Building typology of the non-residential building stock in Germany – methodology and first results

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Abstract

In contrast to residential buildings, the stock of non-residential buildings (NRB) in Germany is not fully represented in any official statistics. This is surprising given the economic importance of this sector. Not only the increasing relevance of climate protection makes it seem reasonable and necessary to capture the scope and characteristics of this important economic sector more precisely.

The gap in official statistics could be closed by a survey based on a representative sample of building footprints and unbiased extrapolations to the whole stock, a completely new approach in the German NRB stock (Hörner 2020). The goal was to provide statistically valid data on the stock for the first time. This results in an estimated number of thermally conditioned NRBs in Germany that are relevant under the Building Energy Act (BEA) of $\hat{N}_{BEA}$=1.981 ± 0.152 million, considerably less in number but bigger in size than previous estimates (BMWi 2020 S. 30).

To map the characteristics of the building stock in an appropriate manner, a NRB typology was developed, comprising mean values of U-values, building component areas etc. and absolute frequencies of NRBs. The most important feature of the type definition is the concept of "synthetic average buildings", whose values are unbiased extrapolations from the sample to the whole stock. They are "mean estimators" in terms of estimation theory. The areas of the components of the building envelopes (e.g. facades, roofs and floor slabs) were determined from geospatial data of the sample buildings. The survey provided additional geometric values like window area fractions and roof types as well as further monitoring variables such as insulation thicknesses and the current equipment with technical systems. The great diversity of NRBs and their values were summarized in 33 types differentiated according to 11 building functions and 3 building age bands. Model input variables for building energy simulations (e.g. U-values of building components and energy expenditure factors of the heat generators) were derived from monitoring variables of the survey and age-specific properties, similar to the TABULA project for residential buildings (Loga et al. 2012).

Typologies are used to calculate the energy demand of building stocks with reasonable effort, in order to evaluate the impact of climate protection policies and to take the building stock into account adequately in scenarios. In addition, more sophisticated building stock models can be validated. So far, the current stock of non-residential buildings in Germany was mapped to a typology. Future analysis will add structural measures for energy-related modernization and calculations of the energy demand.

Introduction

THE CHALLENGE OF CLIMATE PROTECTION IN THE BUILDING SECTOR

The global climate crisis, for example, as evidenced in the severe flooding in Western Europe in 2021 (WWA 2021), the 2020 Siberian heat wave with overwintering fires (Scholten et al. 2021) and the heat wave of the Pacific North West Coast of North America in 2021 (Philip et al. 2021), is pushing the global transition to a post-fossil age. Buildings contribute significantly to energy use and greenhouse gas (GHG) emissions. The operation of residential and non-residential buildings cause 17 % and 10 % of all global energy-related GHG-emission respectively (UNEP et al. 2021). Accounting for the indirect embodied emissions the global building stock (BS) is responsible for 37 % of global energy-related GHG-emission (UNEP et al. 2021).

In Europe the building stock is responsible for 36 % (Brøgger, Wittchen 2018; Tuominen et al. 2014) of the territorial GHG-emissions. In Germany the non-residential and residential building stocks accounted for 14.2 % and 27.4 % of the total final energy consumption in 2010, respectively (IEA-BEEP 2019). Therefore, the energy transition in the building sector[1] plays an important role in many climate protection strategies. For climate change mitigation, a decisive factor is how quickly and profoundly the existing buildings can be modernized in terms of energy efficiency, through measures that reduce the final energy consumption[2], and through the decarbonization of the energy supply. At the same time, material-related emissions must be minimized.

Driven by the groundbreaking ruling of the Federal Constitutional Court (BVerfG 2021) about the impact of climate change in the future, the German Government has amended the German Climate Protection Act (CPA) and sets net GHG-neutrality in 2045 as the national climate protection target (BReg 2021) for all sectors including the building sector.

BUILDING TYPOLOGIES

To accomplish this, reliable information on the building stock, ideally with known uncertainties, are necessary to understand the status of the stock and to identify the most emission-, energy- and cost-efficient options of BS decarbonisation pathways via scenario simulations. Building typologies are an established form of communicating the status of a BS. Further, they are a flexible data aggregation option for the input of building stock and urban building energy models due to their flexibility to incorporate different data sources (Bischof, Duffy 2022; Mastrucci et al. 2017; Reinhart, Cerezo Davila 2016).

We essentially distinguish two main areas of application of building typologies: There are typologies that work with real example buildings for use in energy consulting, representing the first application area. Consultants can use case studies of the example buildings to illustrate, for example, the effect of energy-efficient modernization measures, without having to carry out complex data collection on a specific object first. In the second application area, building typologies are applied as input data for the modelling (most commonly of building energy consumption) of BSs. Such an approach for example was taken by (García Kerdan et al. 2015).

