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BUILDING COMPONENTS AND BUILDINGS

Developing non-residential building stock archetypes for LCI—a German case study of office and administration buildings

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Abstract

Purpose To accomplish the national and international climate goals, building renovation and optimisation of their energy and resource efficiency are essential. Thus, reliable information on the building stock (BS) is necessary. Most previous building typologies are focussing on residential buildings and the operational phase. This paper shows the development of a methodology for generating non-residential building (NRB) typologies for life cycle inventory analysis (LCI) of building constructions. Hereby, archetypes of office, administration and department (OAD) buildings are developed, exemplarily for the German NRB stock.

The methodology can further be utilised for quantity surveying of urban material stocks, related recycling scenarios and waste management. Furthermore, the exemplarily generated archetypes provide necessary information for the estimation of realistic refurbishment scenarios.

Methods Approaches for the development of NRB archetypes, the descriptions of associated building materials and the LCI of BS were analysed and integrated into a methodology. It provides a clear path on the classification in building usage categories and determination of relevant building parameters for conducting LCI studies. Its aim is the creation of NRB typologies, presenting construction materials and building geometry in a useful way for life-cycle assessments (LCA).

To demonstrate the methodology's usability, it is applied to a case study with the sample of 161 OAD buildings, provided by the German NRB database ENOB:dataNWG. In combination with relevant literature on BS archetypes and materials, a sample OAD building typology has been created.

Results and discussion Minimum data requirements for conducting simplified LCI calculation of BSs were identified by analysing existing LCA methods, like the German BNB system. Important clusters for developing NRB archetypes were determined: building usage category, building construction types and building age. These data gaps between required information for simplified LCA studies and available information in ENOB:dataNWG were identified, and solutions for closing these data gaps were proposed and tested. Since building archetypes must reflect the overall BS, uncertainties were discussed. The ENOB:dataNWG database was not completed at the time this paper was written, so comprehensive uncertainty analyses are important next steps.

Conclusions This methodology development forms the groundwork for creating LCI building typologies for simplified LCA studies. It shows practically how to deal with a BS database and illustrates which typical values can be chosen for closing data gaps. The methodology was tested on an exemplary sample of OAD buildings. Based on this case study, the methodology concept was proven useful for the generation of a NRB typology.

Keywords Life cycle inventory · Methodology · Life cycle assessment · Non-residential building stock · Archetypes · Building typology · Building material composition · Office and administration buildings

1 Introduction and aim of the project

In climate policies, building stocks (BS), including energy use as well as material use, are of great relevance, due to their share on the energy consumption and material use. Globally, buildings and constructions are responsible for

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36% of the final energy use and for 39% of the energy-related CO_2-emissions, including upstream power generation and the manufacturing of materials and products for building construction (UN Environment and International Energy Agency 2017). Building construction has a share in global CO_2-emissions of 11% (UN Environment and International Energy Agency 2017). In Germany, buildings are responsible for approximately 35% of the final energy use and 30% of the Greenhouse Gas (GHG) emissions (Umweltbundesamt 2016). On the material side, 90% of the extracted mineral resources are applied in the building sector while 52% of German waste comes from the BS (Zentrum Ressourceneffizienz 2018).

Thus, it is obvious that energy and resource efficiency programs have been established, to accomplish the national and international climate goals. The medium-term EU objectives are for example reducing GHG emissions by 40% and increasing the energy efficiency by about 27% compared with 1990 until 2030 (European Commission 2016). The long-term German and EU climate objectives are to reduce GHG emissions by 80 to 95% or even 100% until 2050 compared with 1990 (BMU 2018; European Commission 2016). The German national targets regarding climate protection in the BS are to reduce the primary energy use by 80% in 2050 compared to the year 2008 as well as GHG emission by 40% compared to 2010 (BMUB 2015).

In Germany, exemplarily for other nations, the refurbishment of the national BS can contribute significantly to the climate protection aims. Reliable information on the BS is necessary to investigate and develop efficiency and refurbishment strategies. Due to the implementation of the European Energy Performance of Building Directive (European Parliament 2010), the energy demand and emissions of the operational phase of buildings have been reduced. On the other hand, the total share of the non-operational (embodied) energy and emissions (e.g. GHG) is increasing by bringing more materials (e.g. insulation, triple glazing) and components (e.g. building management systems, automation systems) into the BS. Thus, the impact of the embodied energy and emissions come to the fore. The challenge here is to provide reliable information to policy-makers for holistic answers to support legislation strategies regarding the whole life cycle (from manufacturing to the demolition of the building).

However, most typologies are still focused on residential buildings and the reduction of operational energy and do not consider required data to analyse the entire life cycle of buildings from manufacturing to demolition. Of course, residential buildings represent around 65% of the German BS (not considering garages and carports) (Hörner et al. 2020), but there is still a significant share of 35% for the non-residential building stock (NRBS) (Hörner et al. 2020). So, there is a need for building typologies of NRBS which allow conducting LCI (life cycle inventory) analysis for LCA (life cycle assessment) studies on a big scale, by offering all relevant building information.

Generally, data on the NRBS is poor or incomplete, as national statistics do not consider this sub-sector in Germany. All estimations, except the current projection of the ENOB:dataNWG-Project (IWU 2020a), are based on statistically non-representative data and have a great variance if compared to each other (BBSR 2016). This variance in the database becomes clear in the estimated number of conditioned non-residential buildings (NRBs) without educational institutions in Germany, which was calculated by four different studies between around 3 million and 7 million in Tichelmann et al. (2019). Compared to the 19.16 million residential buildings in 2019 (Destatis 2020), the assessment of the NRBS is relevant. To identify current conditions of non-residential buildings (NRB) and their past refurbishment rates and future refurbishment potentials, the project ENOB:dataNWG is currently surveying for the first time the German NRBS. The project generates statistically representative and reliable data on this stock and its past development (IWU 2017). These data can be used to conduct LCI, which is the initial part of an LCA.

To overcome the above-mentioned challenges, a methodology for generating a NRB typology (the entirety of archetypes describing the BS) for LCI of building constructions is developed in this paper. Hereby, it is shown, how archetypes (representative buildings) for LCI of the NRBS can be developed. These archetypes are developed by clustering the NRBS by building usage categories (office and administration buildings, school, hotels, etc.), building ages and specific building properties (e.g. building construction materials used, typical building geometries). Clusters are hereby sub-stocks of the BS representing buildings with the same attributes, such as the same building usage category. The developed methodology is, exemplarily for NRBS, applied on the current BS of office, administration and department (OAD) buildings. Data from ENOB:dataNWG supplies the basis for this.

By using an archetype approach and extracting LCI, respectively, LCA-relevant data, from existing building databases the NRBS can be described to identify the material stock leading to embodied energy or emission saving potentials. In a next step, existing building typologies can be refined, especially by describing their life cycle–based properties. The aim is a good trade-off between the highest possible level of detail in describing materials and the minimum number of archetypes necessary to describe the majority of the BS. Furthermore, the methodology can be utilised for the quantification of other material flows concerning the BS (see Sect. 7).

2 State of the art

National building typologies of several European countries already exist. However, the focus is on residential buildings (RB) and assessing the energy performance in the operational phase of the building's life cycle. The TABULA project and its web tool offer building typologies on the operational phase of RB of 21 countries, structured by building age classes (Loga et al. 2016). However, specific information on building construction and materials is still missing or inadequate to assess the environmental impact during the whole life cycle. For example, there is no information on areas and volumes of building construction components and therefore does not allow a life cycle inventory analysis of the building's material quantities.

