Assigning energetic archetypes to a digital cadastre and estimating building heat demand. An example from Hamburg, Germany

Dochev I., Muñoz Hidalgo M. E., Seller H., Peters I.

Technical Urban Infrastructure Systems Group Prof. Irene Peters

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Glossary

IWU	*Institut Wohnen und Umwelt*. A scientific institute based in Darmstadt, Germany
EFH	single-family house
RH	row-house, terraced house
MFH	multi-family building, apartment block
GMH	large multifamily building
HH	high-rise building, a eight or more floors
EnEV	German energy efficiency legislature - *Energieeinsparverordnung*
KfW	German national investment bank - *Kreditanstalt für Wiederaufbau*
ALKIS	*German cadastral system (nation-wide) - Amtliches Liegenschaftskataster Informationssystem*
AdV	Organisation of the german state authorities for land surveying and cadaster - *Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland*

1. Introduction

In the context of the European climate goals and the German Energy Transition, the demand for heat energy is beginning to receive much attention. Thus the understanding of the building stock, being one of the main consumers of energy in general and one of the main consumers of heat energy in particular, becomes a key issue for many European cities – smart cities need smart energy planning. This, on the other hand, requires information on building heat demand, not only in the totals but also spatially distributed. There are two general approaches to urban energy modelling – top-down and bottom-up. The top-down approach usually involves distributing a total energy amount to spatial units – buildings, census tracts etc. based on floor areas, population or similar. These models are easier to set up, potentially more realistic, but less flexible and therefore less suitable for policy analysis than the bottom-up models. The latter involves usually a digital cadastre with non-energetic information about buildings (size, location, age etc.) that is used for deriving energetic properties based on "archetypes" – representative buildings, with known energetic characteristics. Setting up the building model then comes down to matching or assigning the archetypes to the buildings in the cadastre so that energetic properties for each building can be estimated. The next step is energy simulation. We approach this step in simplified manner – using specific heat demand values (kWh/m^2*a) for the archetypes.

2. Objective

The purpose of this paper is to present our work and experience in using the "archetype" approach to urban heat demand modelling at the building scale in Hamburg, Germany. We aim at presenting a comprehensive and detailed description of the steps we took, the difficulties we encountered and the solutions we came up with, in the hope that it would be useful for others in the field.

3. Literature overview

Keirstead, Jennings et al [1] present a review of the broader field of urban energy modelling, identifying six key areas of practice: technology design, building design, urban climate, systems design, policy analysis and land-use and transportation modelling. Reinhart and Cerezo [2] give a good overview of the more concrete area of urban *building* energy modelling with applications in building and policy design. Their conclusions are that the field is emerging and going in the direction of energy flow modelling on neighbourhood level. The challenges are the definition and description of archetypes, the unavailability of measured data for validation and the deterministic modelling of user behaviour. Further, Cerezo et al compared four approaches [3] to archetype modelling – deterministic with a single archetype, deterministic with four archetypes, deterministic with a probabilistic handling of user behaviour and a Bayesian approach to building characteristics combined with the same probabilistic handling of the user behaviour. They report best results with the fourth one. Kristensen et al [4] also make use of Bayesian statistics for a hierarchical calibration of archetypes and dynamic energy modelling of an aggregate of 100 buildings. They report errors of 2.9% and 7.8%. Monteiro et al. [5] present a method for archetype characterization and analyse the impact of the number of archetypes on model performance. Their results vary between 55.2 GWh and 64 GWh for a specific area, noting that the percent difference is relatively small, but 8.8 GWh in absolute terms make a difference for energy supply. A slightly different problem – data standardization and integration in urban energy modelling is discussed by Chen et al [6]. They analyse four US cities and report that all four local datasets are suitable for energy modelling, however they require standardized formats and workflow.

