrieved from architectural plans (Mack 2021), (Lavagna 2018). Figure 1 gives an overview of the LoD concept in CityGML. Recently, the web framework UBM.io has been proposed for generating urban building energy models (Ang 2021). Within this framework, GIS shapefiles (Esri 2021), CityGML (Gröger 2012), or OpenStreetMap (OpenStreetMap contributors 2017) data shall be enriched with simulation inputs using an archetype-based approach to determine possible decarbonisation pathways.
Currently, the available approaches for the heuristic determination of district carbon footprints have been considered for a wide range of use cases, predominantly in the residential sector. However, there is no heuristic district LCA method that considers spatial input data and uses a simplified geometry approach to decrease the energy simulation time of the operational phase. Furthermore, the accuracy and validation of LCA based on low-detailed district models compared to the classical granular approach is yet to be determined.
In order to facilitate the determination of district carbon footprints, this paper introduces Teco, as an extended enrichment framework, enabling LCI and LCIA of dis-
Figure 1: Overview of information in different CityGML Levels of Detail (LoD) (Malhotra 2019)

TEASER+. The use case district is outlined based on the information available.

**TEASER and TEASER+**

The “Tool for Energy Analysis and Simulation for Efficient Retrofit” (TEASER) (Remmen 2018) is an open framework for building stock energy modelling. The TEASER tool facilitates Modelica model generation for single buildings or urban areas (consisting of multiple buildings) using one of the Modelica libraries AixLib (Müller 2016), Buildings (Wetter 2014), BuildingSystems (Nytsch-Geusen 2016) or IDEAS (Jorissen 2018). Previously, the TEASER tool provided an interface for CityGML LoD1 & 2 building models, data enrichment using pre-defined archetypes and export Modelica models for conducting heating demand simulations. However, in the current development, CityGML input is excluded and user inputs are used for model generation. Based on the characteristics year of construction and usage of a building, the pure geometrical information is enriched using pre-defined building archetypes. These archetypes are generally defined by considering a sample building with measured data or by using statistical building related data (Ballarini 2014). In 2016, an article by Reinhart & Davila (Reinhart and Davila 2016) comprehensively described the archetype-based enrichment process and tabulated the different available country- and building-specific archetypes. Using the geometrical information and an archetype-based enrichment, TEASER generates simulation models (compatible with the Modelica environment Dymola (Dassault Systèmes 2020)) for computing heating energy demands for the considered buildings. The simulation is carried out in an hourly resolution over one year to determine the heat load of the buildings. The temporal integral over the simulation results yields the heating energy demand.

Adhering to a similar development and methodology, Malhotra et al. (Malhotra 2019) presented an extension, TEASER+, providing an interface for the most commonly used CityGML LoD0-3 models (Malhotra 2021b) as input, a bottom-up archetype-based enrichment, and exports (i) CityGML EnergyADE v1.0 (Agugiaro 2018) and (ii) Modelica simulation models as output. Both TEASER/TEASER+ generate reduced order Resistance-Capacitance (RC) models with a single homogeneous thermal zone for individual buildings (VDI 2015) (van Treeck, Christoph Alban 2010).

Both tools, TEASER/TEASER+, are available as open-source under the MIT License. In a recent release of TEASER+ (version 0.2), a Graphical User Interface (GUI) has been added for enabling users from different districts using information extracted from CityGML LoD2 data models. Teco is intended to employ a limited range of building- and district-related parameters and calculate the environmental impact to a satisfying degree of accuracy, i.e. heuristically determine the LCA results. This contribution describes the methodology, i.e. the development and overall enrichment architecture of Teco based on TEASER/TEASER+. This development has been motivated by an urban scale LCA use case of an ongoing research project. In this paper, Teco is applied on the use case of a residential district under construction to calculate the LCI and LCIA. For validation, LCI and LCIA are determined in a separate manual approach. The results will be discussed and an outlook to future work will be given.

**Methodology**

This section describes the development and architecture of the Teco framework based on TEASER and

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1https://github.com/RWTH-E3D/TEASER/tree/Teco
backgrounds to efficiently work with the tool.