Several other approaches for conducting LCI for LCA exist. Hollberg and Ruth (2016), for example, follow a parametric LCA approach by developing the LCA-tool CAALA (CAALA GmbH n.d.). CAALA offers only an assessment of the design phase of new buildings. Currently, the tool does not allow the quantification of the material stock in current BSs. The paper of Allacker et al. (2019) presents an approach to connect LCA-studies at the building level (micro-scale) with energy simulations and then to upscale the estimations to meso- (neighbourhood, city) or macro-scale (region, country, EU-wide). Using this method, 24 representative RB (archetypes) for the EU were defined and calculated. The approach of defining archetypes is similar to the methodology of this paper, but another usage category is investigated and different data sources are used. Allacker et al. (2019) use four studies from the projects Loga (2010), EPISCOPE Project (2013), ENTRANZE (2014) and ODYSSEE (2016) to generate the archetypes. In the methodology presented here, the main data source comes from the project ENOB:dataNWG, incorporating large representative survey of NRBs throughout Germany, thus providing reliable data for the development of archetypes. Furthermore, the focus of Allacker et al. (2019) is on the calculation of environmental effects of operational energy reduction, rather than the calculation of the current material quantities of German NRBS. However, Allacker et al. (2019) point out the need of considering LCI-studies to the maximum possible extent to improve energy and material efficiency of building.

A geospatial approach for the estimation of material stocks and the evaluation of the end-of-life scenarios of RB is presented by Mastrucci et al. (2017). For the material quantification, a building-by-building geospatial analysis of the geometry provides the relevant envelope surfaces, while the internal material stocks are estimated via specific internal wall to floor area coefficients. The archetypes are hereby clustered by the building category (single-family houses separated into detached, semi-detached and terraced and multi-family houses) and building age. The assigned reference building elements are mainly based on TABULA data. The material quantification is based on archetypes developed for operational energy quantification paired with building-by-building geometric estimations. Archetypes for clustering the BS based on attributes influencing the embodied end-of-life impacts of these buildings are not developed.

The study by Famuyibo (2012) records the Irish housing stock by using an archetype methodology. The aim of this study is to determine how the energy demand, emissions and life cycle costs of the usage phase can be reduced through refurbishment measures. This study delivers a detailed description of developing archetypes by using an Irish building database. Main parameters for describing the archetypes are established based on the building's energy demand.

The HoEff-CIM project develops methods and offers data to evaluate the energy, economic and environmental impacts of large properties on the example of the Ludwig-Maximilians-Universität (LMU) Munich. As part of this project, a generic average building ('reference building'), which represents the geometrical properties of LMU BS, is developed. However, the focus of the HoEff-CIM project is mainly on LMU BS and developing typical energy performance indicators for different building usage categories and renovation strategies (Botzler et al. 2017; Dotzler et al. 2018).

The only study known to the authors, which is providing archetypes with a focus on embodied energy impacts, can be found in the report of the US Advisory Council on Historic Preservation from the year 1979 (ACHP 1979). This work provides a methodology for the determination of material quantities and the embodied energy of typical RB and NRB in the USA. The archetypes of this study are based on a few sample buildings that are analysed via quantity surveying. Therefore, archetypes representative of the whole stock are not developed.

The development of German NRB archetypes, with a description of building materials, is found in two different studies. The first is BMVBS (2011a), which develops a typology on EnEV-relevant buildings by means of the building construction and the energetic quality. Based on literature research and interviews, the building construction for each building age class is described. The other studies, Gruhler and Deilmann (2015) as well as Gruhler and Deilmann (2017), focus on the German BS as a material stock. To analyse the embodied materials, theoretical reference buildings of NRB, called synthetic archetypes by the authors, are developed to determine the average cost of materials by usage category. Hereby, the archetypes are developed based on existing usage categories only. Further differentiation of the NRBS, for example by the building age, is not conducted. Therefore, the focus of the study is to identify typical material quantities for defined archetypes, rather than on defining the archetypes by clustering the NRBS based on material influencing attributes.

The literature sources show several approaches to generate LCI data for evaluating the environmental impact of the current and future BS. However, there is still no practical option available to conduct an LCI of the current NRBS on a big scale. A NRB typology with a focus on LCI, which clusters the stock based on attributes influencing the material quantities, provides the basis for assessing life cycle–based environmental impacts from construction to renovation and demolition. This has not been developed yet on a national scale. The recent studies utilise developed archetypal definitions, initially developed for clustering the BS on operational energy influencing attributes.

The novelty of the following methodology is the clustering of the NRBS based solely on building materials, their LC-Impact and the practical determination of the buildings' LC-Inventory.

3 Methodology

Figure 1 summarises the general methodology and structure of the section. The methodology and described workflow relate to all NRBs with the aim of generating typical archetypes. Section 4 shows the application of this methodology in the research project 'ENOB:dataNWG'. Hereby, a sample dataset of OAD buildings is used as a case study to create an exemplary OAD building typology.

3.1 Step 1: Classification of building usage categories

Like RB, NRB can be described by several archetypes, which are distinguished by their functional, structural and energy-relevant characteristics (BMVBS 2011). Many characteristics correlate to the usage of the buildings. The usage influences the building floor plans and the used materials by legislation requirements in the context of health and safety. For example, structural safety factors or daylighting

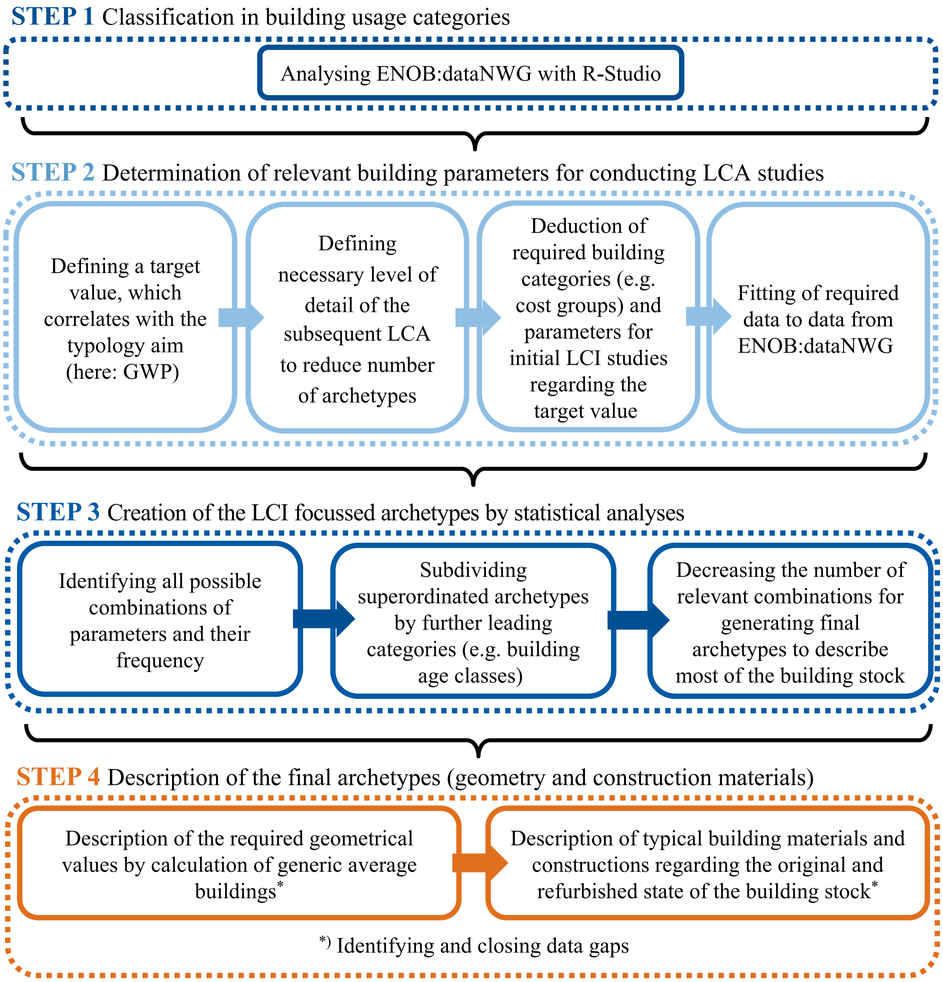


Fig. 1 Methodology for the creation of LCI focused NRB archetypes in four main steps

requirements depend on the usage of the building. Most available data on NRB is provided already differentiated by their usage categories (BMVBS 2011). Therefore, the grouping by the building usage categories, besides the determination of the relevant age bands, is the first step towards the development of archetypes (Bürger et al. 2018; Caputo et al. 2013; Klauß et al. 2010; Loga et al. 2016; Stein and Hörner 2015; Stephan and Athanassiadis 2017). This is also the case for the DataNWG database applied in this study (Hörner et al. 2017).