The literature overview shows that various scientific groups are working on different ends of this emerging field, however we could not locate sources reporting on the details of assigning pre-defined archetypes to a digital cadastre. Thus we consider our paper a good addition to a growing body of literature.

4. Methodology

In this chapter we first describe the two sets of archetypes that we use (one for residential and one for non-residential buildings). Then we describe the features and properties of the digital cadastre that we use and lastly the challenges of mapping the archetypes to the individual buildings in the cadastre. We also discuss the pitfalls when dealing with building uses, mixed-use buildings and floor areas. A python script for automating the whole process is available on GitHub:

https://github.com/ivandochev/assigning-energetic-types-to-buildings

4.1. Data and archetypes

4.1.1. The IWU Typology

The IWU residential building typology was prepared by the *Institut Wohnen und Umwelt Darmstadt* (IWU) [7] as part of the European TABULA Project and deals with residential buildings and demand for space heating and hot water only. It is based upon a sample study of the German residential building stock. It makes use of three building characteristics which are used to classify a building into a specific energetic “archetype”: the construction epoch (e.g. epoch ‘B’: 1860 ... 1918), construction type (e.g. “single-family house” or “apartment building”) and a renovation level.

An overview of the archetypes of the IWU Typology is presented in Table 1 below. The abbreviations are as follows: EFH – single-family house, RH – row-house, MFH – multi-family building, GMH – large multifamily building, HH – high-rise building. Note that there are missing positions, for example there is no archetype for RH_A. We address this issue in chapter 4.2.3.

Epoch	Construction epoch code	Construction types				
... 1859	A	EFH	-	MFH	-	-
1860 ... 1918	B	EFH	RH	MFH	GMH	
1919 ... 1948	C	EFH	RH	MFH	GMH	-
1949 ... 1957	D	EFH	RH	MFH	GMH	
1958 ... 1968	E	EFH	RH	MFH	GMH	HH
1969 ... 1978	F	EFH	RH	MFH	GMH	HH
1979 ... 1983	G	EFH	RH	MFH		
1984 ... 1994	H	EFH	RH	MFH		
1995 ... 2001	I	EFH	RH	MFH	-	
2002 ... 2009	J	EFH	RH	MFH		
2010 ... 2015	K	EFH	RH	MFH		
2016 ...	L	EFH	RH	MFH		

Table 1 Overview of all IWU types together with the subtypes relevant for Hamburg

The typology includes all of the listed types in three renovation levels. The renovation levels are: ‘0’ or “baseline”, ‘1’ corresponding to the energy efficiency standard of the German energy efficiency legislature (*Energieeinsparverordnung, EnEV 2014*) and ‘2’ which is the “Passive House” standard developed at the TU Darmstadt in the 1990s. “Passive” in this sense means it building does not require active heating due to very high levels of insulation and can be heating via the ventilation system. Note that “baseline” in this context differs from “original state”. “Baseline” means the energetic state in which a certain archetype is currently mostly to be found. It does not assume any original building characteristics. For example, the “baseline” state of a single-family house built prior to 1859 includes windows with a two-pane insulated glazing and a U-value of 2.8 W/(m²K) [7], which is not with what the building was originally built with. Since the original windows were no more to be found, according to the sample survey of IWU, the “baseline” state does not contain original windows, but the most common ones currently, for the respective archetype. For newer buildings (epochs K and L) the “renovation level” translates to the energy efficiency standard of construction with ‘0’ being the current minimum standard for new buildings according to the EnEV. The next two levels (‘1’ and ‘2’) correspond to the so called “*KfW-Effizienzhaus 70*” and “*KfW-Effizienzhaus 40*” standards. These were defined by the KfW (*Kreditanstalt für Wiederaufbau*), which is the German national investment bank. The numbers 70 and 40 mean 70%, respectively 40% less primary energy demand (per sq. meter) compared to the current energy efficiency standard.