Generally, typologies are developed in a clustering process (Kluge 2000), using variables that significantly correlate with the typology's target value (e.g. the operational energy consumption) to separate the building stock in clear sub-stocks. These sub-stocks are represented each by a so-called archetype or building type (further only the term archetype is used). An example of an archetype is an "Office, Administrative or Government Building" in the age group "New Buildings (from 2010)". The set of all building archetypes resembles the building typology. A common aim of a typology development is the reduction of the diversity of the target population, as a trade-off between a detailed consideration of all possible combinations of relevant attribute values occurring and keeping the total number of types as small as possible for the representation of the population. (Buschka et al. 2021)

Many typologies have been developed for building stocks, residential (Eicke-Hennig, Siepe 1997; Famuyibo et al. 2012; Filogamo et al. 2014; Klauß et al. 2009, 2010; Loga et al. 2015, 2016; Ortlepp et al. 2016) and non-residential building stocks (BMVBS 2011; Deilmann et al. 2013; García Kerdan et al. 2015; Gierga, Erhorn 1993; Hjortling et al. 2017; Klauß et al. 2010; Kretzschmar et al. 2019; Mittner 1992; Stein, Hörner 2015; TABULA Project Team 2012) alike.

RESEARCH GAP AND OBJECTIVES

No approach for a non-residential building typology based on a statistically valid database could be identified, neither as a full survey nor as a representative sample. None of the above-mentioned typologies, is representative in a statistical sense, due to generally poor data availability, not providing sample data randomly drawn from the building population in question. Therefore, the aim of this work is to use statistically representative data of the German non-residential building stock for the development of a corresponding typology, providing average buildings as archetypes, with quantifiable variable deviations, allowing for an uncertainty quantification of any further archetype-based analysis.

THE DATA-SET

The above stated objective can only be achieved with a suitable data-set at hand. Fortunately, the project ENOB:dataNWG[3] undertook the task of gathering statistically representative data of the German non-residential building stock in a sample survey for the first time (Hörner 2020). Due to the lack of a building register, the Official Building Polygons (BPs) of Germany (HU-DE)[4], comprising all building shapes of the official Land Registry in Germany, served as sampling frame. In an on-site screening subsequent to the sampling, relevance of the poly-

1. The sectors are defined in the German Climate Protection Act (CPA) (BReg 2021 S. 19) according to the source categories of the Common Reporting Format (CRF) of the United Nations Framework Convention on Climate Change (UNFCCC) and the corresponding European implementing acts (currently Implementing Regulation EU No. 749/2014) or according to a successor regulation adopted on the basis of Article 26(7) of the European Governance Regulation (CPA Annex 1). Source categories in the building sector include the combustion of fuels in households, commerce and public authorities, as well as other activities related to the combustion of fuels (in particular in military installations). Annex 2 of the CPA lists the permissible annual emission quantities.

2. In the 2nd Progress Report on the Energy Transition, The Energy of the Future, reporting year 2017 (BMWi 2019 p. 105), the final energy consumption in buildings is referred to as heat demand. This "building-relevant final energy consumption" accounts for 34.5 % of total final energy consumption and considers private households, commercial and services sectors (GHD) and industry. "The building-relevant final energy consumption for heat (heat demand) is the consumption values for room heating (heating), room cooling and water heating. In addition, in non-residential buildings, the electricity consumption for the (permanently installed) lighting is accounted for."

3. ENOB:dataNWG – Research Database Non–Residential Buildings: Primary Data Collection to Record the Structure and Energy-related Quality of Non-Residential Buildings in Germany.

4. Available at the "Central Office House Coordinates and Building Polygons" (ZSHH), https://www.adv-online.de/Products/Real-Estate-Cadastre/House-Coordinates/

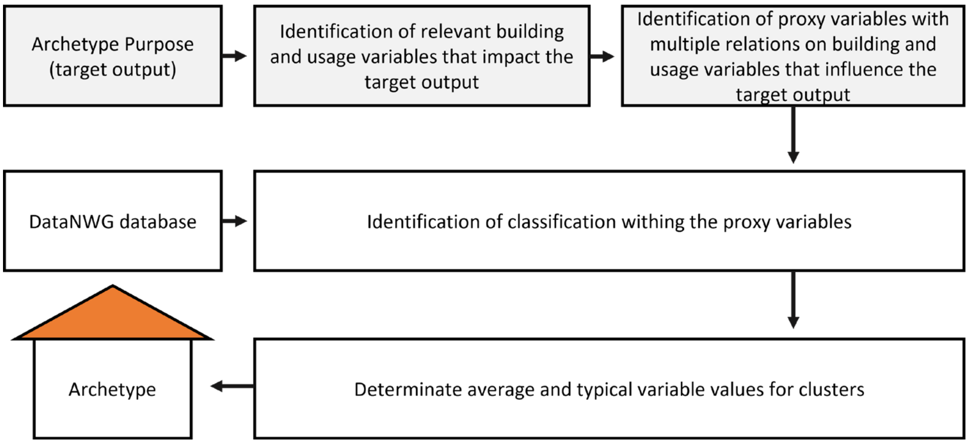

Figure 1. Non-residential building archetype development methodology.

gons to the survey was assessed and necessary data were added, such as references to the owners.