**Teco: Development and architecture**

In order to determine the LCI and LCIA including the Global Warming Potential (GWP) on an urban scale, TEASER+ is further extended as Teco. Herein, the LCA data is added to the enrichment architecture of TEASER+. For the presented use case in this paper, the ÖKOBAUDAT database (BMI 2021) is used, primarily focussing on the German building stock. The life cycle phases are adapted according to DIN EN 15804 (DIN 2020), i.e. (A) production and construction, (B) operation and maintenance, (C) disposal, and (D) recycling potential. Generally, there are two types of GWP data: i) Static data for the production, construction, maintenance and disposal phases. This data is added to the materials by similarity between material name and category. The environmental indicators of the combined datasets are then upscaled according to the dataset’s reference flow and the geometry and material parameters from TEASER. As an example, the GWP indicator of an external wall insulation dataset with a CO$_2$/m$^2$ reference flow is multiplied with the insulation layer size in m$^2$ to yield the GWP resulting from this wall insulation. Additional static LCA data can be subordinated to building elements and the complete building, if the respective objects are not considered by TEASER’s resistance-capacitance model. For instance, GWP indicators and amounts of window frames or of radiators may be appended to the building element window or to the building, respectively.

ii) Dynamic simulation data for the operational phase, enriched with LCA datasets for energy carriers. Here, the LCA datasets are multiplied with the simulated heating energy demands and an overall efficiency factor of the heating system to compute the GWP from the heating demand. Moreover, the electricity demand of a building $Q_{el}$ is estimated by equation 1.

$$Q_{el} = \left( q_{el,b} + q_{el,l} \right) \cdot A \cdot t$$

$$= \left( 63 \frac{Wh}{m^2d} + 10 \frac{Wh}{m^2d} \right) \cdot NLA \cdot 50a \quad (1)$$

In this equation, guideline values from DIN V 18599 for the electricity demand of appliances $q_{el,b}$ and lighting $q_{el,l}$ (DIN 2018) are multiplied with the Net Leased Area (NLA) and number of years in the life cycle. The electricity demand $Q_{el}$ is then multiplied with another LCA energy carrier dataset to determine the GWP from the electricity demand $PENRT_{elec}^2$. To enable component replacements in the subsequent maintenance phase, a “service life” attribute is attached to the building materials and corresponding elements. Figure 2 gives an overview of the developed architecture in Teco.

**Use case outline**

In this paper, the presented use case consists of residential buildings and is currently being developed in an ongoing research project. The district consists of 104 Single Family Houses (SFH) of four different configurations, i.e. NLA and number of storeys. A central heat pump station acts as a supplier of district heating via a low exergy network (Hepbasli 2012). This geothermal system provides a relatively low inlet temperature to minimise heat losses from the pipelines to the environment. The inlet temperature is then increased by decentral heat pumps in each building. An overview of the relevant information provided by the industrial partners within the research project is given in Table 1. The net leased area, $PENRT_{elec}$, $GWP_{PENRT_{elec}}^3$, as well as the constructional setup of the dwelling types have been retrieved from architectural plans and feasibility studies. The data represents the current planning status. However, the building owners may individually alter some features. For instance, the roof type or the thickness of the insulation layer in external walls may be changed before the construction process begins. Figure 3 illustrates the CityGML building models developed using CityBIT.

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2$PENRT_{elec}$: Total amount of non-renewable primary energy with respect to electricity

3$GWP_{PENRT_{elec}}$: GWP resulting from $PENRT_{elec}$
The models have been generated according to the geometrical information available for the individual buildings.