IWU described the energetic characteristics (U-values, A/V ratios etc.) and calculated specific heat demand (kWh/m^2*a) by using a “reference building” – a building that mostly represents a given archetype. Although IWU calculated the specific heat demand for each archetype they also provide a “consumption” correction – an empirical function to reduce the discrepancy between “demand” (calculated with a standard, usually static, heat balancing method) and “consumption“ (measured empirically). Thus the values for the archetypes are comparable with empirical data. Still, since the demand is calculated (albeit with a consumption correction), IWU could provide values at different points in the heating system - for “useful heat” (emitted by radiators, water taps), for “demand at generation" (*Wärmeerzeugung*, amount needed as output of heat generator) and for "final energy" (amount needed as input to heat generator). All specific heat demands have the heated residential floor area (*Wohnfläche*) as the reference area.

We chose this typology because: a) it is well-documented, b) is well established in Germany, c) is part of an international EU project - TABULA EPISCOPE, where similar typologies are prepared for more than 20 European countries and d) includes a consumption correction to allow comparison with measured data.

4.1.2. VDI 3807-2

The German VDI 3807-2 (Characteristic consumption values for buildings) [8] is a publication by the Association of German Engineers (*Verein Deutscher Ingenieure*). It includes a classification of non-residential buildings into building uses and specific consumption values for each. The building uses can then be viewed as 'archetypes' in the context of this paper. The main goal of the publication is to allow the comparison between non-residential buildings of the same archetype and thus provide building owners, or energy auditors with an idea how energy efficient is the building.

For each of the archetypes, the VDI includes a sample of buildings with measured consumption of water, electricity and heat (including domestic hot water). The heat consumption is for space heating and hot water only, process heat is not included, although some VDI archetypes can be classified as "industrial" buildings. The VDI publication includes mean, mode and median values as well as a frequency distribution. The specific values (per sq. meters) use the mode value of the frequency distribution. The publication also includes a "reference value" (we call it "target value", to avoid confusion with "reference area") – the arithmetic mean of the lower quartile. In a sense, the mode value is where most buildings currently are and the target value is the value that buildings should "strive for". All specific values have the heated gross floor area as the reference area. We use the mode value of the VDI as an equivalent to the IWU "baseline" renovation level and the "target value" as an equivalent to "renovation level 1". For non-residential buildings we do not have an equivalent of renovation level 2. All values from the VDI are, per definition, final energy, since they are based on measured consumption. The IWU consumption correction allows the use of the IWU archetypes alongside the VDI archetypes, since both, in the end, reflect consumption.

We chose this typology for the non-residential archetypes, because it is well documented, consumption-based and derived from a sample with available frequency distribution. The latter means the suspected heterogeneity of archetypes is more quantifiable and transparent. Modelling non-residential buildings is a more difficult task than modelling residential ones exactly because these buildings vary greatly. The cadastres in Germany are not rich enough in detail to allow the assigning of more finely defined archetypes. Therefore we decided not to search for more detailed non-residential archetypes, but to rely on average consumptions for heterogenic archetypes, so that at least at an aggregated level we can be have more realistic results.

4.1.3. ALKIS

The Hamburg digital cadastre (*ALKIS - Amtliches Liegenschaftskataster Informationssystem*) is the target for the assigning of the building archetypes. The *ALKIS* is a standardized cadastral system used throughout Germany. We make use of the building objects (*AX_Gebäude*) in the cadastre*,* stored as polygon geometry and attributes. There are approximately 300 000 building objects in Hamburg. The attributes relevant for our purposes are: building use, construction year, construction type, number or floors, roof type and footprint area. The ALKIS of Hamburg is freely available in CityGML format from the "transparency portal" of Hamburg [9].

4.2. Assigning archetypes

This chapter deals with the interpretation of the attributes and the logic used for assigning both sets of archetypes (IWU and VDI) to each building object, based on its attributes.