In the survey, primary data on fundamental values (such as building function, age class, etc.), the state and dynamics of energy-related quality (such as thickness of thermal insulation, year of installation, percentage of building envelope area already insulated etc.) and the decision-making processes for modernization were determined. The data was collected along an extensive questionnaire in online or computer-assisted telephone interviews. In addition, the official 3D Building Models of Germany in Level of Detail 1[5], which are available throughout Germany, were used to obtain geometric values of all NRBs in the sample, such as circumference, envelope areas according to main cardinal directions and volumes.

The sample of the ENOB:dataNWG project was designed in such a way that "representativeness"[6] is achieved. In the sense of sample theory this means that the unbiased estimation[7] of true values of the (target) population`s parameters from the sample is possible. As a result, the variable values of the average buildings can be unbiasedly estimated as average values of the sample buildings' variables. The associated sampling uncertainty is quantifiable and was kept acceptable to the projects objectives by appropriately selecting the size of the sample (100,000 BPs). The sampling model of the project ENOB:dataNWG is described in detail in (Cischinsky 2021) and is therefore not repeated here.

5. Available at the "Central Office House Coordinates and Building Polygons" (ZSHH), https://www.adv-online.de/Products/3D-Building-Models/

6. The term "representativeness" is a colloquial term not defined in sample theory; it is therefore enclosed in quotation marks here. The unbiased estimate of parameters of the population from a sample is possible if three conditions are met:
Sampling must be random.
The inclusion probabilities of the non-residential buildings included in the sample must be known (they do not have to be identical though) and must be adequately considered in the estimation.
Each non-residential building must have a chance to be included in the sample, i.e. must have a positive inclusion probability.

7. In sample and estimation theory the approximate determination of the distribution or parameters of the population on the basis of samples is referred to as an "estimate" and the rule for estimation as an "estimation method". An estimator is unbiased if the difference between this estimator's expected value and the true value of the parameter is zero.

Methodology

The typology is developed following the methodology sketched in Figure 1. First the archetypes' purpose, the target output of relevance is to be defined (e.g. the building energy demand). Second relevant building and usage attributes (e.g. the envelope thermal properties) impacting the target output are identified. In a next step, proxy variables with relation to these relevant building and usage attributes (e.g. the building function) are determined, to reduce the number of clustering variables. The proxy variables database representatives are in a next step further categorized to meet the purpose of representing the diversity of the population with a minimum number of archetypes. The identified categorization of the proxy variables (e.g. via building function and building age class) acts as basis for clustering the stock into sub-stocks, the archetypes. For these archetypes the average and typical variable values are estimated from the representative sample survey of ENOB:dataNWG. These steps to develop a non-residential building typology are in detail described below.

The Typology Concept

TYPOLOGY PURPOSE AND TARGET VARIABLE

The typology purpose is to provide archetypes representing the non-residential building stock for reduced order building energy demand modelling. Since the focus is on simplified models the total number of resulting archetypes is supposed to be kept small, however, at the same time, to represent the range of construction and usage options in the very diverse non-residential building stock adequately. In particular, the typology introduced here was developed in the FlexGeber[8] project to be used as input data for the simulation of typical load profiles of building energy use, in order to quantify flexibility options between the electricity grid and the German non-residential building stock. As the typology is to act as a universal input data-set for energy demand simulations regarding the German non-residential building stock in general, target variable therefore is the building energy demand.

8. FlexGeber – Demonstration of flexibility options in the building sector and their integration with the energy system in Germany.

Table 1. Aggregation levels of Building function values as typology proxy variable.

Buildings for People	Technical Buildings
1. Office, Administrative or Government Buildings	8. Production, Workshop, Warehouse or Operations
2. Buildings for Research and University Teaching	10. Technical and Utility Buildings (supply and disposal)
3. Buildings for Health and Care	11. Transport Buildings
4. School, Day Nursery and other Care Buildings	
5. Buildings for Culture and Leisure	
6. Sports Facilities	
7. Hotels, Boarding, Restaurants or Catering	
9. Trade Buildings	

IDENTIFICATION OF RELEVANT ATTRIBUTES INFLUENCING THE BUILDING ENERGY DEMAND

The key variables with a major influence on the building energy demand and consumption have been identified by several studies such as (Corrado, Mechri 2009; Famuyibo et al. 2012; Heo 2011; Olivero et al. 2016; Smith 2009). They can essentially be assigned to two categories: Building related variables like envelope (walls, roof, floor and windows) thermal properties (Resistance and Conductivity) including thermal-bridges, size and form (Area/ Volume), technical system efficiency (heating, cooling and ventilation (heat recovery)) etc. and usage-related variables like indoor air temperature and set-points for heating, cooling and humidification, air change rate including infiltration, mechanical and natural ventilation rates, number of occupants, kind of occupants (metabolism rate), appliance power density etc.

Also, environmental factors such as the climate, site (shading situation) and orientation have a great impact on a building's operational energy demand and GHG-emission. However, as the simulations bring in the environmental factors the focus of the typology development is on the building and usage related factors.

