Sensitivity analysis of building archetypes for the life cycle assessment of districts

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February 21, 2024

Abstract

District-scale building Life Cycle Assessment (LCA) simulations suffer from a lack of consistent input data and high computational as well as manual effort. Yet, City Geographical Markup Language (CityGML)-based data is widely available and can be used as input for a pre-existing enrichment framework, involving dynamic heat load simulations (“Teco”). However, the information contained within CityGML building models needs to be combined with environmental impact information whose accuracy depends on the chosen building template, i.e. archetype. Environmental impacts vary by different construction types and regional differences in building construction. Thus, this contribution extends Teco with a range of regionalised archetypes of different construction types. This involves a sensitivity analysis of the simulation output among different building age classes and building elements, for different environmental indicators. It is demonstrated that the chosen archetype has a significant influence on the simulation outcome, including the sequence of environmental impact intensity, changing possible refurbishment paths for a district. Future work on this issue will have to complement different archetypes with statistical information to better allocate archetypes to buildings during the modelling approach.

Key innovations

- Spatial refinement of archetypes used for a heuristic approach to determine district-scale Life Cycle Impact Assessment (LCIA), using City Geography Markup Language (CityGML) input data and dynamic heat load simulations.
- Critical juxtaposition of environmental indicators, moving beyond the usual LCA scope of Global Warming Potential (GWP).
- Further development of an open-source, district-scale LCA enrichment framework.

Practical implications

Simulation scientists and practitioners should always consider the spatial resolution of archetypes in bottom-up modelling approaches for the quality of their simulation results. In the field of Life Cycle Assessment, they should be aware of the implications of different construction types.

Introduction

The Reduced Order Modelling or Model (ROM) of buildings and districts is a common methodology to reduce the number of input parameters and computational time while retaining an appropriate accuracy of the simulation output. In the field of Building Energy Performance Simulations (BEPS) and Urban Building Energy Modelling (UBEM), this is commonly referred to as the bottom-up approach. This method considers every individual building of the dataset to determine relationships between building characteristics and output values such as the buildings’ energy demand (Swan and Ugursal (2009)). The bottom-up modelling approach inherently requires a large amount of input data (Harter et al. (2020)). This has motivated the development of archetypes. These are representative templates of buildings that are classified based on a limited range of building properties, such as age class, geometry, usage, and building type (Lauster (2018)). In the field of Life Cycle Assessment (LCA), the data requirement issue is aggravated by the consideration of all district and building life cycle phases, implying a high sensitivity of input and output parameters (Schneider-Marin et al. (2020)). This raises the question of the appropriate degree of accuracy for building archetypes in district-scale LCA. Previous work has emphasised the significance of a building’s construction type, and utility configuration (Harter et al. (2021)). There is an ongoing development of tools to heuristically determine the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) of buildings and districts, employing data based on Geographical Information Systems (GIS), involving heat load simulations. These tools include urbi+ (Harter et al. (2021)), ubem.io (Ang et al. (2021)), and Teco (Schildt et al. (2022)). Urbi+ and Teco enable the use of building information from City Geographical Markup Language (CityGML)-based data (Gröger et al. (2012)). CityGML is the most frequently used, oftentimes publicly available input data taxonomy in BEPS (Malhotra et al. (2021)). CityGML employs a Level of Detail (LoD) concept, with an increasing amount of information contained within the building model (see Figure 1).
To the knowledge of the authors, Teco is the only open-source tool for district-scale LCA using CityGML, involving dynamic heat load simulations to determine the energy demand for the life cycle operational phase. However, recent work with a use case district of LoD2 buildings has shown a significant divergence between Teco’s LCIA results and a manual validation approach based on project-related, building-specific information. This was due to the tool’s archetypes’ misrepresentation of the local construction type and specific building materials (Schildt et al. (2022)). Thus, this contribution intends to extend Teco’s preexisting archetype set with a range of regionalised templates of different construction types, and to demonstrate the increased accuracy of the tool with the LCA of an exemplary district of 302 residential buildings. The simulation results will be discussed extensively to highlight the impact of specified building archetypes on a range of environmental indicators. This paper concludes with an outlook on future work on Teco, and recommendations for the data availability and informational content of GIS files.