4.2.1. Building uses

In order to assign an archetype to a building polygon, the first thing to decide is whether the building is residential or non-residential, since we have two sets of archetypes. This immediately poses a problem with mixed-use buildings. In the ALKIS each mixed-use building has its own use-name. For example "Residential building with Commerce and Services" (*Wohngebäude mit Handel und Dienstleistungen*) is a distinct building use. Rather than defining "custom-made" archetypes for mixed-use buildings, we view each building polygon as having two zones – a residential and a non-residential. Purely residential buildings, have zero non-residential area, while purely non-residential buildings have zero residential area. Mixed-use buildings have both. Respectively, mixed-use buildings have both an IWU and a VDI archetype assigned, while buildings of a single use, only one archetype. We consider only a mix of residential and another type of building use. Other mix of uses is simplified by assigning only a VDI archetype.

To tackle the mixed-use buildings, we had to decide what non-residential use to assign, based on the building's name and definition in the cadastre. Additionally we had to define the ratio between the residential and non-residential area (the two zones). Table 2 shows how these issues are tackled. The table starts with four single-use building uses, which is an excerpt from the total of 232 building uses. Out of these 232 uses, 13 are mixed-use buildings and are presented below the four examples of single-use buildings. We operationalize the assigning of types by first assigning an "Overall use class", which can be "residential", "commerce and industry", "public", "mixed-residential" and "irrelevant". Since the VDI differentiates only between building uses, the assigning of a VDI archetype to the ALKIS is simply mapping the appropriate VDI use-name to the respective ALKIS use-name, as shown in Table 2. For residential buildings we further differentiate between the archetypes of IWU. This means that a polygon with "residential" overall use class is taken to a second step where we assign the appropriate IWU archetype. Mixed-use buildings receive a non-residential archetype as shown in Table, but is also taken later to assign an appropriate IWU archetype. "Irrelevant" buildings are buildings that we assume have none or negligible amount of heat demand. The "public" overall use class does not affect the assigning of archetypes. We added it for quicker querying and further analysis after the types are assigned and the building model is prepared. The assumed share of residential area is based on our experience and knowledge of the Hamburg building stock. It is clear that heterogeneity is highly likely to be present within a single ALKIS use code, but this is an innate problem of the archetype approach. An extreme example of such heterogeneity is the *Gemischt genutztes Gebäude mit Wohnen* (Code 1100, “mixed-use building with residential”). The recently completed *Elbphilharmonie* of Hamburg has this building use in the *ALKIS* together with some large shopping centres (*Billstedt Zentrum*) but also some much smaller 1-2 storey buildings that can be viewed as single-family houses. Since the name didn’t tell us much, we took some of the largest such buildings and looked at each to get an idea about the possible split. Based on this, we assumed a share of 15% residentially used area. This represents a best guess from a non-representative sample.

ALKIS Name	ALKIS Code	Overall building use*	VDI Name	Assumed share of residential area
Wohngebäude	1000	residential	-	100%
Gebäude für Wirtschaft oder Gewerbe	2000	commerce and industry	Werkstätten	0%
Verwaltungsgebäude	3000	public	Verwaltungsgebäude allg	0%
Gartenhaus	1313	irrelevant	-	-
…	…	…	…	…
Wohngebäude mit Handel und Dienstleistungen	1120	mixed residential	Verkaufsstätten	100% minus the area of the ground floor
Wohn- und Geschäftsgebäude	1123	mixed residential	Verkaufsstätten	100% minus the area of the ground floor
Wohngebäude mit Gemeinbedarf	1110	mixed residential	Gemeindehäuser	50%
Wohn- und Verwaltungsgebäude	1121	mixed residential	Verwaltungsgebäude allg	50%
Wohn- und Bürogebäude	1122	mixed residential	Verwaltungsgebäude allg	50%
Wohngebäude mit Gewerbe und Industrie	*1130*	mixed residential	Betriebsgebäude/-höfe	50%
Wohn- und Betriebsgebäude	*1131*	mixed residential	Betriebsgebäude/-höfe	50%
Land- und forstwirtschaftliches Wohngebäude	*1210*	mixed residential	Betriebsgebäude/-höfe	50%
Land- und forstwirtschaftliches Wohn- und Betriebsgebäude	*1220*	mixed residential	Betriebsgebäude/-höfe	50%
Wohn- und Wirtschaftsgebäude	*1222*	mixed residential	Betriebsgebäude/-höfe	50%
Gemischt genutztes Gebäude mit Wohnen	1100	mixed residential	Verwaltungsgebäude allg	15%
Gebäude für Handel und Dienstleistung mit Wohnen	*2310*	mixed residential	Verkaufsstätten	15%
Gebäude für Gewerbe und Industrie mit Wohnen	*2320*	mixed residential	Betriebsgebäude/-höfe	15%

