Comparative Life Cycle Assessment on City Quarter Level – A Case Study of Redensification

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Abstract. The German and European climate action programs and the ongoing discussion of resource efficiency require an in-depth analysis of the building sector, especially with the background of the German refurbishment backlog and high energy demands of the German building stock. A Life Cycle Assessment (LCA) on the city quarter level allows fast and efficient evaluation of environmental impacts, emissions, and energy demands of densification in urban areas. This study presents LCA results for a specific urban city quarter. Thereby environmental and energetic values for specific building ages are developed and used to conduct LCA for the building construction and technical building services components. A 3D city model in CityGML-format of residential buildings serves as the basis for assessment. The results can be used to identify decisive drivers of energy demands and emissions and the saving potentials of different building development scenarios.

1. Introduction

The German [1] and European [2] climate action programs and the ongoing discussion of resource efficiency require an in-depth analysis of the building sector. The buildings sector and the construction industry are responsible for 38% of all energy related CO_2-emissions [3]. However, these numbers do not include the energy demands and emissions of the whole building life cycle. A Life Cycle Assessment (LCA) based on DIN EN ISO 14040:2009-11, DIN EN ISO 14044:2021-02 defines the evaluation of environmental impacts, emissions and energy demands of products during a determined lifespan from production through operation to end of life. Further, DIN EN 15978:2012-10 provides the calculation method for buildings – for defined life cycle phases (see figure 1).

Due to the building refurbishment backlog in Germany and the need to densify neighbourhoods in urban areas, there is a need for methods which allow for fast and efficient comparative LCAs of large building stocks in order to identify environmental saving potentials in early planning phases and to derive recommendations for sustainable development of existing city quarters.

In this context the connection of geo-referenced, spatial 3D city models and environmental values of building components show great potential. Semantic 3D city models in CityGML-standard [4] provide data about building geometries and areas of large building stocks up to the national level, including roof types, when Level of Detail (LoD) 2 is chosen.

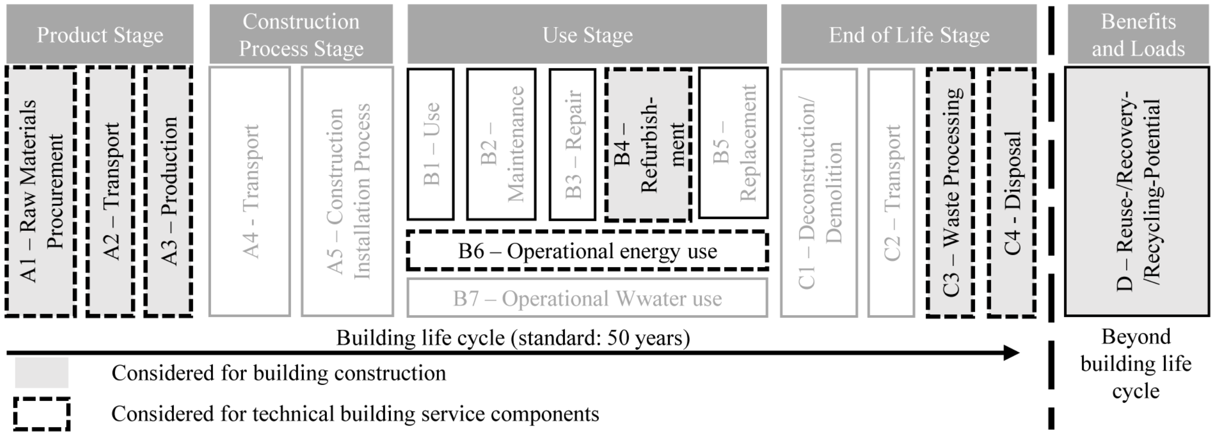

Figure 1. Overall and considered life cycle stages for LCA of buildings (according to DIN EN 15804:2014-07, Figure 1)

These data can be linked with further external databases, like environmental values for different building components or energy demands. Using this method, LCA studies of large building stocks can be executed in a fraction of the time required for manual and project-specific calculations.

Up to now, 3D city models have been used to analyse the energy demand and environmental impacts of large building stocks. The focus of these studies has, however, been on the operational energy demands or the embodied energies and emissions of the building constructions (BC), rather than on technical building service components (TBSC) [5, 6].