Methods

This section outlines the development of Teco as an extension to the preexisting tools TEASER and TEASER+. This is followed by an in-depth description of the tool’s original and newly developed archetypes. Finally, the exemplary district is described.

Teco: An extension to TEASER(+)  

The Tool for Energy Analysis and Simulation for Efficient Retrofit (TEASER) (Remmen et al. (2017)) is an enrichment framework for the energy modelling of building stocks. It enables the generation of Modelica models for single or multiple buildings using one of the libraries Aixlib (Müller (2016)), Buildings (Wetter et al. (2014)), BuildingSystems (Nytsch-Geusen (2016)), or IDEAS (Jorissen (2018)). TEASER uses the characteristics year of construction and usage to enrich geometrical information with pre-defined building archetypes (e.g. Institut Wohnen und Umwelt (2012)) for the generation of simulation models. These models are compatible with the Modelica environment Dymola (Dassault Systèmes (2020)) to determine the heat energy demands of the considered buildings. Malhotra et al. have presented an extension, TEASER+ (Malhotra et al. (2019)), which provides an interface for CityGML LoD0-3 models (Malhotra et al. (2021)) as input. The tool uses the same bottom-up archetype-based enrichment process as TEASER to output CityGML. EnergyADE v1.0 (Agugiaro (2018)) and Modelica simulation models. Both TEASER and TEASER+ generate reduced order Resistance-Capacitance (RC) models with a single homogeneous zone for individual buildings (van Treek, Christoph Alban (2010); VDI (2015)). Both tools are available as open-source under the MIT License.

For the determination of buildings’ LCI and LCIA on an urban scale, TEASER+ has been further extended as Teco (Schildt et al. (2022)).¹ This tool adds LCA data to the enrichment architecture of TEASER+, using the ÖKOBAUDAT database (Federal Ministry of the Interior (2022)) that primarily focuses on the German building stock. The environmental indicators of the LCIA are categorised according to the life cycle modules of DIN EN 15804 (DIN (2020)), namely (A) production and construction, (B) operation and maintenance, (C) disposal, and (D) recycling potential. For the operational phase, the output of the dynamic heat load simulation is enriched with LCA datasets for energy carriers. These are multiplied with the simulated heating energy demands, and an overall efficiency factor of the respective building’s heating system, to compute the environmental indicators from the heating demand. A similar process is carried out for the electricity demand for lighting appliances, which is determined according to DIN V 18599-10 (DIN (2018)). For the remaining life cycle modules, environmental indicators are upscaled according to the dataset’s reference flow, and the geometry and material parameters from TEASER. For instance, an environmental indicator of a roof insulation dataset with a $CO_{2eq}/m^2$ reference flow is multiplied with the insulation layer size in $m^2$ to determine the overall environmental indicator from the roof insulation. Teco’s enrichment process enables the addition of LCA data to several levels of a building’s hierarchy, i.e. such data may be added to the overall building, as well as to its elements or single materials. Figure 2 illustrates the enrichment architecture within Teco for the determination of buildings’ environmental indicators. The tool is fundamentally able to determine all LCIA indicators according

¹https://github.com/RWTH-E3D/Teco

Figure 1: Overview of information in different CityGML LoD (according to Malhotra et al. (2019))
to DIN EN 15804 (DIN (2020)), provided that the respective data is available in ÖKOBAUDAT.

Exemplary district use case
The investigated exemplary district consists of 302 multi-family houses that are located in a city of northern Germany (see Figure 3 for a visual representation). All buildings’ years of construction, usage types, Net Leased Areas (NLA), and postal codes have been retrieved from an LoD2 CityGML file of the district. The distribution of buildings and respective $m^{2}_{\text{NLA}}$ per building age class is illustrated in Figure 4. There is a vague correlation between the respective proportion of each class, albeit the majority of all buildings have been built between 1949 and 1968.