PROXY VARIABLES FOR CLUSTERING

For clustering the population of non-residential buildings into archetypes, the above identified relevant variables, strongly correlating with the target variable (building energy demand), act as a basis for the selection of proxy variables. Two proxy variables are commonly used in building typologies targeting the energy demand (Loga et al. 2016; TABULA Project Team 2012): the construction age class (CAC) and the building function/use (BF). The reason for their common application is the correlation between them and many building values related to energy demand.

The building-related variables identified in the former subsection strongly correlate to the building's construction year. This is due to the influence of architectural trends, material availabilities, and structural, fire and energy regulations in different periods. This influence shows for example in the typical U-values (Klauß et al. 2009; Thiel, Riedel 2011) and building systems (Niklasch, Veerkamp 2014). Therefore, the CAC is a major proxy variable representing many building-related variables.

The usage-related variables can be clearly linked to building function, namely the influence of the occupancy schedules, the specific appliance power density and the occupancy load profiles (e.g. see the usage profiles of the DIN V 18599 or the SIA 2024). Their consideration is of great importance, as every measured energy consumption necessarily includes user influence. Thus, the building function is a proxy for usage-related factors.

The values of proxy variable CAC are based on the energy regulation implementation in Germany. The first thermal insulation ordinance (1. Wärmeschutzverordnung (WSchV)) was implemented in 1978 and strongly influenced the values of the building envelopes. Therefore, all buildings constructed before 1978 did not require to fulfil any minimum energy standards and are considered as "Old Buildings". "New Buildings", from the perspective of the ENOB:dataNWG data-set, developed between 2010 and 2019, are all buildings subject to the last major increase in the minimum energy standard, the energy efficiency ordinance (Energieeinsparverordnung (EnEV) 2009), effective from 2010 onward. All buildings neither "new" nor "old" were subject to different stages of energy regulation and are considered as "Intermediate Buildings".

The primary building functions listed in the ENOB:dataNWG questionnaire are suitable as values of typology proxy variable BF as well. These eleven values were developed to cover all relevant building functions of non-residential buildings in Germany summarizing former typologies and catalogues, namely the "Bauwerkszuordnungskatalog" (catalogue of non-residential building functions for the estimation of public procurement costs(ARGEBAU 2010)), the building function signing keys of the German Federal Statistical Office and the most recent (project perspective) non-residential building typology for Germany (Deilmann et al. 2013). This classification also was influenced by the necessity that the building's function had to be determinable from viewing the buildings from the outside in the Screening process of the ENOB:dataNWG project (Busch, Müller 2020).

However, sample size is a limiting factor in the formation of archetypes, especially in the BF. For some values, the proposed number of archetypes is already associated with very low case numbers in some archetypes and due to missing values in the survey (see below). Therefore, an additional aggregation level as in *Table 1* is proposed: Buildings for People (BF 1 to 7 and 9, i.e. office buildings, hospitals, hotels, etc.) and Technical Buildings (BF 8, 10 and 11, i.e. storage buildings, industrial production buildings, etc.). Significant differences in usage related factors like comfort requirements for heating, cooling, ventilation and lighting, occupancy schedules etc. are supposed along this division.

AVERAGE FROM THE SAMPLE: MEAN ESTIMATOR AND STANDARD ERROR

The archetypes of the building typology described here are "synthetic average buildings" according to the concept introduced by (Loga et al. 2012). Archetypes may be illustrated by pictures of example buildings, but are not identical to them.

The variable values of these average buildings, as explained above, are estimated from a sample, they are not derived from complete knowledge of the population. To understand the results, the terms used are defined below and their meaning is briefly explained. A detailed description of the estimation procedure is given in (Cischinsky 2021 S. 55 ff.).

Our goal in ENOB:dataNWG was to estimate population parameters like the population total t, i.e. the number of Building Energy Act (BEA)-relevant[9] NRBs in Germany, from a sample s for the (target-)population M of NRBs, applying the so-called Horvitz-Thompson estimator $\hat{t}_\pi$ (Särndal et al. 2003 S. 42) (cf. Equation 1).

$$\hat{t}_\pi = \sum_{k \in s} \frac{y_k}{\pi_k} \quad (1)$$

With

$\pi_k > 0$ Inclusion probability for NRB k

y_k variable value y of the population unit of interest k (i.e. of NRB k)

s Set of population units (i.e. NRBs) identified through sampling

Since the HT estimator divides a variable's value y of each sample NRB k by the corresponding building inclusion probability π_k and then sums it up over all sample NRBs, the variable values of NRBs in the sample with a high inclusion probability are weighted low and those with a low inclusion probability correspondingly high. The reciprocal value of a NRB`s inclusion probability $1/\pi_k$ is the weighting factor, which indicates how many NRBs of the population the sample NRB represents.