*Table 2 Assumptions about mixed-use buildings - share of residential area and corresponding non-residential archetype. The residential archetype is assigned at a later stage. *We assign this “Overall building use” to designate mixed-use buildings.*

4.2.2. Construction epoch

The construction epoch is used to differentiate between different residential archetypes. The logic behind using the epoch as a proxy for building characteristics lies in the assumption that buildings built within one epoch were similar, therefore allow classification into archetypes. For older epochs, the assumption mostly relies upon typical materials and construction. For newer epochs, after the oil crisis in the late 1970s, it lies in the energy efficiency legislature that saw energy efficiency standards being increasingly demanding. That is why newer epochs encompass fewer years – because legislation to increase energy efficiency changed (and changes) more rapidly in the last 10-15 years.

Although information on the construction year of buildings is part of the ALKIS, its quality varies throughout Germany. In the concrete case of Hamburg, the ALKIS provides data on the construction year of roughly 50% of the residential buildings. These 50% however cover approximately 80% of the floor area, since most multi-family buildings have this entry. Whether these construction years in the ALKIS are correct is out of the scope of this paper, but we are further researching this question. Since most of the floor area of residential buildings has construction year entries, we decided to tackle the buildings without construction year in a simplistic way. We define a generic IWU archetype for each IWU construction type as an average of the heat demand for all epochs. For example, the generic single-family house type we define as EFH_ and its specific heat demand is equal to the arithmetic mean of all single family house types (EFH_A to EFH_I). Note that the average excludes epochs J, K, and L, spanning 2002 to 2016. We found out after personal talks with the local administration, that an obligation to note down the construction year was introduced after 1998, so it is unlikely that a building without a construction year in the ALKIS would have been built after this date. We take 2002 as the cut-off as a precaution.

4.2.3. Construction type or "Bauweise"

In order to assign the IWU archetypes, the construction type of each polygon has to be defined. The ALKIS includes an attribute "*Bauweise*", which can be translated to "construction type". However, the "*Bauweise*" is not the same as the IWU definition of construction type. When assigning their types to German Census data, IWU came up with the following allocation of types to data in the census [7]:

Type	***Description***
Einfamilienhaus (EFH)	Detached residential building with 1 or 2 dwellings
Reihenhaus (RH)	Semi-detached residential building or row house with 1 or 2 dwellings
Mehrfamilienhaus (MFH)	*Residential building with between 3 and 12 dwellings*
Großes Mehrfamilienhaus (GMH)	*Residential building with more than 13 dwellings*

Table 3 Definitions of the construction types of the IWU archetypes, when IWU assigned them to German Census data

IWU explicitly states that this logic is **not** to be followed strictly if other building data is available [7]. For example, the distinction between *MFH* and *GMH* is set at twelve dwelling units, only because this was the threshold that was distinguished in the census. However, this approach cannot be taken for Hamburg since the *ALKIS* does not record number of dwellings per building. Therefore we assigned the construction types of IWU based on the *Bauweise* and the number of floors of a building polygon.