![Figure 2: Overview of the enrichment architecture in Teco (Schildt et al. (2022))](image)

![Figure 3: Visual representation of the exemplary district using FZK viewer (IAI/KIT (2021))](image)

![Figure 4: Distribution of buildings and $m^{2}_{\text{NLA}}$ thereof for each building age class in the exemplary district](image)

Both archetype sets of (i) TABULA and (ii) ZUB are employed to allocate building materials with thermo-physical and LCA-related information to the processed building geometry in Teco. The considered building elements are external walls, roofs, foundations, internal floors, windows, and utilities. Internal walls have been excluded from this examination since previous research has shown the tool’s tendency to overestimate the corresponding LCI. For utilities it is assumed that, following TABULA archetypes, each building has one or more of the following (where applicable): Central heating, 200 l hot water storage per 300 $m^{2}_{\text{NLA}}$, one third of the roof area being used for solar-thermal energy systems, and one decentralised ventilation device including pipes and cables per 100 $m^{2}_{\text{NLA}}$. The scope of the presented LCA use case comprises the determination and juxtaposition of the GWP $[kgCO_{2eq}\cdot m^{2}_{\text{NLA}} \times 10^{3}]$, the Ozone Depletion Potential (ODP

Archetype extension
An archetype is a statistical representation of building properties based on a limited range of variables, predominantly building age class and usage type. Such archetypes are widely employed in UBEM to reduce data collection efforts and computational time (Reinhart and Cerezo Davila (2016)). In case of TEASER, archetypes constitute building element layers and thermo-physical properties thereof by year of construction and usage type. Archetypes have been implemented based on structural and energetic indicators of urban spaces of the research project UrbanReNet (Hegger and Dettmar (2014)), German federal research (Federal Ministry of Transport, Building and Urban Development (2010)), and the Typology Approach for Building Stock Energy Assessment (TABULA) project (Institut Wohnen und Umwelt (2012)).

The latter have been used for the Teco extension, where materials and building elements have been complemented with data from ÖKOBAUDAT (Federal Ministry of the Interior (2022)). It was revealed that these archetypes do not necessarily reflect the embodied energy and consecutive Global Warming Potential (GWP) of the actual buildings. This is due to the vast difference of inherent energy usage and subsequent emissions for different building materials. For example, wooden structures are far less carbon intensive than concrete-based buildings (Schildt et al. (2022)). This has led to the motivation for this contribution to increase the spatial resolution of building archetypes in Teco, distinguishing between different construction types for certain postal code areas. This is achieved by implementing a catalogue of regionally typical building material layers as a new choice of archetypes (Klaub et al. (2009)). The catalogue generally provides building information for years of construction between 1860 and 1994. These archetypes will be referred to as “ZUB” in the following sections. ZUB archetypes are differentiated by postal code area, building age group, and construction type including prevalence statements.

Figure 2: Overview of the enrichment architecture in Teco (Schildt et al. (2022))

Figure 3: Visual representation of the exemplary district using FZK viewer (IAI/KIT (2021))

Figure 4: Distribution of buildings and $m^{2}_{\text{NLA}}$ thereof for each building age class in the exemplary district

Both archetype sets of (i) TABULA and (ii) ZUB are employed to allocate building materials with thermo-physical and LCA-related information to the processed building geometry in Teco. The considered building elements are external walls, roofs, foundations, internal floors, windows, and utilities. Internal walls have been excluded from this examination since previous research has shown the tool’s tendency to overestimate the corresponding LCI. For utilities it is assumed that, following TABULA archetypes, each building has one or more of the following (where applicable): Central heating, 200 l hot water storage per 300 $m^{2}_{\text{NLA}}$, one third of the roof area being used for solar-thermal energy systems, and one decentralised ventilation device including pipes and cables per 100 $m^{2}_{\text{NLA}}$. The scope of the presented LCA use case comprises the determination and juxtaposition of the GWP $[kgCO_{2eq}\cdot m^{2}_{\text{NLA}} \times 10^{3}]$, the Ozone Depletion Potential (ODP
[\text{k}_{\text{GRe1.eq,SO}_4} \times 10^{-6}])$, and the Acidification Potential (AP $[\text{k}_{\text{GRe2.eq,SO}_4}]$) in the LCIA along all life cycle modules. The construction types’ prevalence statements in ZUB archetypes show inconsistencies and are therefore unusable for statistical evaluations such as probability density functions or weighted arithmetic means. Instead, all relevant archetypes are used to analyse each construction type’s influence on the environmental indicators. For the present postal code area, ZUB archetypes are available up until the year of construction 1978, thereby affecting more than 60% of all buildings and $m_{\text{NLA}}^2$ in the district. Table 1 gives an overview of the available construction types per building age group for the present use case. If unavailable, the programme chooses a TABULA fallback archetype or building elements thereof.