A framework for performing LCAs for BC is integrated in umi 2.0, but before LCAs can be performed, BC and LCA parameters must first be defined. [7] In our approach, typical BC and TBSC are defined for each building age class and LCA parameters are stored for them. These can then be linked to the building-specific information (year of construction, areas of the building components, etc.) from the 3D city models (CityGML format) to calculate the LCA automatically. The building stock chosen is an urban quarter with 105 linear buildings located in Munich, Germany. The buildings were constructed between 1949 and 1968 and were intended to be renovated and densified by adding one more storey or have to be replaced by new and larger buildings.

2. Methodology

Figure 2 shows the workflow to identify the current and future life cycle based energy demands, emissions, and potentials for improvements to the case study.

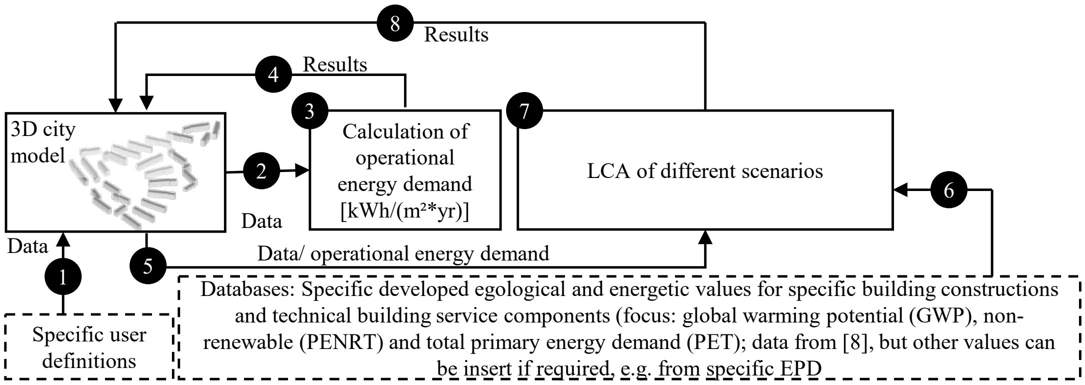

Figure 2. Methodology – workflow, divided in step 1 to 8

The 3D city model provides exterior wall areas, shared wall areas, the ground area, the roof area, the roof type (pitched or flat roof), the number of storeys above ground and the volume of each building.

Additionally, it provides information about the use of the buildings (residential or non-residential) and their year of construction. These specifications are combined with other specific user defined parameters in step 1. By analysing the building size and geometry, the building type can be specified as single family/semi-detached houses (SFH) or multi-family houses (MFH). To define window areas, a factor for the window-to-wall ratio is defined (SFH: 0.12; MFH: 0.15) according to [9]. To define areas for interior walls and foundation, other factors for interior-wall-to-exterior-wall-per-floor (0.2) and foundation-to-ground-floor (0.27) are inserted according to [9]. By defining one storey below ground, areas for exterior cellar walls and shared cellar walls are generated based on exterior wall and shared wall areas above ground.

In total, we defined five main development scenarios (one renovation scenario and four replacement scenarios), which are further divided into subscenarios (see table 1).

Table 1. Description of Scenarios

Scenario	Description
1a	renovation of building envelope to German KfW-55 standard (U-values see table 2); addition of another storey in lightweight timber construction and U-values of passive house standard; pitched roof after renovation; consideration of life cycle phases presented in figure 1; extension of the life cycle by 50 years
1b	like scenario 1a, in addition consideration of stage D
2.1a	all existing buildings are demolished, disposed and replaced by new buildings in lightweight timber construction and passive house standard with the same ground floor, but with one more storey as before; the new buildings have a flat roof; assumptions for life cycle like scenario 1a
2.1b	like scenario 2.1a, in addition consideration of stage D
2.2a	like scenario 2.1a, but new buildings in massive timber construction
2.2b	like scenario 2.2a, in addition consideration of stage D
2.3a	like scenario 2.1a, but new buildings in reinforced concrete construction
2.3b	like scenario 2.3a, in addition consideration of stage D
2.4a	like scenario 2.1a, but new buildings in masonry construction
2.4b	like scenario 2.4a, in addition consideration of stage D