3.2 Step 2: Determination of relevant building parameters

After the categorisation by usage, the second step is the determination of the main building parameters regarding the typology, which can vary greatly for different NRB usage categories. This step aims to further differentiate the determined usage categories based on existing parameter groups, such as the construction type of exterior walls (Fig. 1). In addition, the target value of the archetype development has to be defined. In this case, relevant parameters can be all kind of information on the building, which correlates with the buildings' environmental impacts, such as the global warming potential (GWP). Similar handling of a building database is conducted in Famuyibo (2012). In that study, the purpose of the typology is to estimate the GWP. Therefore, the GWP is identified as a relevant variable and is utilised for clustering of the available database in the following steps. To determine the GWP, there are different methods, which depend on the level of detail. Since detailed building data is not always available, as in the case study database of this paper, the required information for calculating GWP and other environmental impacts need to be considered indirectly by second-level independent variables, which are explanatory variables of the GWP. Therefore, suitable LCA studies of NRB are investigated to determine the relevant construction components and building parameters for a related LCI.

The LCA level of detail affects the scope of the LCI and therefore the building typology. That implies that a more detailed calculation of the GWP leads to more detailed archetypes. Since building typologies should be a simplified representation of the complex reality (BMVBS 2011), the subsequent LCA method should also be simplified and only request the most relevant building parameters. According to Gantner et al. (2015), there are three levels of details of building LCAs that are utilised in different planning stages. First, there is the so-called *Screening LCA* for early planning stages. This '*Screening LCA*' includes according to Meex et al. (2018) the building inventory of at least the building envelope and primary load-bearing structures using generic material and component data. Second, the so-called *Simplified LCA* is used in a more progressed planning stage, aligning with building certification requirements (e.g. 'Bewertungssystem Nachhaltiges Bauen' (BNB)), thereby adding fundaments, interior walls, surfaces etc. to the building inventory to the extent of the *Screening LCA*. Last, the '*Complete LCA*' incorporates all information of the completed planning adding to the *Simplified LCA* further specific data for all life-cycle stages (A1–C4 and D) (Meex et al. 2018). The building archetype level of detail available in the case study database is comparable with the available information in early and more progressed planning stages. So consequently, the *Screening LCA* and the *Simplified LCA* is a suitable option for the case of NRB-LCI archetype development. To utilise the available detail of the case study database to the best extent, the *Simplified LCA* was chosen for the archetype development. Combined with the operational phase life-cycle impacts, the *Simplified LCA* accounts to least 70 to 90% of the environmental life-cycle impacts, of a *Complete LCA*, of residential buildings of the *Screening LCA* (Meex et al. 2018).

The current green building certification systems deliver such simple methods to calculate the LCA of buildings during their planning phases. The German certification system Bewertungssystem Nachhaltiges Bauen (BNB) describes an LCA method that can be used on GWP, acidification, eutrophication and primary energy demand (renewable and non-renewable). This so-called *Simplified LCA* method defined in the BNB only considers the building constructions components according to KG 300 and energy systems according to KG 400 of DIN 276:2018–12. The German DIN 276:2018–12 defines and groups building components into cost types. This standard defines the cost type KG 300 for the building construction and the cost type KG 400 for the building services. The LCA results of the building services according to KG 400 are considered via multiplying the environmental impacts of KG 300 and energy systems with a factor of 1,2 (BBSR 2015). This *Simplified-LCA* and accompanying LCI method is still very time consuming, while it only considers the building components of KG 300 and simplifies the LCI of KG 400 with a high uncertainty. More simplified approaches regarding inventory analyses cannot be found on the building level. According to BNB (BMUB 2015), seven building components are essential to calculate a *Simplified LCA* (Table 1). Therefore, in the next step, the utilised database is examined for these parameters. Depending on their availability, the needed parameters are deduced from the given database.

3.3 Step 3: Creation of LCI-focused archetypes by statistical analyses

After choosing the explanatory parameters, which influence the GWP of NRB from the database, further statistical analyses are necessary. As in Famuyibo (2012), all possible

Table 1 Required LCI parameters of the analysed database according to the simplified LCA method by BNB (BMUB 2015). *N.A.* data not available, *GFA* gross floor area

Relevant building construction components	Required/given measurements (ENOB:dataNWG)
Exterior walls, basement walls including windows and coatings	Dimensions of the components
Roof	Dimensions of the components
Internal floors and ceilings (including floor structures, coverings and coatings)	GFA of the floors
Ground-level floor (including floor construction, coverings and coatings, as well as floors above open space)	Dimensions of the components
Foundations	N. A
Interior walls including coatings as well as supports	Dimensions in executive plans
Doors	N. A

combinations of these parameters have to be considered and analysed by their frequency. The sum of these combinations available in the input database is the basis for further specifying the archetypes. To add information on the materials of the buildings, these types are subdivided by their age as a relevant indicator for the material composition (BMVBS 2011). A classification by building age classes can be helpful to cover the main architectural changes in history. To get a manageable number of archetypes, further reductions of the archetypes, for example, by the number of cases corresponding to the archetypes or the gross floor area (GFA), are an option. The threshold for this reduction has to be approximated by an iterative approach. In the case of this study (see Sect. 4), the archetypes are designed to directly describe most of the BS represented in the database while at the same time reducing the number of archetypes for the NRB typology to a minimum. As an orientation for the archetype reduction, the aim for the archetypes is to directly describe over 50% of the BS represented in the case study database. This threshold greatly influences the resulting number of archetypes. Several thresholds are tested in Sect. 4.4.

3.4 Step 4: Description of final archetypes by geometry and construction materials

The last step in the development of so-called LCI NRB-types is to describe the main archetypes in detail. This step includes the determination and description of all required information regarding the preceding classifications and defined purposes of the typology. Therefore, it is necessary to define the needed geometrical values identified in Sect. 3.2 and to assign the building materials to the archetypes. The average geometry can be described by developing generic average buildings. Generic average buildings do not represent real objects but are formed based on a selection of objects in the database to reflect the average of this database (Gruhler and Deilmann 2015).

To describe the typical materials and constructions for the selected building components, two states are determined. First, the state of the original BS at the year of construction and second the state of the refurbished BS, which represents the actual condition of the building at the time the database was created. The information on the construction details should be extracted from the database. To close data gaps, existing case studies on the construction of the BS should be considered. In the case of Germany, there is almost no literature on construction details of NRB available. The main sources providing information on construction details for RB are Böhmer et al. (2010), Kirchof and Gissel (2009) and ZUB (2010). To compare the usage of these constructions for NRB, literature with non-representative information on NRB constructions is used. For identification of typical residential building constructions, the publications of Böhmer et al. (2010), Kirchof and Gissel (2009) and ZUB (2010) were considered, while for verification purposes BMVBS (2011), Gruhler and Deilmann (2015) and Thiel and Riedel (2011) were utilised.

4 Case study

The applicability of the developed methodology for the usage category of OAD buildings is tested based on a case study. Thereto, data of ENOB:dataNWG, the first representative survey of NRB in Germany, is investigated.

4.1 Integration in the research project ENOB:dataNWG

The overall aim of the conducted survey in the project 'ENOB:dataNWG — research database of the German non-residential building stock' is to build a database for NRB in Germany, which can describe the distribution and number of all NRB and can be used for 'real estate, energy and geo-informatics analyses' (IWU 2017). This database will provide information for the evaluations of structural and energy-related data as well as the refurbishment rate of the NRB-Stock (IWU 2017).