Table 1: Availability of construction types per building age group in ZUB archetypes

<table>
<thead>
<tr>
<th></th>
<th>1860 to 1918</th>
<th>1919 to 1948</th>
<th>1949 to 1957</th>
<th>1958 to 1968</th>
<th>1969 to 1978</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Double-skin</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Clad</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Wooden</td>
<td>X</td>
<td></td>
<td></td>
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Results

In this section, the simulation results of the aforementioned setups are presented. The environmental impacts by building age class are illustrated in the form of three-dimensional stacked bar charts (referred to as “profiles”), whereas the environmental intensities of all building elements are depicted as heat maps. Thus, figures 5, 6, 7, 8, and 9 show the influence of the different archetype setups on each building age class’ contribution to the environmental impact categories and life cycle modules. Figures 10, 11, and 12 emphasise the sequence of GWP, ODP, and AP intensities for each building element and archetype. All values of life cycle module D are noted as absolutes for visual consistency of the profiles. Furthermore, module D has been excluded from the heat map values in accordance with ISO 14040 (International Organization for Standardization (2006)) to avoid distortions.
Proceedings of the 18th IBPSA Conference
Shanghai, China, Sept. 4-6, 2023
https://doi.org/10.26868/25222708.2023.1154

The aforementioned profiles show differences for all involved building age classes. Most notably, the simulation using the ZUB Clad archetype for building age class 1969 to 1978 leads to an extraordinary increase of GWP and AP in life cycle module A, despite accounting for only about 20% of the district’s NLA (see Figures 4 and 8). This can be traced back to the involved perforated limestone material, showing particularly high values in the respective life cycle phases. Double-skin and wooden construction types tend to reduce the overall impact of the district (compare Figures 7 and 9 with 5). This is due to the favourable environmental properties of the wooden materials used for these types of construction. This leads to a higher proportion of the newer building age classes non-affected by the regionalised archetypes. The ZUB monolithic archetype results show the smallest deviation from TABULA, indicating a high degree of concordance between the respective data sources.

The ZUB archetypes particularly influence the simulation results for external walls, roofs, and foundations. Most strikingly, the aforementioned tremendous influence of the Clad archetype leads to a high environmental intensity of external walls for all indicators. In fact, the GWP and AP intensities of this archetype have proven to be of several magnitudes higher than the remaining values (see figures 10 and 12). All values for floors and windows remain identical up to the third digit for every indicator,
emphasising the mostly comparable setup of the respective materials. Analogously, the values for operational energy are the same throughout each environmental indicator, implying largely identical thermo-physical properties for each building archetype of the same age class. Each impact category shows a different pattern, albeit the constant values for floors and windows tend to be among the highest. The material-related environmental implications of the utilities tend to be insignificant, i.e. there are no recognizable values for GWP and ODP, and the AP intensity is among the lowest.