The estimate of the number of BEA-relevant NRBs in Germany, i.e. the cardinality $\hat{N}_{BEA}$ of the target population $BEA \subset M$, results as a sum estimate presented in Equation 2:

$$\hat{N}_{BEA} = \sum_{k \in s} \frac{NRB_k}{\pi_k} \quad (2)$$

With

$$NRB_k = \begin{cases} 1, & if\ population\ unit\ k\ is\ BEA-relevant \\ 0, & otherwise \end{cases}$$

$\boldsymbol{BEA \subset M}$ Target population of BEA-relevant NRBs as a subset of the population of all NRBs M.

Such a population estimation from a sample is always subject to a sample-immanent uncertainty, the standard error $\hat{\sigma}(\hat{N}_{BEA})$[10], which can be estimated from the sample. This results in the estimated number of BEA-relevant NRBs in Germany of $\hat{N}_{BEA}$=1.981 ± 0.152 million.

9. Buildings that are subject to the Building Energy Act (GEG2020 2020), formerly the Energy Saving Ordinance (EnEV 2016 2015), and generally are thermally conditioned (heated and/or cooled).

10. The standard error is specified in all expansions, but "error" does not mean "wrong". Instead, "errors" in the sense of sampling theory are uncertainties that cannot be completely eliminated, which stem from the fact that, for various reasons, it is not possible to guarantee with absolute certainty the conformity of the estimation results of a sample survey with the true conditions in the population. Standard errors are always part of the scientifically correct presentation of results. One has to read it like this: The mean value is the most probable value determined from the sample for the true but unknown number of NRBs. With a probability of 68 %, the true but unknown value is in the range of a standard error around the specified mean.

For other variable value sums, however, there are invalid values for some sample NRBs regarding the variable in question, for instance because some respondents to the survey could not provide the necessary information. For example, if the specific transmission heat loss of all GEG-relevant non-residential buildings´ exterior walls, $\hat{H}_{T, Wall}$ is to be estimated, some sample NRBs have no provided answers for the wall area or heat transfer coefficients respectively. For such buildings, the variable values are encoded as so-called invalid or missing values[11]. The calculation of the average value for such a case follows Equation 3, where an average value of the variable is estimated across all NRBs in the sample, with valid values for the variable concerned, in a first step.

$$\hat{\hat{H}}_{T,Wall} = \frac{\sum_{k \in \tilde{s}} \frac{U_{Wall,k} \cdot A_{Wall,k}}{\pi_k}}{\sum_{i \in \tilde{s}} \frac{NRB_i}{\pi_i}} = \frac{\sum_{k \in \tilde{s}} \frac{H_{T,Wall,k}}{\pi_k}}{\hat{N}_{\widehat{BEA}}} \quad (3)$$

with

$\widehat{BEA} \subset M$ Population of BEA-relevant NRBs with valid values $U_{Wall,k}$ and $A_{Wall,k}$ as a subset of all NRBs

$\tilde{s} \subset s$ subset of population units with valid values $U_{Wall,k}$ and $A_{Wall,k}$, which have been identified by the sample drawn.

The entire building stock's specific transmission heat loss, $\hat{H}_{T, Wall}$, results as shown in Equation 4:

$$\hat{H}_{T,Wall} = \hat{\hat{H}}_{T,Wall} \cdot \hat{N}_{BEA} \quad (4)$$

It is assumed that the subset of the sample NRBs with invalid variable values is structurally identical to the subset of those with valid values[12]. The standard error of this product is determined in the project with the help of the Gaussian error propagation law.

SURVEY AND MODEL INPUT VARIABLES

Some relevant variables for an energy demand calculation are difficult to determine directly in a survey. For example, typically not each respondent knows what the heat transfer coefficient U of a wall is or how this information can be determined for the building in question. For this reason, the questionnaire asked for variables, the so-called survey variables, which supposedly can be specified by the respondents without further aids. Using the example of the u-value of opaque components, the following paragraphs explain how the required model inputs for the simulation of the building energy demand were derived from the survey variables. It should be borne in mind that it is dealt with existing NRBs, i.e. buildings that may have been modernized to varying degrees in terms of energy efficiency.

The questionnaire first enquired the construction type of the opaque components and secondly their current condition. Above all, it was determined whether an opaque component of the building incorporates a thermal insulation layer, if so, which percentage of the component area $a_{bc,si}$ was insulated, when it was installed, and, in case of subsequent insulation,

11. Variables´ invalid or missing values are encoded with negative integers.

12. This assumption is permissible if the missing information on the value in question does not correlate with another value, i.e. is distributed purely randomly in the sample.

which total insulation thickness $d_{bc,si}[m]$ was attached at the time of the interview.

Further, it is assumed that buildings met the minimum legal requirements for thermal insulation in force at the time when they were erected[13]. The corresponding standard values of the heat transfer coefficients of the components $U_{bc,0}$ come from the relevant literature, for external walls and windows from (BMWi, BMU 2015) and (Thiel, Riedel 2011) as well as for the roof or top floor ceiling and the floor slab or basement ceiling from (Loga et al. 2021 S. 125 ff.). Based on typical constructions of opaque components, standard values for the corresponding insulation thicknesses d_0 [m] are derived[14].