We assume that all the existing buildings have an unheated basement and, when there is a pitched roof, an unheated top floor. After renovation or replacement with new buildings, the top floor is assumed to be heated and the cellar floor to be unheated. In the course of the renovation, all components of the TBSC under consideration will be replaced. For heating and domestic hot water, this includes in particular the heat generators and storage tanks, heat transfer system, pipelines and their insulation. In step 2 the data given by the 3D city model and expert definitions are used to calculate the current and future operational energy demand for heating and cooling with umi [7] with simulation boundaries based on German DIN 4108-2:2013-02 (step 3) and U-values in table 2. In step 4, the specific heating and cooling demands are imported from umi into the 3D city models. In step 5 and 6 all data given by the 3D city model is joined with energetic and environmental values of specific BC and TBSC (see figure 2). Therefore, the decisive construction components and energy systems before and after renovation are defined together with the City of Munich, which opened a competitive bidding process for the design of the district development. The environmental and energy related impacts of all defined building age specific components (exterior walls, interior walls, shared walls, roofs, ceilings, windows, baseplates, foundations) and systems (energy systems for heating and hot water preparation as well as heat transfer system etc.) are then assessed with only using the open source data of the German LCA-database Ökobaudat [8]. In step 7, we conducted the LCA of the city quarter by extrapolating the impacts per m² construction area, component of the energy system or linear metre of pipelines at city quarter level. Here, the assessment of the Global Warming Potential (GWP in [kg CO_2-eq./(m^2yr)]), the nonrenewable primary energy demand (“PENRT” in [kWh/(m^{2}yr)]) and the total primary energy demand (“PET” in [kWh/(m^{2}yr)]) of relevant life cycle stages (see figure 1) per scenario is included, whereby m^2 is for living area. The results are imported into the 3D city model in step 8 for further evaluation.

Table 2. Coefficients of heat transmission (U-values) for existing, renovated, and new BC of the heated building envelope (m.c.: massive construction; m.m.c: massive monolithic construction)

	U-value [W/m^{2}K]			
	Existing buildings 1949 - 1957	Existing buildings 1958-1968	Renovated buildings[a]	New buildings[b]
Pitched Roof	-	-	0.14	0.15
Flat Roof (m.c.)	2.10	1.30	0.14	0.15
ExteriorWall (m.m.c.)	1.80	1.40	0.20	0.15
Top ceiling (m.c.)	2.10	2.10	-	-
Cellar Ceiling (m.c.)	1.90	1.00	0.25	0.15
Windows	2.70	2.70	0.90	0.80

[a] U-value following KfW-55 standard [10]; [b] U-value following passive house standard [11]

3. Results

3.1. *Net energy demand and indoor comfort*

We determined the energy demand for heating and cooling for the current state (buildings from 1949-1968) and for KfW-55 and passive house standard. The majority of residential buildings in Germany are not equipped with active cooling. However, the cooling demand was simulated in order to evaluate the potential of overheating and an indirect assessment of the thermal comfort. In summary, we discovered that the heating demand of the city quarter in life cycle stage B6 can be significantly reduced from the range of 113.9–173.7 to 22.3–39.8 kWh/(m^{2}yr) (KfW-55 standard) or to 7.4–17.0 kWh/(m^{2}yr) (passive house standard). This is an average improvement of 78%. In addition, the potential cooling demand plays a decisive role in near zero energy standards with values from 7.6–20.5 (KfW-55 standard) or 9.9–27.0 kWh/(m^{2}yr). Consequently, the potential cooling demand must be reduced by passive measures. Here, green infrastructure, especially big trees can prevent overheating via shading.

3.2. *LCA of building constructions*

Figure 3 shows the GWP of each considered scenario (see section 2). Based on scenario 1a the influences of different construction types regarding the GWP are shown. Considering the life cycle stages A1-A3, B4, and C3/C4 (black bars), the renovation scenario has the lowest GWP of all scenarios. Comparing the renovation (scenario 1a) with the demolition and replacement (scenarios 2.1a to 2.4a, the saving potential of GWP is up to 71%. If all known benefits and loads beyond the life cycle (stage D) are considered (scenarios 2.1b to 2.4b; see grey bars of figure 3), the demolition and replacement in massive timber construction has the lowest GWP per m^2 living area and year. The tendencies of GWP for each scenario are, in summary, equivalent to the tendencies of PENRT. Here the values are between 1.63 and 18.89 kWh/(m^{2}yr) Scenario 1a and 1b also have the lowest values of PET with 7.80 and 6.25 kWh/(m^{2}yr), but the proportions in the replacement scenarios are slightly different from the proportions of GWP and PENRT. Here the massive timber construction has the highest PET with 28.29 kWh/(m^{2}yr), without considering stage D (scenario 2.2a). Scenario 2.4a has the lowest PET of the replacement scenarios, without stage D, with 24.53 kWh/m^{2}yr. However, it has to be considered whether the percentage of primary renewable energy of timber constructions (Sc. 2.1a: 35%; Sc. 2.2a: 37%) is higher than the percentage of massive constructions (Sc. 2.3a: 25%; Sc. 2.4a: 25%).