To draw a representative sample, the available geo-referenced level of detail 1 (LOD1) 3D building's perimeters are selected as a sampling frame for the whole of Germany. In LOD1, the buildings are represented via simple blocks providing the building perimeter and height. A detailed definition of LOD1 in the German official 3D building model and generally can be found in Biljecki et al. (2016) and Schwarz (2021) respectively. The ENOB:dataNWG project is separated into four phases. Phase 00 is designed to deliver information on the building layouts via LOD1 geo-data. A sample of 100,000 buildings, which is designed to include at least 50,000 NRB, is surveyed via an optical screening (Phase 01). More detailed information on the NRB will be collected by telephone and web interviews in Phase 02 for up to 10,000 buildings. In the last step, the on-site inspection phase, up to 1000 buildings are surveyed in detail (IWU 2017).

4.2 Classification of building usage categories

Due to work in progress regarding the ongoing survey of ENOB:dataNWG (IWU et al. 2018), a sample database of the current results will be used for the case study in this paper. The survey data includes information on basic building attributes (e.g. building usage, areas and volumes, age, owner-structure and rental rates), building envelope information (e.g. façade-, window- and wall-types and distribution on the envelope, information on the roof and basement) and building systems information (e.g. heating, cooling, ventilation and lighting) (IWU 2016). In total, 398 attributes including comments are defined in the interview data set (IWU 2020b). As mentioned above, the buildings in this case study are already separated into their usage categories (see Table 2).

Table 2 Abbreviations of usage categories by ENOB:dataNWG (IWU et al. 2018), *Abbrev.* Abbreviation

Building usage category	
Abbrev	**Primary category**
Res	Residential
HMBG	Hotel/motel/boarding/guest house
OAD	Office/administration/department
SCC	Schools and child care
ReHE	Research and higher education
CuLe	Culture and leisure
Sprt	Sports facilities
Med	Medical
PWSO	Production/work-shop/storage/operations
Trade	Trade
Trans	Transport
Tech	Technical/utility building
Other	Other non-residential buildings
None	No building

4.3 Choosing sample data

The category with the most current survey data (September 2018) is 'office, administration and department buildings' (OAD) with 161 cases. So, this category will be chosen for the application of the methodology. For these 161 cases, only 88 buildings have information concerning their geometry (IWU et al. 2018). The following procedure still considers all 161 buildings. However, the generic average geometry will be developed with the smaller dataset.

4.4 Determination of relevant building parameters in ENOB:dataNWG

The ENOB:dataNWG database used for this case study does not provide all required information about building parameters, which have been determined in Table 1. Hence, this database has to be examined for suitable explanatory parameters to substitute the required building parameters as well as possible. Data not provided by ENOB:dataNWG is information on foundations, interior walls and pillars, as well as doors. These missing attributes have to be estimated according to the given information in the literature. Thus, the building age, construction types, information on the basement, roof shape and windows are selected as main parameters. The window-to-wall ratio in the dataset does not affect the construction types, due to the fact that post-and-beam constructions are part of the construction types of the exterior wall (IWU et al. 2018). Therefore, the explicit window information is not part of the main parameters describing the archetypes. The parameters in Table 3 are the selected main parameters for creating the NRB-archetypes with the ENOB:dataNWG database as the main input source.

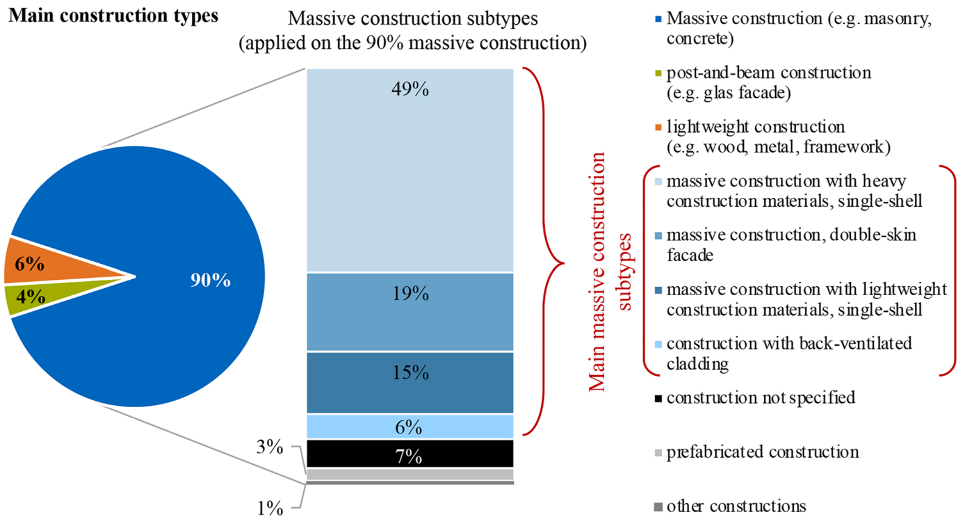
4.5 Development LCI archetypes for OAD sample data

After choosing the main parameters for the NRB-archetype development, further statistical analyses of them are necessary. First, all possible combinations of the parameters in Table 3 define the building archetypes.

Table 3 Main parameters from IWU et al. (2018) for describing the NRB-archetypes

Main parameters
Main construction type
Facade construction type
Roof shape
Basement
Building Age

Fig. 2 Results of IWU et al. (2018) on the shares by the number of main construction types (left) and massive construction subtypes (right) of the office and administration buildings category



For the assessment and determination of the main construction type, the façade construction type can be seen as the main parameter. First, the homogeneity of the buildings is clarified. The homogeneity describes if the building consists of one or more construction types. An analysis of the OAD buildings case study reveals that in this test sample, 93% of all façades are based on one construction type (IWU et al. 2018). So, it will be approximated that all buildings are defined by just one type of façade construction. The next step is the identification of the main façade construction type and consequently the main construction type at the building level. Hereby, a direct correlation between the main façade and the overall main building construction is assumed. Recorded main construction types in the ENOB:dataNWG database are 'massive', 'lightweight' or 'post-and-beam constructions'. Thereby, the massive construction type represents 90% of all surveyed construction types over the different building age classes. The massive construction type is further divided into seven subtypes, which lead to four main massive construction subtypes that can describe 80% of all OAD buildings in this case study (Fig. 2). These four subtypes are '*single-shell, massive construction with heavy construction materials*' with a share of 49%, '*double-skin façade, massive construction*' with a share of 19%, '*single-shell, massive construction with lightweight construction materials*' with a share of 15% and '*construction with back-ventilated cladding*' with a share of 6% (Fig. 2) (IWU et al. 2018).

Based on these construction subtypes, it is possible to describe four archetypes. For further characterisation, the two parameters, roof shape and basement, are combined with the construction types. Applied on the sample dataset, 14 combinations are possible (Fig. 3) which represent about 80% of all case study OAD buildings (IWU et al. 2018).

The 14 combinations can deliver a rough assessment of the building structure and construction materials. Structural differences within these archetypes exist due to historical differences in architecture. On the one hand, materials were chosen due to historical events, e.g. the shortage of resources in World War II in Germany. On the other hand, the German regulations on thermal insulation such as the thermal protection ordinance and energy-saving ordinance as well as general structural regulations since the year 1952 defined differences in the building's envelope design (BMVBS 2011; Loga et al. 2012).

Considering the historical differences, it is useful to subdivide the archetypes by their building age. Therefore, current building archetype development studies, such as the TABULA project, use building age classes for categorisation. This case study compares two current approaches to building age classes. First is the actual most known classification by TABULA for RB, which is aligned to 'historical incisions, dates of statistical surveys and changes in building regulations' (Loga et al. 2015). This classification defines 12 building age classes (Table 4). Applied on the 14 combinations of this case study, this categorisation theoretically results in 168 archetypes. However, in 'reality', only 66 archetypes subdivided by building age classes exist in the database sample (IWU et al. 2018).