An overview of the *Bauweise* and some explanations are presented in Table 4. Establishing the connection between the *Bauweise* and the IWU construction type requires some explanations.

According to the Federal Building Code, the *Bauweise* only defines whether a building is attached, semi-detached or detached and where in the plot is a building positioned (SOURCEBGB, § 22). The definitions of the *Bauweise* types for the ALKIS in the ALKIS documentation, however, give some more details. For example, the *Bauweise* "Gruppenhaus" is defined by the AdV (Organisation of the german state authorities for land surveying and cadastre - *Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland*) as:

"Gruppenhaus' is one of more than two attached buildings of the same kind, with usually up to 2½ floors, which are arranged in such a way that no single axis exists between them

[„Gruppenhaus' ist eines von mehr als 2 gleichartigen, aneinandergebauten Wohnhäusern mit in der Regel bis zu 2½ Geschossen, die so gegeneinander verschoben sind, dass keine gemeinsame Achse gegeben ist"] [10]

Firstly, this definition includes also floor counts. Secondly, and more importantly, there is a discrepancy between this definition and the reality of most buildings with this "*Bauweise*" in Hamburg. Although these *Gruppenhaus* buildings should usually have up to 2½ floors, in 11 000 cases in Hamburg, the buildings have three or more floors (as noted in their floor counts). In most cases these buildings can be viewed as rows of multi-family buildings, so the "no single axis exists between them" is also not applicable.

We traced this inconsistency between the official definitions of the *Bauweise* and the Hamburg *ALKIS* to when Hamburg adopted the ALKIS (around 2010). Before this, Hamburg had a digital cadastre that used a building use classification that was a mixture between "use" and "*Bauweise*". For example, single-family residential buildings had the **use** name – "detached single-family house" (*Einfamilienhaus–Einzelhaus*). So uses included three pieces of information: a) the building is residential, b) the building is detached and c) the building is a single-family house. When Hamburg opted for the *ALKIS*, these former use names were translated into the building uses of the ALKIS **and** the *Bauweise* of the *ALKIS*, as two separate attributes. As part of this transformation however, discrepancies occurred between the official definition of the different *Bauweise* and the actual characteristics of the buildings, which were given these *Bauweise* types. Because of this we view the *Bauweise* as a translation of the older building use types and not as defined by the AdV. We found the most probable correspondence between the older cadastre and the ALKIS by spatially joining the ALKIS with a version of the older cadastre.

Table 4 gives an overview of the "*Bauweise*", the corresponding use codes in the old cadastre and the assumptions and reasoning we use for translating into IWU construction types.

***Bauweise* Code**	**Name**	**Description and use code prior to ALKIS**	**IWU construction type**
1100	*Freistehendes Einzelgebäude*	Usually used for detached single-family houses, this corresponds to the *"Einfamilienhaus–Einzelhaus"* in the digital cadastre of Hamburg before the *ALKIS* was adopted	Can be regarded as **EFH** (single-family house) in the IWU typology. However some buildings have more than two floors. It is unlikely that a building with three or four stories is a single-family house. Therefore it could be closer to a **MFH.**
1200	*Freistehender Gebäudeblock*	Usually used for detached multi-family houses, this corresponds to the *"Mehrfamilienhaus–Einzelhaus"*	Can be regarded as **MFH, GMH** or **HH** (multi-family building, large multi- family building or high-rise).
1300	*Einzelgarage*	Not relevant, we consider garages as non-heated.	
1400	*Doppelgarage*		
1500	*Sammelgarage*		
2100	*Doppelhaushälfte*	Twin-buildings, usually used for single-family houses; corresponds to the *"Einfamilienhaus–Doppelhaus"*	Can be regarded as **RH** (row-house) or **EFH.**
2200	*Reihenhaus*	Row-houses, usually single-family houses; corresponds to *"Einfamilienhaus–Gruppenhaus"*	Regarded as **RH**
2300	*Haus in Reihe*	Not present in Hamburg ALKIS	Can be regarded as **MFH, GMH or HH**
2400	*Gruppenhaus*	Corresponds to *"Mehrfamilienhaus–Gruppenhaus"*	Generally regarded as **MFH, GMH or HH**
2500	*Gebäudeblock in geschlossener Bauweise*	Corresponds to *"Mehrfamilienhaus–Wohnblock"*	
4000	*Offene Halle*	Not relevant, considered as "Missing" if building function is residential.	
9999	*Sonstiges*		
0	*K.A.*		