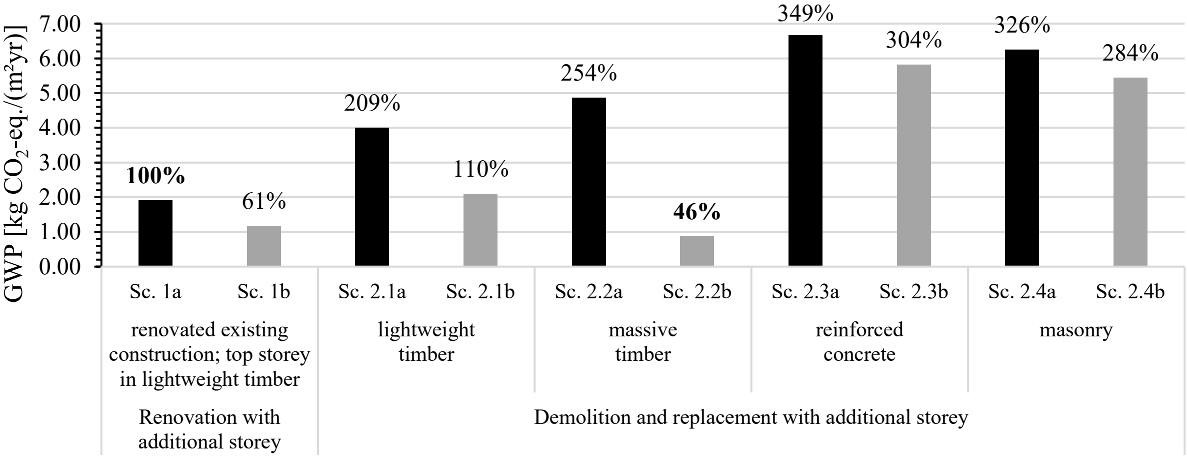

Figure 3. Specific Global Warming Potential [kg CO_2-eq.] of building constructions of each scenario per m² living area and year (building life cycle of 50 years)

3.3. LCA of technical building service components

To determine the dimensions and consequently the life cycle based environmental and energetic impacts of the TBSC, the heating load of each building has to be calculated first. We assumed that every current component is deconstructed and replaced regarding the requirements of the KfW-55 or the passive house standard. Due to the higher energetic standard after renovation or new construction, the total heating load is reduced by -76% or -77% compared to the status quo. This has a significant influence on the dimensions of the new TBSCs. In addition, the selected district heating network and solar heating system for drinking water result in a marginal percentage of TBSC for life cycle stage A1-A3, B4 and C3/C4. In sum, the TBSC are responsible for a GWP of 0.32 kg CO_2-eq./(m²yr) (scenario 1 to 2.4), a PENRT of 1.11 (scenario 1) or 1.08 kWh/(m²yr) (scenario 2.1 to 2.4) and a PET of 1.34 (scenario 1) or 1.32 kWh/(m²yr) (scenario 2.1 to 2.4). The heating demand (see section 3.1) is responsible for the environmental and energetic impacts during phase B6 with a GWP of 3.51 kg CO_2-eq./(m²yr) (scenario 1) or 2.39 kg CO_2-eq./(m²yr) (scenario 2.1 to 2.4), a PENRT of 7.92 (scenario 1) or 5.39 kWh/(m²yr) (scenario 2.1 to 2.4) and a PET of 11.46 (scenario 1) or 7.79 kWh/(m²yr) (scenario 2.1 to 2.4). The grid emission factors for these calculations are also sourced from the Ökobaudat (e.g., average of 0.162 kg CO_2-eq./kWh of district heating).