Based on the TABULA age bands, also BMVBS (2011) defines building age classes. These are explicitly defined for NRB but deliver a much broader division. These broad age bands have been distinguished by 'prevailing building practises' (BMVBS 2011) and regulations on thermal insulation since the middle of the twentieth century. Due to the focus on energetic evaluations, the main criteria for defining the building age classes are the U-value of the building envelope. Thus, the building age band archetypes are reduced to

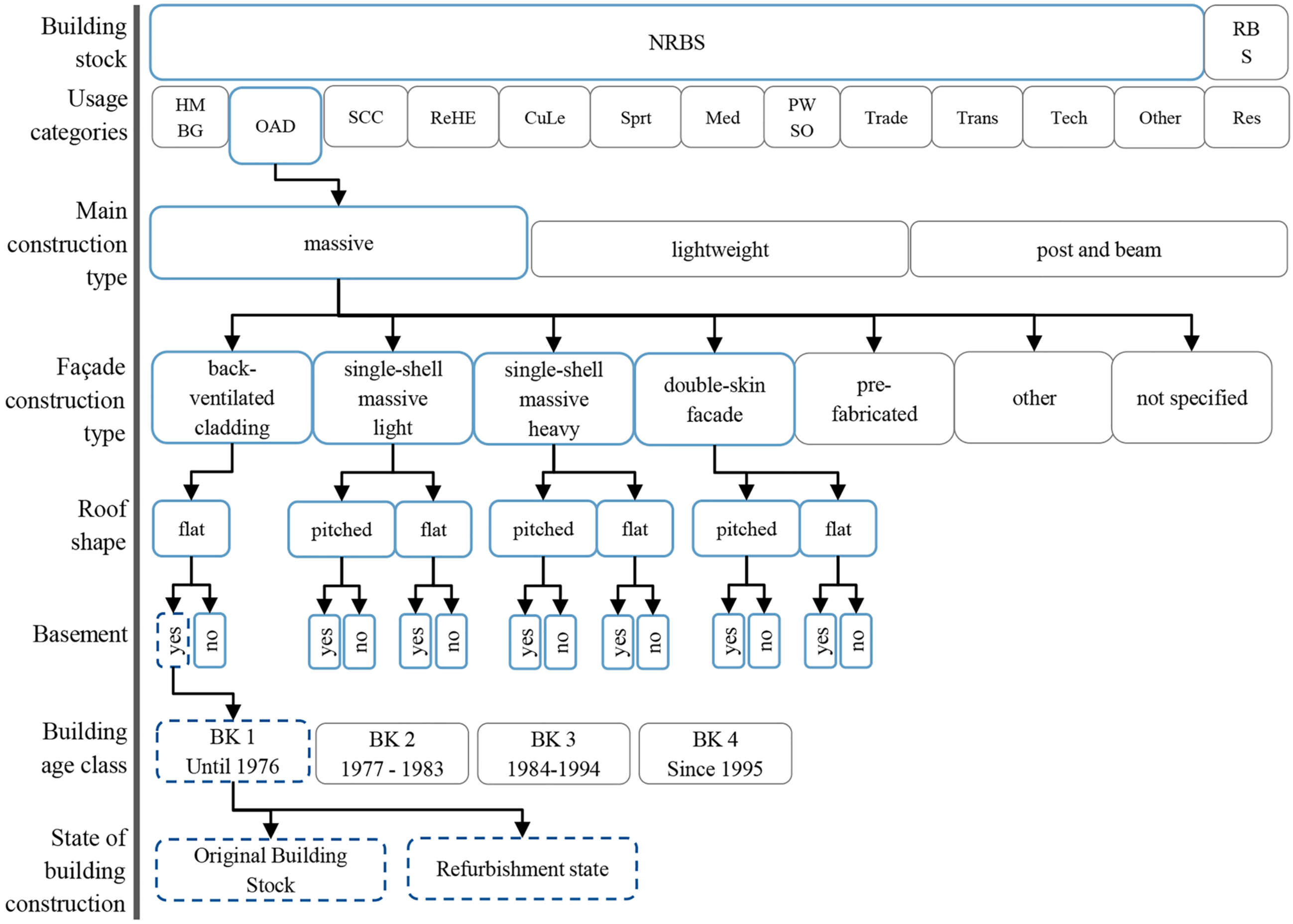


Fig. 3 Combinations possible in IWU et al. (2018) of main parameters. BK Building Age Class. Blue frames represent the case study archetype clustering implemented, while blue-dotted frames exemplarily show further clustering by building age classes and the state of building construction

Table 4 Building age classes by TABULA (IWU 2018) and BMVBS (2011), *BK* Building Age Class

Building Age	Building Age Class TABULA (IWU 2018)	Building Age Class BMVBS (2011)
Until 1859	BK A	BK 1 (until 1976)
1860–1919	BK B	
1919–1948	BK C	
1949–1957	BK D	
1958–1968	BK E	
1969–1978	BK F	
1979–1983	BK G	BK 2 (1977–1983)
1984–1994	BK H	BK 3 (1984–1994)
1995–2001	BK I	BK 4 (since 1995)
2002–2009	BK J	
2010–2015	BK K	
Since 2016	BK L	

4. Also applied to the 14 combinations in this case study, 56 archetypes are possible, but just 37 of these archetypes can be found in the database sample (IWU et al. 2018).

Considering the complexity of NRB and the number of archetypes to describe them, the reduced building age classes by BMVBS (2011) lead to fewer archetypes. These 37 archetypes are used for further analyses.

Still, 37 archetypes can be considered too many for the typology of the OAD buildings and are not expedient for a practical and broad application. Considering that the actual state of the typology can describe 80% of all OAD buildings of the case study sample (IWU et al. 2018), a potential for further reductions still exists. Therefore, these archetypes are analysed by their relative frequency. Due to an iterative process of reduction, the archetypes, which only represent one or two cases, are eliminated. The archetypes are to represent at least 50% of all OAD buildings, which can be realised by fewer archetypes. For this purpose, three thresholds will be assumed and tested (Table 5). These thresholds eliminate archetypes that represent less or equal to 1%, 2% or 3% of

Table 5 Thresholds, results and anomalies from IWU et al. (2018)

Threshold	Number of archetypes (-)	Number of buildings per archetype (BpA) (-)	Number of OAD buildings (-)	Share of BpA to OAD buildings (%)	Anomalies
1%	22	141	161	71	BK 2 missing
2%	11	88	161	55	BK 2 missing
3%	7	72	161	45	BK 2 missing

the entire OAD dataset. The first threshold at ≤ 1 building per archetype (1% of OAD dataset) delivers 22 archetypes, describing 71% of all OAD buildings. The second threshold at ≤ 3 buildings per archetype (2% of the OAD data set) delivers 11 archetypes representing 55% of all OAD buildings, and the last threshold at ≤ 4 buildings per archetype (3% of the OAD data set) delivers 7 archetypes directly representing 45% of the input OAD dataset buildings (IWU et al. 2018) (Fig. 4).

To choose the right threshold, additional factors are considered. Besides the number and the share of archetypes, the threshold variations ideally represent all identified construction types and building age classes. After the application of the thresholds, all construction types are considered in the archetype sum. However, every threshold variation is lacking the building age class BK 2 (1977–1983) (Table 5) (IWU et al. 2018). The continuous representation of all construction types leads to the decision to set the threshold at 2% with a reasonable share and number of archetypes.

Therefore, 11 archetypes will describe the OAD buildings of the database sample. These archetypes describe 55% of the OAD buildings by frequency and 65% by GFA (IWU et al. 2018). Taking a closer look at the 11 identified archetypes (Table 6), it is obvious that archetype number 22 with 4 buildings cannot be defined due to a lack of available information on the building age. This leads to a reduction to 10 archetypes that now are describing 52% by frequency and 63% by GFA (IWU et al. 2018).

4.6 Defining the archetype geometry and associated materials

After defining the 10 archetypes (number 07 cannot be used due to missing data on the building age class) by their building design, more detailed information on the buildings is implemented. It is necessary to analyse the building archetypes by their geometry and defining the materiality of the building construction components for LCI. Due to the given parameters in Sect. 3.2, the values of the geometric model and the dimensions of the building elements are further defined in this section. The methodology is explained by the example of archetype number 5 (see Tables 6 and 7).