The heat transfer coefficient of an opaque component, subsequently insulated with a material of thermal conductivity $\lambda\left[\frac{W}{mK}\right]$ and the total insulation thickness d_{si} [m], is calculated according to Equation 5:

$$U_{bc,si} = \frac{1}{\frac{1}{U_{bc,0}} + \frac{d_{si} - d_0}{\lambda}} \left[\frac{W}{m^2K}\right] \qquad 5$$

We refer to the heat transfer coefficient of a component that has been modernized partially with $a_{bc,si}$% of its component area as in the following Equation 6 considering the additional insulation thickness and the modernized percentage a of the component area:

$$U_{bc} = U_{bc,si} \cdot a_{bc,si} + U_{bc,0} \cdot \left(1 - a_{bc,si}\right) \qquad 6$$

For the case of transparent components, it was analogously assumed that the glass types installed initially during the building construction are in accordance with the legal minimum requirements and that glazing quality improvements were implemented only in the event of modernization.

Results

The NRB typology was developed from a sample survey to provide a statistically valid basis for the calculation of the building energy demand, as target value, of the non-residential building stock in Germany, as target population. At least 6, in many cases 33 building archetypes are differentiated according to 3 values of the proxy variable construction age class and 2 or 11 values of building function respectively, if case numbers are big enough. In this classification schema, variable values of the building archetypes are specified as mean estimators for both, state variables such as u-values and quantity variables such as component surfaces. The state variables are available for the time of the buildings' construction year and for the (partly) modernized condition at the time of the survey between April 2018 and August 2019, the quantity variables are derived from geospatial data with the issue date April 2015.

For all quantitative evaluations in the target population, the absolute frequencies of the archetypes are important, which can also be estimated from the sample. These are given in *Table 2* as an exemplary representation of the contents of the typology, together with the respective standard error. The frequencies are enclosed in parentheses if the relative standard error $\hat{\sigma}(\hat{N}_{BEA,i})\geq 50$ % or the case number of valid values $n_i \leq 5$. When using them for further calculations, the limited significance should always be pointed out.

The typology currently comprises mean estimators of the archetypes´ following variables required for energy demand calculations: specific transmission heat losses $\hat{\bar{H}}_{T,bc}$ (cf. Table 3) and component surfaces $\hat{\bar{A}}_{bc}$ (cf. Table 4) as well as heat transfer coefficients $\hat{\bar{U}}_{bc}$ (cf. Table 5) of the four building components *bc* exterior wall, roof or top floor ceiling, floor slab or basement ceiling, windows or glazing. In addition, the mean estimators of building-related geometric variables such as gross floor area, net floor area, gross volume as well as area ratios, as for instance exterior wall area to net room area, and the compactness of the buildings as a ratio of the building envelope area and the gross volume (A/V) are provided. For the technical systems for heat generation, cooling and ventilation, relative and absolute frequencies are only differentiated according to one of the two proxy variables construction age classes or building function, due to the variety of technical solutions.[15]

As an example, demonstrating the typology´s application the absolute transmission heat demand $\hat{Q}_{T,wall}[TWh/a]$ through the exterior walls of the whole BEA-relevant NRB stock in Germany is estimated from the sample. Analogous to Equation 3 the average value of the specific transmission heat loss of the exterior walls $\hat{\bar{H}}_{T,wall}[W/K]$ (without thermal bridges) is determined (see Table 3). With Equation 4, the number of all NRBs $\hat{N}_{BEA}$ from Table 2 and the degree day numbers $D_{20/15}$=*3,515 Kd/a*[16] we get:

$$\begin{aligned} \hat{Q}_{T,wall} &= \hat{\bar{H}}_{T,wall} \cdot \hat{N}_{BEA} \cdot D_{20/15} \\ &= 517\left[\frac{W}{K}\right] \cdot 1.981 \cdot 10^6 \cdot 10^{-12}\left[\frac{TW}{W}\right] \cdot 3{,}515\left[\frac{Kd}{a}\right] \cdot 24\left[\frac{h}{d}\right] \\ &= 86.3 \pm 9.1\left[\frac{TWh}{a}\right] \end{aligned} \qquad 7$$

The associated standard errors are to be determined according to the Gaussian error propagation law (cf. (Cischinsky 2021 S. 59 ff.).

The area-weighted mean estimator of the building components´ heat transfer coefficients of archetype i, $\hat{\bar{U}}_{bc,i}$, results from Equation 8:

$$\hat{\bar{U}}_{bc,i}\left[\frac{W}{m^2K}\right] = \frac{\hat{H}_{T,bc,i}}{\hat{A}_{bc,i}} = \frac{\hat{\bar{H}}_{T,bc,i}}{\hat{\bar{A}}_{bc,i}} \qquad 8$$

Discussion and Outlook

The above-mentioned results represent just a portion of the available archetypes´ variables included in the German non-residential building typology. In a next step further relevant variables for building energy demand calculation will be added to the typology and published on the ENOB:dataNWG home-

13. Since buildings may also have deviated from the minimum legal requirements during construction, this can lead to additional uncertainty, which could be quantified in the survey.