4. Discussion

Recommendations for the sustainable development of the existing city quarter for a study period of 50 years can be derived from the results in section 3. By renovating all existing buildings or replacing the city quarter with new buildings with a near zero energy standard, the operational energy use for heating can be reduced significantly. The prospective cooling demand should be reduced by passive ventilation and shading measures to minimize the life cycle based energy demand and emissions. With the focus on BC the renovation scenario has the lowest GWP and PENRT, followed by replacement and new construction in timber. The PET of timber constructions is higher than the PET of massive constructions, but it should be considered that the percentage of renewable primary energy demand is also higher for timber constructions. Finally, we found that for low energy buildings, such as near zero energy houses, the percentage of the environmental and energy related impacts of the BC during the whole building life cycle increases significantly, while the operational energy demand decreases to a minimum. An increase in the share of renewable resources in energy supply over 50 years was taken into account and calculated by specifying the share in the starting and target year. The increase is distributed evenly over all years. While the GWP of stage B6 has a percentage of 61% and the BC 33% in the renovation scenario, this changes in the scenario ‘replacement with reinforced concrete construction’. Here, stage B6 has a percentage of only 25% and the BC of 71%. The impacts of the TBSC play a marginal role with a percentage of 3–6%.

5. Conclusion

The results of this study show the necessity of conducting LCA to improve the environmental quality of large building stocks over the whole building life cycle. The methodology developed here can be applied to other city quarters or even whole cities for which CityGML-data is available. The generated environmental values of building components (see section 2) can also be used to assess other city quarter development scenarios, wherein the parameters chosen here can be replaced with other national or international building typologies, and user assumptions. Further research is necessary to translate the methodology into an automated and user friendly simulation tool. In addition, the database of environmental and energetic values of the building components should be published for use in other LCA studies and building models, potentially in combination with building information modelling (BIM).

6. Acknowledgement

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References

[1] German Federal Government 2021 *Climate Action Programme 2030* https://www.bundesregierung.de/breg-en/issues/climate-action
[2] European Commision n.d. *Climate strategies and targets – 2050 long-term strategy* https://ec.europa.eu/clima/policies/strategies/2050_en.
[3] UNEP Dec. 16, 2020 *Building sector emissions hit record high, but low-carbon pandemic recovery can help transform sector – UN report* https://www.unep.org/news-and-stories/press-release/building-sector-emissions-hit-record-high-low-carbon-pandemic
[4] Open Geospatial Consortium. n.d. *CityGML* https://www.ogc.org/standards/citygml (accessed: Apr. 13 2021)
[5] Chen Y, Hong T and Piette M A 2017 *Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis. Applied Energy* **205** 323–35 doi: 10.1016/j.apenergy.2017.07.128.
[6] Mastrucci A, Popovici E, Marvuglia A, de Sousa L, Benetto E. and Leopold U 2015 *GIS-based Life Cycle Assessment of urban building stocks retrofitting- a bottom-up framework applied to Luxembourg. EnviroInfo2015 and ICT4S 2015* 47–56 doi: 10.2991/ict4s-env-15.2015.6.O
[7] MIT Sustainable Design Lab 2017 *Welcome to umi Online Documentation – umidocs 2.3a4 documentation.* https://umidocs.readthedocs.io/en/develop/index.html (accessed: Apr. 13 2021).
[8] BBSR Apr 06 2021 *ÖKOBAUDAT* https://oekobaudat.de/
[9] Gruhler K, Böhm R, Deilmann C and Schiller G 2002 *Stofflich-energetische Gebäudesteckbriefe – Gebäudevergleiche und Hochrechnungen für Bebauungsstrukturen* IÖR Schriften **38** https://www.ssoar.info/ssoar/handle/document/39685 (accessed: Apr 13 2021)
[10] KfW 2020 *Anlage zu den Merkblättern – Energieeffizient Sanieren – Technische Mindestanforderungen.* https://www.kfw.de/PDF/Download-Center/F%c3%b6rderprogramme-(Inlandsf%c3%b6rderung)/PDF-Dokumente/6000003612_M_151_152_430_Anlage_TMA_2018_04.PDF (accessed. Apr. 06 2021)
[11] Passive House Institute 2015 *Passive House Requirements.* https://passivehouse.com/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm (accessed: Apr. 06 2021)