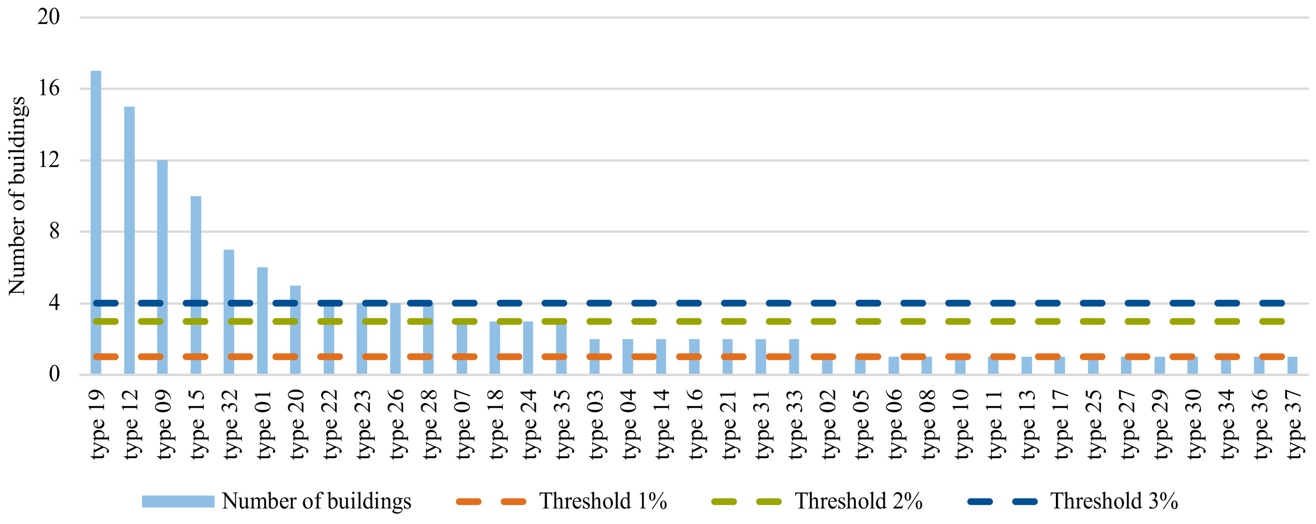


Fig. 4 Sample of the current ENOB:dataNWG database structured by the number of buildings per specific reference building: 129 buildings out of 161 (IWU et al. 2018)

Table 6 Final OAD archetypes, from IWU et al. (2018), *BK* building age class, *GFA* gross floor area, *N.A.* no data available

Type no	Type no. according to Fig. 4	Construction type	Roof shape	Basement	BAC	Number	$GFA_{Type\ i}$ (m^2)
01	01	Back-ventilated cladding	Flat	Yes	BK1	6	17,497
02	09	Single-shell massive light	Pitched	Yes	BK1	12	11,931
03	12	Single-shell massive heavy	Flat	Yes	BK1	15	26,200
04	15	Single-shell massive heavy	Flat	Yes	BK4	10	103,869
05	19	Single-shell massive heavy	Pitched	Yes	BK1	17	39,806
06	20	Single-shell massive heavy	Pitched	Yes	BK3	5	4045
07	*22*	*Single-shell massive heavy*	*Pitched*	*Yes*	*N.A*	*4*	*4544*
08	23	Single-shell massive heavy	Pitched	No	BK1	4	2528
09	26	Double-skin façade	Flat	Yes	BK1	4	8230
10	28	Double-skin façade	Flat	Yes	BK4	4	9508
11	32	Double-skin façade	Pitched	Yes	BK1	7	22,746

4.6.1 Building geometry

As mentioned in Table 1, the areas of exterior walls, basement walls, windows, roofs, floors and foundations have to be determined. The database sample on OAD buildings delivers basic values for this evaluation. These basic values are the external dimensions of the buildings, like the base area, building circumference, building height and the number and height of the floors. Additionally, the values for GFA and the building compactness are calculated. All archetypes are analysed by the frequency of these base values. To determine the matching values, the minimum, maximum, mean and median are evaluated. Furthermore, the distribution of the base values is analysed in histograms. This can be observed by checking the example of the base area for archetype number 5. The histogram shows that the median value is the most plausible one because it leaves out the extreme values (Fig. 5). Based on that method, it is possible to choose the most plausible values to define the building's external dimensions as seen in Table 7. To align the statistical values on measurements that occur in the actual German building practice, these values (Table 7) are converted, to comply with the German brick dimensions. For example, the statistical base area of 319 m^2 (Fig. 5) is converted into 317.63 m^2 (Table 7).

Table 7 Model values of archetype 5. Calculated from IWU et al. (2018) values and converted to German brick dimensions

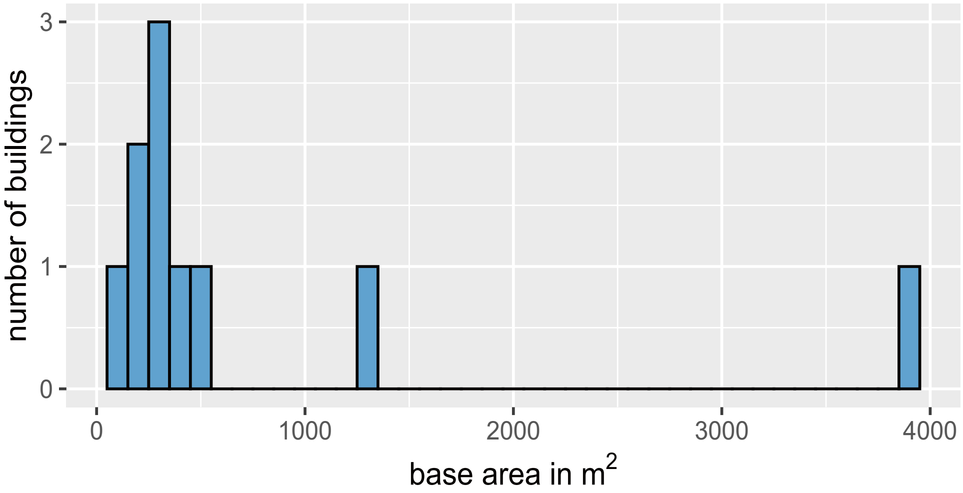
Parameter	Functional unit	Result
Base area	(m^2)	317.63
Max. building length	(m)	23.99
Mid. building width	(m)	13.24
Perimeter	(m)	74.46
Mid. building height	(m)	12.00
Fenestration share	(–)	0.375
Floor number	(–)	2
Basement number	(–)	1
Floor height	(cm)	2.70
Basement height	(cm)	2.50
Gross floor area (GFA)	(m^2)	952.88
A/V	(–)	0.42

4.6.2 Area of building construction components

After defining the base values, the areas of the building construction components are calculated. The calculated areas comply with the parameters described in Table 1. These are the areas for exterior walls, windows, basement walls, base plate, basement ceiling, floors, foundation, roof, interior walls and doors. Almost all building construction components can be calculated based on the information given by the database on OAD buildings (IWU et al. 2018). The results are presented in Table 8. Assumptions have to be made only for the foundations, roof, interior walls and interior doors.

Either the base plate, individual foundations or strip foundations can be used as the foundation. Based on an analysis of office buildings by Gruhler and Deilmann (2015), a share of 30% of the base plate area can be assumed for the foundations. The roof area depends on whether the roof is flat or pitched. The definition of a pitched roof in the database IWU et al. (2018) describes a roof pitch over 22°. Information on the maximum roof pitch of German buildings leads to a pitch of 60° (BauNetz Media GmbH n.d.). Therefore, all buildings with a pitched roof are considered as having an incline of 41°. This assumption bares uncertainties and should be validated when applied. Interior walls and doors are estimated applying the same method as used for the foundations. The analysed office buildings in Gruhler and Deilmann (2015) show an average internal wall area of 78% of the building's GFA. The interior doors are approximated by the analyses

Fig. 5 Base area (m^2); calculated statistical values: min = 140; mean = 759; median = 319; max = 3948. (IWU et al. 2018)



of Gruhler et al. (2002) for RB, which lead to a share of 13% of interior wall area.