14. NRBs whose exterior walls have been constructed in solid construction with lightweight building materials usually meet the thermal insulation requirements even without insulation layers. If the question of whether the component is insulated was answered with "no" for these buildings, the standard U-value was assumed, but an insulation thickness of 0.00 [m] was set.

15. The entire typology will soon be available under https://www.datanwg.de/downloads/

16. Long-term average of the degree day numbers at indoor temperature 20°C and heating limit temperature 15°C from 2001 to 2021 at the climate station Potsdam (Brandenburg), source: Gradtagzahlen Deutschland available under https://www.iwu.de/publikationen/fachinformationen/energiebilanzen/#c205

Table 2. Absolute Frequencies ($\hat{N}_{BEA,i}$), standard errors $\hat{\sigma}(\hat{N}_{BEA,i})$ and corresponding case numbers <n_i> of BEA-relevant non-residential buildings' archetypes i in Germany.

Archetype i **absolute frequencies $\hat{N}_{BEA,i} \pm \hat{\sigma}(\hat{N}_{BEA,i})$** **and case numbers <$n_i$>** **(ENOB:dataNWG Evaluation 1.3.13)**	**Old Buildings (before 1978) [k]**	**Intermediate Buildings (1979 - 2009) [k]**	**New Buildings (from 2010) [k]**	**Total [k]**
Buildings for People	**751 ± 84 <2,522>**	**426 ± 63 <1,269>**	**(45 ± 47) <149>**	**1,222 ± 115 <3,940>**
1. Office, Administrative or Government Buildings	190 ± 31 <632>	106 ± 27 <351>	(11 ± 6) <31>	307 ± 45 <1,014>
2. Buildings for Research and University Teaching	(12 ± 7) <63>	(8 ± 4) <51>	(3 ± 2) <16>	23 ± 9 <130>
3. Buildings for Health and Care	24 ± 8 <110>	33 ± 12 <70>	(5 ± 3) <13>	63 ± 15 <193>
4. School, Day Nursery and other Care Buildings	87 ± 12 <806>	58 ± 27 <290>	(9 ± 6) <33>	154 ± 31 <1,129>
5. Buildings for Culture and Leisure	92 ± 18 <349>	41 ± 19 <132>	(8 ± 6) <20>	141 ± 28 <501>
6. Sports Facilities	51 ± 14 <231>	22 ± 6 <134>	(4 ± 4) <11>	78 ± 17 <376>
7. Buildings providing Boarding, Hotels, Restaurants or Catering	202 ± 51 <227>	67 ± 32 <115>	(2 ± 1) <11>	270 ± 58 <353>
9. Trade Buildings	93 ± 25 <104>	90 ± 26 <126>	3 ± 1 <14>	187 ± 39 <244>
Technical Buildings	**395 ± 66 <542>**	**331 ± 54 <555>**	**32 ± 11 <66>**	**758 ± 88 <1,163>**
8. Production, Workshop, Warehouse or Operations	365 ± 66 <501>	271 ± 46 <521>	30 ± 11 <64>	666 ± 82 <1,086>
10. Technical and Utility Buildings (supply and disposal)	17 ± 7 <26>	53 ± 25 <25>	(0) <1>	70 ± 26 <52>
11. Transport Buildings	(13 ± 7) <15>	(7 ± 6) <9>	(1 ± 1) <1>	22 ± 9 <25>
Total	1,146 ± 110 <3,064>	757 ± 87 <1,824>	77 ± 16 <215>	**1,981 ± 152 <5,107>**

Frequencies in parentheses (y ± Δy) mean that the relative standard error is ≥ 50% or the valid case number $n_i \leq 5$.

Table 3. Excerpt from external walls' average transmission heat loss $\hat{\hat{H}}_{T,wall}$ of BEA-relevant non-residential buildings' archetypes in Germany.

Archetype i **average wall transmission heat loss** **$\hat{\hat{H}}_{T,wall,i} \pm \hat{\sigma}(\hat{\hat{H}}_{wall,i})$** **and case numbers <$n_i$>** **(ENOB:dataNWG Evaluation 1.3.7.1)**	**Old Buildings (before 1978) [W/K]**	…	**Total** [W/K]
Buildings for People	**767 ± 71 <2,242>**		**560 ± 50 <3,427>**
1. Office, Administrative or Government Buildings	914 ± 196 <560>		644 ± 131 <880>
2. Buildings for Research and University Teaching	1,450 ± 609 <58>		844 ± 282 <119>
3. Buildings for Health and Care	1,349 ± 330 <99>		731 ± 184 <165>
…			
Total	697 ± 56 <2,724>		**517 ± 38 <4.460>**

Table 4. Excerpt from external walls' average area $\hat{\bar{A}}_{wall,i}$ of BEA-relevant non-residential buildings' archetypes in Germany.