Table 1: Basic parameters of the district use case

<table>
<thead>
<tr>
<th>House type</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of construction</td>
<td>2022</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of buildings</td>
<td>20</td>
<td>27</td>
<td>16</td>
<td>41</td>
</tr>
<tr>
<td>NLA [m²]</td>
<td>167</td>
<td>180</td>
<td>141</td>
<td>172</td>
</tr>
<tr>
<td>Building height [m]</td>
<td>6.15</td>
<td>9.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storeys</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storey height [m]</td>
<td>2.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof type</td>
<td>Flat roof</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PENR&lt;sub&gt;elec&lt;/sub&gt; [kWh/m²a]</td>
<td>8.76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWP&lt;sub&gt;PENR&lt;sub&gt;elec&lt;/sub&gt;&lt;/sub&gt; [kg CO₂eq/m²a]</td>
<td>1.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External wall</td>
<td>10 cm wood layer 18 cm insulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal wall</td>
<td>10 cm wood layer 8 cm insulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>13 cm wood layer 20 cm insulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foundation</td>
<td>3 cm footfall sound insulation 8 cm insulation 30 cm concrete 10 cm perimeter insulation underfloor heating</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>3 cm footfall sound insulation 13 cm wood layer 6 cm insulation underfloor heating</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windows</td>
<td>Triple glazing (25% of façade) wooden framing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stairs</td>
<td>Wooden stairs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doors</td>
<td>Wooden front door Aluminium garage door</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utilities</td>
<td>Heat transmission station 10kW electrical heat pump 500l steel buffer storage 2x70kW central electrical heat pumps</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results and Validation

In this section, Teco is applied on the aforementioned district. Initially, the area of each building element type in the district is calculated for LCI purposes. Furthermore, in the scope of the LCIA, the GWPs per building element and house type (I-IV, see table 1) are determined across all life cycle phases (A to D, see section Teco: Development and architecture). For validation, LCI and LCIA are conducted analogously in a manual dataframe approach to discuss any deviations of LCA results. For visual clarity, the negative values of phase D are depicted as absolutes.

Application of Teco on the use case district

To determine the LCI and LCIA of the district, the tool requires a range of input parameters, namely (i) building usage type, (ii) year of construction, (iii) NLA, (iv) storey height, (v) building utilities, (vi) energy conversion efficiency of the heating system. Parameters (i)-(iv) can generally be retrieved from the CityGML data. Since information on the use case buildings is not present in publicly available CityGML data, this data has been modelled using CityBIT (Malhotra 2021a) with input parameters according to architectural plans. Parameters (v) and (vi) have to be set manually. For the present use case, (v) has been set according to the parameters defined in table 1, whereas (vi) has been defined as 1.525. The archetype has been chosen as “single family house” from TABULA (IWU 2012). The LCI results with the overall area of each building element type within the district are illustrated in figure 4. The area of external walls, roofs and foundations originates from the CityGML building models and, thereby, from table 1. The area of internal walls and floors is calculated by the alignment of the building archetype’s thermal zones with typical room lengths and widths from (SIA 2015).

The LCIA of the district has determined a GWP<sub>50</sub> of the operational phase of 12,728.1 kg CO₂eq. Figures 5 and 6 depict the LCIA results (GWP) for each building element type and each house type.

The comparatively low environmental impact of the roof element results from the archetype’s material configuration and the respective environmental indicators. While
the walls, foundation and internal floors consist of a high proportion of concrete, the roof element is a combination of extruded bricks, wood fibreboard, and an expanded polystyrene (EPS) insulation. The building modelling time including the setup was 2 hours. The simulation time including the setup was 15 minutes on a standard laptop from 2017.

Validation
For the validation, both LCI and LCIA have been performed by creating a Pandas dataframe (McKinney 2010), wherein, the basic parameters (see table 1) have been manually enriched with further information. For the LCI, replacement cycles of building elements retrieved from German standards and sustainability certification guidelines have been added (BMI 2017), (VDI 2012). For the LCIA, the dataframe has been further extended with publicly available datasets of building energy demands (IWU 2012) and environmental indicators (BMI 2021), (CSTB 2021). The LCI results of the considered district are illustrated in figure 7. While the general deviation of estimated areas ranges between 3-15%, Teco has overestimated the amount of interior wall area by about 400% (see figure 4). This indicates that an archetype’s number of thermal zones and/or typical zone lengths and widths do not accurately represent the room setup based on actual architectural plans of the buildings.
mined as 1,388.9 tCO₂eq. Thus, Teco has overestimated the environmental impact of the building energy demand by 816 %. This deviation originates from the comparatively low assumption on the GWP_{PENRT,elec} (see table 1), which in turn has been derived from the predominant usage of wind power in the given district. The GWP per building element type and house type are visualised in figures 8 and 9.