4.6.3 Building construction details

Aside from the construction type of the exterior walls, only little further information on materials and construction details is available in ENOB:dataNWG. As described in Sect. 3.4, the details to close data gaps are taken from literature for RB (**Error! Reference source not found.**). This is possible due to the fact that OAD buildings show similar construction types as RB. The construction details in the literature describe the state of the original BS. The refurbished BS is developed based on information from ENOB:dataNWG (IWU et al. 2018) on the insulation for exterior walls, roof, basement walls and the building's base plate. Additional information on the date of construction and thickness of the insulation is given for the exterior walls and the roof. Data gaps are closed using information from Böhmer et al. (2010), Kierdorf et al. (2017) and IWU et al. (2018). To assess the degree of refurbishment, the *U*-values of the constructions are calculated.

The construction details are defined for every archetype as well as every building construction component according to Table 1. The following Table 9 shows the general results on the building construction components of archetype number 5. The table is explained in the example of the exterior walls.

The exterior walls of archetype number 5 are described by ENOB:dataNWG (IWU et al. 2018) as *single-shell, massive construction with heavy construction materials*. Both studies Böhmer et al. (2010) and Kirchof and Gissel (2009) show that the main construction type for this archetype is a solid brick construction plastered on both sides. Further possibilities identified by the studies above are constructions with gravel concrete and lime sand bricks. There is no further information on the percentage share of each construction type. Due to the mean *U*-value of constructions in BK1 of 1.5 W/m^2 K, as defined in BMVBS (2011), a solid brick construction can be assumed for this archetype. Most buildings of archetype number 5 within the building age class were constructed before 1948 (IWU et al. 2018).

The refurbished BS is defined by information based on ENOB:dataNWG (IWU et al. 2018) referring to the 17 buildings describing archetype number 5 (Table 6). These show that 18% of the buildings have been insulated. Twelve

Table 8 Building component areas of archetype 5. Calculated using IWU et al. (2018)

Building component	Functional unit	Measures
Gross exterior wall area	m^2	893.52
Net exterior wall area	m^2	558.45
Window area	m^2	335.07
Basement wall area	m^2	186.15
Base plate/basement ceiling/floors	m^2	317.63
Foundation	m^2	95.30
Roof area	m^2	420.86
Gross interior wall area	m^2	743.25
Net interior wall area	m^2	644.15
Doors	m^2	99.10

Table 9 Overview on construction details for archetype 5

		Original building stock	**Refurbished building stock**	
Building component	**Construction type**	**Information on insulation** (IWU et al. 2018)	**Information on insulation** (IWU et al. 2018)	**Information on building construction**
Exterior Wall	Massive, solid brick	Not insulated 82% (14/17)	Insulated 18% (3/17) Insulation thickness 30 cm (1/3)	Kirchof and Gissel (2009), p. 8; Kierdorf et al. (2017), appendix: AW_massiv;
Basement Wall	Massive, solid brick	Not insulated 41% (7/17)	Insulated full 6% (1/17) Insulated partly 18% (3/17) No information 35% (6/17) Insulation thickness: N.A	Kierdorf et.al. (2017), appendix KW_Polystyrol (based on Kirchof and Gissel (2009), pp. 11 and 88)
Base Plate	Massive, concrete	Not insulated 71% (12/17)	Insulated: 12% (2/17) No information 18% (3/17) Insulation thickness: N.A	Kierdorf et al. (2017), appendix Bodenplatte (based on Böhmer et al. (2010), p. 177)
Basement Ceiling	Possible constructions: vaulted ceiling; reinforced concrete slab; perforated brick ceiling with reinforced concrete joints and cover; ribbed slab — precast reinforced concrete units filled with pumice concrete Further determination was not possible			
Upper Floor	Wood-beamed ceiling	Not insulated 82% (14/17)	Insulated: 18% (3/17) Fully (100%) 12% (2/17) Partly (50%) 6% (1/17) Insulation thickness 30 cm (1/3)	Kierdorf et al. (2017), appendix: OGD_Holz_MF (based on Kirchof and Gissel (2009), p. 136)
Ceiling	Wood-beamed ceiling	No information on ceilings in ENOB:dataNWG		Kierdorf et al. (2017), appendix: OGD_Holz_MF (based on Kirchof and Gissel (2009), p. 136)
Roof	Pitched roof, wooden beams	Not insulated 59% (10/17)	Insulated 41% (7/17) …fully (100%) 29% (5/17) …largely (75%) 6% (1/17) …mainly (50%) 6% (1/17) Insulation thickness 25 cm (4/7)	Böhmer et al. (2010), pp. 124,129; Thiel and Riedel (2011), p.55;
Interior Walls	Massive; vertically perforated brick sand-lime brick cellular concrete	No information on interior walls in ENOB:dataNWG		Gruhler and Deilmann (2015), p. 29
Windows	Wood/PVC/Aluminium	Double glazed 88%	–	Kierdorf et al. (2017), appendix Fenster (based on the assumption of the author)
Doors	No information is available. Assumption author: wooden doors or plastic doors			
Foundations	Buildings until 1970 should have reinforced concrete (Gruhler and Deilmann 2015). Older Buildings could have brick or tamped concrete (Schedl 2018)			

per cent were subsequently insulated, and 6% were insulated at the time of construction. The insulation thickness of 30 cm is based on the information of one single building. The remaining 16 sample buildings in the archetype do not provide information on this parameter (IWU et al. 2018). Nevertheless, this value is plausible, because the refurbishment was executed to a passive-house standard. For further processing, these construction details can be considered as the basis for conducting simplified LCAs for the OAD BS.

5 Discussion

This paper describes a methodology to identify the most relevant information of a building database to develop an LCI typology and consequently conduct simplified LCI studies. To verify the applicability of the methodology, a sample case study of the German database ENOB:dataNWG is used to develop building archetypes of OAD-buildings as an example for NRB.

In this process, the minimum data, necessary for LCI calculation of OAD buildings, is identified. Essential information on relevant materials of construction components can be found in existing LCA certification methods like the German BNB system. As seen in Sect. 3.2, necessary data for LCI includes the type and mass of the utilised materials for exterior walls (including windows), roofs, floors, foundations, interior walls and doors.

The method's workflow is the same for other NRB, but the necessary data might be very different. To describe most buildings of a BS, archetypes can help to reduce the complexity of existing material combinations. However, as the material composition is only one relevant and detailed aspect for an LCI archetypal development, the first step is to separate the BS into building usage categories. Further information on the building geometry (e.g. base area, building length and width, average building height, window-to-wall ratio, floor numbers and heights) and the building construction materials (e.g. massive or wooden constructions of roof or walls, building age and renovation state, thickness of existing insulations) are necessary parameters for estimating the overall material volume and weight to conduct an LCI.

The data for the case study, based on the ENOB:dataNWG database, provides only partial information on the building construction materials and building geometry. Table 10 illustrates the required information and available data sources for conducting an LCI and rates the data quality. For example, it shows that there is no information available on the material of construction components of doors (second column), but assumptions about the geometry can be made according to relevant literature (third column).

The ENOB:dataNWG database provides resilient information for all NRB on the geometry of the buildings and the area of the building construction components. Data gaps exist for the building construction materials, also for OAD buildings. Therefore, most of the detailed data on the construction is based on other studies focussing on the construction material and further assumptions (see Sect. 4.5.2).

The given data in this case study is not adequate to generate final OAD archetypes, which can be used for further LCI studies, because the ENOB:dataNWG project does not cover all required data. ENOB:dataNWG focuses on the structure (usage categories and numbers), energy-related properties of the buildings and progress of refurbishment in the NRBS. LCA and embodied materials were not part of the project's scope. The utilised information was not initially gathered for the estimation of material quantities. Consequently, not all parameters for material LCI are available in ENOB:dataNWG. More data must be collected and analysed for creating statistically representative LCI archetypes. Currently, several assumptions have to be made due to missing data. Especially defining the material composition of OAD buildings, volume and weight of foundations, interior walls and interior doors required assumptions. Using information contained in the BKI database (building cost information of the German architecture chamber) on office buildings (Gruhler and Deilmann 2015), the foundation area can be calculated by adding 30% to the base area of the building. Most of the foundation is generally made of concrete (Gruhler and Deilmann 2015). However, for older OAD buildings, one can assume that brick construction and tamped concrete were used (Schedl 2018).