Archetype i **average wall area** $\hat{\bar{A}}_{wall,i} \pm \hat{\sigma}\left(\hat{\bar{A}}_{wall,i}\right)$ **and case numbers** $\langle n_i \rangle$ **(ENOB: dataNWG Evaluation 1.3.4)**	**Old Buildings (before 1978) [m²]**	**…**	**Total** [m²]
Office, Administrative or Government Buildings	706 ± 111 <618>		605 ± 79 <994>
Buildings for Research and University Teaching	1,136 ± 400 <60>		905 ± 234 <126>
Buildings for Health and Care	1,418 ± 261 <110>		976 ± 154 <189>
…			
Total	630 ± 50 <2,983>		611 ± 37 <4.981>

Table 5. Excerpt from external walls' average heat transfer coefficients $\hat{\bar{U}}_{Wall,i}$ of BEA-relevant non-residential buildings' archetypes in Germany.

Archetype i **average wall heat transf. coeff.** $\hat{\bar{U}}_{wall,i} \pm \hat{\sigma}\left(\hat{\bar{U}}_{wall,i}\right)$ **and case numbers** $\langle n_i \rangle$ **(ENOB: dataNWG Evaluation 1.3.7.1)**	**Old Buildings (before 1978) [W/m²K]**	**…**	**Total** **[W/m²K]**
Buildings for People	**1.12 ± 0.10** **<2,242>**		**0.90 ± 0.08** **<3,427>**
1. Office, Administrative or Government Buildings	1.29 ± 0.28 <560>		1.06 ± 0.22 <880>
2. Buildings for Research and University Teaching	1.28 ± 0.54 <58>		0.93 ± 0.31 <119>
3. Buildings for Health and Care	0.95 ± 0.23 <99>		0.75 ± 0.19 <165>
…			
Total	1.11 ± 0.09 <2,724>		**0.85 ± 0.06** **<4,460>**

page (www.datanwg.de). Future analysis will add standardized measures for energy-related modernization and the energy demand of the average buildings. Also the determination of the material quantities of the average archetypes and typical refurbishment measures, adopting the methodology developed by (Buschka et al. 2021), would be a beneficial future expansion of the German NRB typology.

As shown in the previous section, a non-residential building typology, based on data from a representative sample survey, with synthetical average buildings as archetypes and mean estimators with standard errors as set of variables, is a useful tool for calculating the energy demand of a building stock and for the analysis in climate protection scenarios. Nevertheless, the limits of the application must be observed, which can be seen in the fact that case numbers n for some archetypes become very small (e.g. $n \leq 5$) and standard errors subsequently too large to be able to draw reliable conclusions from the data. In such cases, it must be considered whether the differentiation of the archetypes according to 3 construction age classes and 2 building functions instead of 11 is sufficient for the intended analysis. While reliable extrapolation results could be achieved for old buildings' and most intermediate buildings' archetypes, the number of cases in the sample is not sufficient for others, especially for new buildings. Future sample surveys should be planned with higher numbers of cases to reduce the statistical uncertainties further. A regular repetition of such surveys, in the sense of monitoring the building stock, is also desirable in order to be able to measure the impact of climate protection programs.

Although, the standard errors of archetype variables are provided, these only cover the statistical uncertainties introduced in the estimation for the population total. Model input variables, such as the u-values, based on external sources not specifying uncertainties, cause additional non-statistical uncertainties that cannot be quantified systematically so far. Therefore, the uncertainties of such processed variables are expected to be greater than the presented values. More detailed research to establish more reliable construction age class- and construction/component-types' variables is required for a reliable quantification and consideration of their uncertainties.

With the growing availability of geospatial data, building typologies are often used to assign energy-relevant features of the corresponding archetype to geometric building objects, as in "heat atlases" for example (Amt für Energie und Klima 2022). This is problematic in that the average variable values of the archetypes usually differ from the real properties of the individual buildings, sometimes even considerably. Therefore, this application of building typologies is not recommended. Building typologies should only be used in the modelling of entire building stocks.

With the INSPIRE Directive, EU Member States were obliged to make their spatial data infrastructures cross-border compatible and shareable.[17] According to the INSPIRE Roadmap, the requirements should have been implemented in all EU-Member States (EU-MS) by end of 2021. Thus, the methodology of data collection on building stocks as implemented in ENOB:dataNWG and the preparation of a typology should have become transferable to other EU-MS.

With this typology, statistically valid data are available for the first time for disaggregated bottom-up analysis of the energy demand of the non-residential building stock in Germany. The typology is to be expanded in the future. The use of the typology of non-residential buildings in Germany in other third-party projects is desired. With comparable quality, their results could in turn be included in the typology.

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CRediT authorship contribution statement

Michael Hörner: Conceptualization, Methodology, Investigation, Formal analysis (major part), Project administration, Writing original draft, Writing – review & editing.

Julian Bischof: Conceptualization, Methodology, Investigation, Formal analysis (minor part), Visualization, Writing original draft, Writing – review & editing.

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