Figure 8: LCIA (GWP) per building element (validation)

Figure 9: LCIA (GWP) per house type and life cycle phase (validation)

Deviations in the Teco results (see figures 5, 6) can partially be explained by the different area proportions of the building elements, and a much higher GWP_{50a} of the operational phase. However, windows have almost identical areas and yet depict a much lower overall GWP. Furthermore, there is a vast difference in the proportions of the life cycle phases between figures 6 and 9. These discrepancies result in part from the material configuration. While the material setup from Teco’s archetype is largely concrete- and brick-based, the actual construction of the district, according to table 1, mainly relies on wooden materials. The GWP indicators of wooden materials generally depict large negative values in life cycle phases A and D (see section Teco: Development and architecture) by comparison to concrete and brick (BMI 2021), and are thus a major contributor to the lower values of phases A to C (see figure 8), and higher values of phase D. The generic window glass material of the existing material catalogue in TEASER did not align with the triple glazing and wooden framing of the basic parameters. Analogous to the estimation of the inner wall areas, using the archetypes, defined based on the building function and year of construction, TEASER generates Modelica models with existing Annex 60 libraries (Müller 2016), which do not precisely align with the actual setup of the building. The amount of time required for the granular LCI and LCIA, based on an extended framework of project-related information, ÖKOBAUDAT (BMI 2021) and further norm-based assumptions, was 20 hours approx. The presented approach of using CityBIT for the creation of CityGML building models, and employing Teco for the model enrichment and subsequent determination of the district’s carbon footprint, is thus 88.75 % more time-efficient. The general overestimation of the building elements’ and buildings’ GWPs does serve the advantage of conservatively estimating the occurring emissions. However, deviations of up to 816 % hinder the overall comparability between different construction types and utility configurations. For example, the current version of Teco computes the same results for the presented district with wooden building constructions and a vicinal wind park, and a district with concrete-based buildings supplied by the general electricity mix.

Conclusion and outlook

The heuristic LCA method of Teco has proven to yield LCI and LCIA results of similar resolution as manual validation procedures, while requiring substantially less working time. Furthermore, the presented tool does enable the usage of CityGML LoD2 data models for determining the LCI and LCIA of all life cycle phases. However, both LCI and LCIA partly depict large deviations from the validation. In context of LCI, the determination of building envelope components and internal floors also shows minor deviations. Moreover, the estimation of internal wall area surpasses the actual area by a factor of 4. This is due
to the inherent calculation of the internal wall area in the original TEASER architecture, as it is derived from the archetype and additional norms relating to zone geometries. Although the archetype-based approach using TEASER might suffice the primary intention of building heat load calculations, it does not accurately reflect the inventory of building materials and subsequent environmental implications. Future work on this aspect should, therefore, focus on (i) a more realistic approximation of interior areas for individual buildings, and (ii) the functionality of using CityGML LoD4 models as inputs in Teco. This thereby helps in extracting and using information highlighting the buildings’ interior architecture (see figure 1).

The environmental impacts within LCIA correlate linearly with the results from LCI and also show partial deviations, accordingly. In addition, the material setup of the chosen archetype significantly differs from the actual materials that are used for the construction of the considered building. Thus, the deviation of GWP s largely stems from the different environmental indicator values of concrete and wood. Again, the difference of physical properties between these materials might be insignificant to the estimation of building heat loads. However, for an accurate representation of environmental impacts, a future version of Teco will take into consideration a much more differentiated archetype-based approach, including the distinction between construction types.

For accurately representing PENRT and GWP of the operational phase, the integration of renewable energy sources in a district should be made possible in Teco. For instance, a factor representing the average electricity demand for lighting and appliances might be insignificant to the estimation of building heat loads. However, for an accurate representation of environmental impacts, a future version of Teco will take into consideration a much more differentiated archetype-based approach, including the distinction between construction types.

For accurately representing PENRT and GWP of the operational phase, the integration of renewable energy sources in a district should be made possible in Teco. For instance, a factor representing the average electricity supply from renewable sources could be added in the equation of the GWPPENRT_{elec} determination.

To account for the regional variety of environmental indicators and building archetypes, datasets based on equivalents of ÖKOBAUDAT and TABULA could be added. With the aforementioned adaptations of Teco, an efficient method for district LCA based on CityGML building models is available for the public. A release as open-source is planned in future.

### Acknowledgements

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### Nomenclature

- **BEPS**  Building Energy Performance Simulation

### References


BMI. 2017. BNB - Service life of building components.


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