The evaluation of these findings highly depends on a stakeholder’s perspective, and the overall use case. A district ROM cannot be employed for a highly detailed investigation of single buildings as it lacks the appropriate granularity of building geometry and materials. It is rather suitable for a broad estimate of energy consumption and environmental impacts of a limited number of building elements, and buildings per age class. In this context, the LCA scope can only be as detailed as the granularity of the available data, i.e. LoD2 CityGML building models, and LCA building archetypes allocated to them by age class and construction type distribution. The tool produces output that can only be used on a district scale, i.e. considering a larger number of buildings. Such data might serve lawmakers, urban planners, real estate owners, and financial investors in identifying the buildings and building elements with the highest environmental impact. Thus, it enables the decision-making process for various stakeholders in terms of building sustainability on a district scale, such as architectural planning, the setup of refurbishment incentive programmes, and investment criteria like Environmental, Social, and Governance (ESG). (Robinson and McIntosh (2022)) For instance, the tool’s output can be used to establish threshold values, or refurbishment sequences and incentives. The regionalised archetypes either provide a higher degree of accuracy, or serve the conservative estimate of environmental impacts. In particular, the priority of reducing the environmental impact of the buildings’ operational energy demand depends on the kind of archetype used for the simulation. From the perspective of a simulation scientist, the results indicate the significant impact of different archetypes on the simulation results. The presented set of regionalised archetypes noticeably alters the simulation outcome, i.e. environmental impacts, for different building age classes and elements, despite only partial availability of archetype data for different construction types (see Figure 1). The inconsistency of the archetype’s data source’s prevalence statements for different materials makes it difficult to assess the number of affected buildings. The usage of a CityGML file and the LoD2 building models therein has been favourable for this contribution in using a large number of buildings’ geometries, years of construction, and postal codes. However, a general lack of building construction type statements in the CityGML encoding standard has prevented the authors from refining the allocation of the presented archetypes to each building.

**Conclusion**

The presented use case of a district-scale LCA simulation employing different regionalised archetypes shows a significant range of results. Since the provided data source for the ZUB archetypes gives regional statements for building materials and elements, it can be inferred that an increase of the archetypes’ spatial resolution yields a significant increase of the simulation accuracy. It has been demonstrated that the choice of archetypes significantly alters the total amount of environmental impacts, as well as their distribution among different buildings and building elements. This leads to practical implications for a range of stakeholders who are interested in identifying refurbishment priorities.

A lack of consistent prevalence statements in the ZUB data source and no general provision thereof in CityGML files currently impede a more refined analysis including the precise number of buildings considered by each construction type’s archetype. While this can be attributed to the ZUB data source’s lack of consistent statements, it should be emphasised that the inclusion of such information in the CityGML encoding standard and respective files would enable a simple allocation of archetypes to each building model of a GML file. For this matter, the authors strongly suggest to extend the CityGML LoD definition to reflect LCA-related information, and to encourage the large-scale data acquisition by institutions who are responsible for the provision of CityGML files.

Future work on the usage of archetypes for district-scale building LCA simulations will have to concentrate on combining regionalised construction-related information with different statistical sources of prevalence statements to increase the degree of modelling and simulation accuracy.

**Acknowledgments**

We gratefully acknowledge the financial support by BMWK (German Federal Ministry of Economic Affairs and Climate Action), promotional reference 03EWR010B.

**Nomenclature**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AP</td>
<td>Acidification Potential</td>
</tr>
<tr>
<td>BEPS</td>
<td>Building Energy Performance Simulation</td>
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<tr>
<td>CityGML</td>
<td>City Geography Markup Language</td>
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<tr>
<td>ESG</td>
<td>Environmental, Social, Governance</td>
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<tr>
<td>GIS</td>
<td>Geographic Information System</td>
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<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
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<td>LCA</td>
<td>Life Cycle Assessment</td>
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<tr>
<td>LCI</td>
<td>Life Cycle Inventory</td>
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<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
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<tr>
<td>LoD</td>
<td>Level of Detail</td>
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<tr>
<td>NLA</td>
<td>Net Leased Area</td>
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ODP  Ozone Depletion Potential
ROM  Reduced Order Modeling
TABULA  Typology Approach for Building Stock Energy Assessment
TEASER  Tool for the Energy Analysis and Simulation for Efficient Retrofit
UBEM  Urban Building Energy Model(ing)

References


van Treeck, Christoph Alban (2010). *Introduction to Building Performance Modeling and Simulation.*