The vertical surface area of interior walls of OAD buildings can be assumed as 78% of the GFA. Interior wall constructions in the German BS are vertically perforated bricks, limestone and cellular concrete (Gruhler and Deilmann 2015). No information on interior doors in OAD buildings can be found. According to Gruhler et al. (2002), the area of interior doors represents a share of 13% of the vertical interior wall area of multi-family houses. The way of constructing residential buildings is similar to that of OAD buildings. Both building categories (multi-family and office) are generally made to provide space for people, spending daily

Table 10 Developing archetypes for OAD buildings in ENOB:dataNWG (IWU et al. 2018) — overview of required information for LCI and available data regarding construction materials and building geometry

Required information for LCI	Database for building construction materials	Database for building geometry
Exterior and basement walls including coating	Resilient data[1]	Resilient data[1]
Windows	Resilient data[1]	Resilient data[1]
Roof	Resilient data[1]	Resilient data[1]
Internal floors and ceilings	Assumptions[1]	Resilient data[1]
Base plate and ground-level floor	Assumptions[1]	Resilient data[1]
Foundations	Approximations[2]	Assumptions[1]
Interior walls including coating and supports	Approximations[2]	Approximations[2]
Exterior and interior doors	No data available	Approximations[2]

[1] ENOB:dataNWG.

[2] For example, Kirchof and Gissel (2009); Böhmer et al. (2010); Thiel and Riedel (2011); Gruhler and Deilmann (2015); Kierdorf et al. (2017); Schedl (2018)

much time in both. This influences typical geometries and zoning in a similar way. Both have staircases and corridors to access flats or offices with sanitary areas, kitchens, technical rooms, recreation and meeting areas (Jocher et al. 2012; Neufert et al. 2012). While open floor offices have probably less doors, the door area of single offices is probably similar to those of multi-family houses (Quellen EINBAUEN).

Therefore, it is assumed that the proportion of the area of interior doors is in the same range for OAD buildings.

As seen in Sect. 4.4, some OAD building archetypes of minor representation of the overall stock are neglected. This is necessary to reduce the number of building archetypes to a feasible number. The threshold for neglecting archetypes in Sect. 4.4 is set to reduce the total archetype number. Further research is necessary to identify the ideal threshold for reducing OAD and other NRB archetypes.

Due to the fact that there is no information about construction materials on German NRBs available, most of the above-mentioned studies focus on RBs. Using this data for OAD buildings is reasonable due to the similarity between RBs and OAD buildings regarding the usage and technical equipment. Other usage categories like *Med*, *CuLe*, *ReHE* and *SCC buildings* (abbreviations are defined in Table 2 could be approximated with this construction information as well). On the other hand, categories like *Tech* and *Sprt buildings* would be difficult to describe using this assumption. For these, the used materials and building construction components will need to be proven or evaluated via further research. In addition, further research is needed to quantify the building service components, because they could dominate the material quantities and environmental impacts of building constructions in a few cases of NRB. This paper is focused on German OAD buildings. Due to the differences in cultural and climatic conditions across the EU, the results are not applicable for the whole spectrum of the EU-BS. Nevertheless, the reviewed literature in Sect. 2 can be applied to other countries with similar archetypes, like Austria or the Netherlands. Building construction is mainly based on the TABULA project (Loga et al. 2016), which defined building construction details for different European countries. By using this information, the usage categories mentioned above could be described for further countries.

This determination of archetypes based on the ENOB:dataNWG database comes with some uncertainties. First, the chosen archetypes only describe massive constructions, since 90% of the OAD buildings in the data set sample of ENOB:dataNWG have a massive main construction (see Fig. 2). To receive a reasonable small number of archetypes, further reduction measures are applied, as seen in Sect. 4.4. This led to 10 building archetypes describing 52% of OAD buildings by frequency and 63% by GFA. Because the ENOB:dataNWG database was still under development during this analysis, this percentage of representation is only true for the sample utilised in the case study. A second main source of uncertainty in the context of the developed archetypes is the uncertainties of the data itself. In case of fully available dataset, the associated variances of the values should be analysed accordingly. The data variance and standard error should then be provided along with the average or typical values of the archetypes. The uncertainties of the data used for enriching the archetypes with missing information can, in case it is not provided in the publications, only be estimated. This uncertainty quantification is an important next step in the development of building archetypes for simplified LCI and consequently LCA.

6 Conclusion

The shown methodology provides a workflow to assess LCI of building construction materials of NRB. Using a two-part approach to develop a methodology for creating LCI-focused NRB typologies led to several relevant results. The theoretical development of the methodology formed the groundwork by using relevant literature on creating archetypes and simplified LCI and, on this basis, LCA studies. These methods were tested and extended with a sample database of the German NRB stock, more precisely with a sample database of OAD buildings. Therefore, requirements for an LCI-based typology and the minimum database content have been provided. Also, a suitable database assessment methodology for the development of archetypes has been introduced. This includes a scaling method for selecting a defined number of archetypes. The method was developed and tested. This paper shows how to deal with relevant literature and illustrates which assumptions can be made for closing data gaps in typology development. When this method is applied, the resulting building typology can be utilised not only for LCA studies but also for the quantification of other material flows concerning the NRBS, for example to identify urban mining potentials or demolition waste forecasts.

The methodology does not consider the LCI of building service components, because literature about it is exceedingly rare and building specific and does not support the extraction of archetype-specific values. Nevertheless, the environmental performance of building service components can play a crucial role for some NRB, for example, laboratories. The methodology is developed with a sample database of German NRB stock. In other countries, the information given by literature can be different and less detailed. So, it could be necessary to adapt the methodology to other building stocks and their given data. Finally, it must be mentioned that developed archetypes can only be as resilient as the given database. ENOB:dataNWG, for example, describes NRB typologies at the national level only. In this case, the archetypes cannot be used for assessing international or regional BS. This shows the necessity of data acquisition at an international level, too.

7 Outlook

A NRB typology with a focus on LCI has several possible use cases. This fundamental research can be used for the application of simplified LCA studies to assess the embodied energy and GHG emissions of BS. For example, it can be implemented in 'level(s)', which is a framework launched by the European Commission to assess and report the sustainability performance of buildings (DG Environment 2021). A European-wide implementation would support a uniform assessment of LCI and hence LCA. Furthermore, if the methodology is executed with the final database of ENOB:dataNWG, the developed archetypes can be used as a reference for assessing other NRBS. That allows comparing single buildings and refurbishment options with the corresponding archetype to rate the performance. Additionally, the archetypes can easily be used for communication of refurbishment options and their embodied impacts. By linking the embodied impact with the operational impact to develop further archetypes, a comparison of the required energy inputs and operational energy savings can easily be conducted. This comparison would therefore enable users to estimate the overall life cycle impact of different refurbishment measures. Furthermore, such an LCI-based building typology also allows for an estimation of the environmental impact of a replacement building vs. a refurbishment option for the existing building. NRB typologies, except for new buildings, are not available for most countries or are only available on a rudimentary level. For future developments of NRB typologies, the embodied impacts should be considered alongside the operational phase of the buildings. This can be supported by the presented methodology.

The published data on the non-operational impacts of buildings and building refurbishment can support a greater awareness of embodied energy and related GHG emissions in general and buildings in particular. This awareness can help to further address the topic of embodied energy and resources in building regulations to improve the BS in the future.

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Data availability The dataset is part of the ENOB:dataNWG dataset, which also contains several instances of sensitive data protected under German and European data protection laws. It has been guaranteed to the building owners and users that data is not given to any third party. The exception is remote calculation (for simple analysis) or access via a visiting researcher position (for more complex analysis) at the Institute for Housing and Environment (IWU).

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