Table 4 " Bauweise" attribute in the Hamburg ALKIS, corresponding use code in the older cadastre and preliminary assigning of IWU construction types

We use Table 2 as a starting point. However, we need other building information to decide between the three multi-family types (MFH, GMH and HH), between EFH and RH for the *Bauweise* "*Doppelhaushälfte*" and between EFH and MFH for *"Freistehendes Einzelgebäude".* For this we use the floor count. Since the purpose of the assigning of archetypes is to assign the one archetype that is most similar to a given building polygon, we looked at the floor counts of the reference buildings of IWU (Table 5). Additionally we looked at the "typical number of floors" as given by IWU in the description of their typology [7].

Note that deciding between EFH, MFH and GMH could be done using the gross floor area, since, for example, a GMH is, by definition, a *large* MFH. This, however, quickly becomes problematic, since the borders between connected buildings are not systematic in the ALKIS. A building with three entrances is sometimes split into three polygon objects, sometimes not. Multiple row-houses are sometimes given as a single polygon object with the "*Bauweise*" *"Reihenhaus".* This will result in gross floor area much larger than that of a row-house and could lead to assigning a MFH type. For such reasons we do not consider the gross floor area as a signal when assigning an IWU construction type.

Years	Epoch	IWU Construction Types									
		EFH		**RH**		**MFH**		**GMH**		**HH**	
		Number of floors above ground									
		typical	Ref.	typical	Ref.	typical	Ref.	typical	Ref.	typical	Ref.
... 1859	A	1-2	2	-		2-4	4	-		-	
1860 ... 1918	B	1-2	2	2	2	3-4	4	4-5	5	-	
1919 ... 1948	C	1-2	2	2	2	3-4	3	5-6	5	-	
1949 ... 1957	D	1-2	1	2	2	3-4	3	5-8	5	-	
1958 ... 1968	E	1-2	1	2	2	3-5	4	5-8	8	>8	15
1969 ... 1978	F	1-2	1	2	2	3-5	4	5-8	8	>8	15
1979 ... 1983	G	1-2	2	2	2	3-5	3	-		-	
1984 ... 1994	H	1-2	1	2-3	2	3-5	3	-		-	
1995 ... 2001	I	1-2	1	2-3	2	3-5	4	-		-	
2002 ... 2009	J	1-2	2	2-3	2	3-5	3	-		-	
2010 ... 2015	K	-	2	-		-		-		-	
2016 ...	L	-	2	- / 2		- / 5		-		-	

Table 5: Overview of the typical number of floors above ground of the construction types and the number of floors of the reference building in the IWU Typology

In most cases a distinction between MFH, GMH and HH can be made based on the typical floor count. In the cases where the typical floor count in one epoch overlaps for two types, we take the construction type with number of floors closest to the reference building. For example, in epoch *E* (1958 ... 1968), a *MFH* typically has four or five floors while a *GMH* – five to eight floors. If a building is a multi-family building with five floors, it could be categorized as both *MFH* and *GMH*. However, looking at the reference buildings, for these two epochs – *MFH_E* and *MFH_F* have four floors, while *GMH_E* and *GMH_F* have eight floors. We estimate that a five-floor building probably has more similar characteristics to a four-floor one than to an eight-floor one both in the same epoch. We assign MFH. This constitutes a "best guess".

Some buildings with *Bauweise* "*Freistehendes Einzelgebäude"* have more than two floors in the ALKIS, which is unlikely for a single-family house. Since all reference buildings of the IWU typology for type EFH are up to two floors, while MFH starts at three in many cases we assign EFH only if it has up to two floors.

The *Doppelhaushälfte*, or "twin buildings" are closest to an "end-house" from a row of row-houses. Since there is no such IWU construction type we assign a row-house type and estimate that the characteristics are closer to a row-house than to a detached single-family house. IWU also classifies these buildings as row-houses [7].

Lastly, tables 1 and 5, indicate an additional problem – there are some combinations of IWU construction type and epoch that are undefined. For example, there is no archetype RH_A, we assign EFH_A, since they are both single-family houses, although one is detached, the other isn't. For the other construction types – GMH, HH, also not present in epoch A, we assign MFH. Having a building with more than 8 floors (HH) before 1859 (epoch A) is highly unlikely, therefore we view this as unproblematic.

We approach the other missing combinations in a similar way – epoch-wise. This means we fill out the gaps with different construction types of the same epoch, rather than with the "appropriate" construction type from another epoch. The majority of relevant missing combinations are GMH and HH for epochs after F. These are combinations that are more likely to exist. Although typically the high-rise buildings in Hamburg were built in the 60s and 70s, there are some built after that and it is not reasonable to assume that they would be only a few. For all of these combinations we assign MFH for the appropriate epoch and not GMH or HH from another epoch. The reason lies in the energy efficiency legislation after the 1970s. It is stated in the *WärmeschutzV* from 1977[1] that the (then) new residential buildings (and some non-residential ones) were required to adhere to standards regarding the U-values of outer walls and windows. The minimal U-values were, however, dependent upon the Area-to-Volume ratio ("*A/V*") of a building – higher minimal U-values were set for lower *A/V*s. Generally, larger buildings have a lower *A/V* ratio making them more energy-efficient. Considering that the U-value standard for larger buildings started being proportional to the *A/V*, means that the overall energy-efficiency of buildings started to even out between smaller and larger buildings after 1977. At least when geometry and transmissivity is viewed. Larger buildings had higher U-values, smaller buildings lower U-values. For this reason we fill the missing combinations of construction type and epoch "horizontally" – retaining the epoch, and not "vertically" retaining the construction type. We are not aware if this was the reasoning for the lack of these combinations in the first place.

There are some building polygons in the ALKIS without a "Bauweise" entry. For these we use only the floor count. An overview of all archetype-assignment rules for residential buildings is given in Table 6.

1 http://www.luftdicht.de/geschichte/WSchV77.pdf

Epoch	Epoch Code	***Bauweise***	***Bauweise* Code**	Number of floors	Assigned type
before 1859	A	*Freistehendes Einzelgebäude*	1100	≤2, else regarded as missing *bauweise*	EFH_A
		Doppelhaushälfte	2100		
		Reihenhaus	2200		
		Freistehender Gebäudeblock	1100	any	MFH_A
		*Haus in Reihe **	2300		
		Gruppenhaus	2400		
		Gebäudeblock in geschlossener Bauweise	2500		
		Missing Bauweise	-	1,2 >2	EFH_A MFH_A
1860 - 1957	B, C, D	*Freistehendes Einzelgebäude*	1100	≤2, else regarded as missing *Bauweise*	EFH_B/C/D
		Doppelhaushälfte	2100		RH_ B/C/D
		Reihenhaus	2200		
		Freistehender Gebäudeblock	1100	≤4 ≥5	MFH_B/C/D GMH_B/C/D
		Haus in Reihe	2300		
		Gruppenhaus	2400		
		Gebäudeblock in geschlossener Bauweise	2500		
		Missing Bauweise	-	1,2 3,4 ≥5	EFH_B/C/D MFH_B/C/D GMH_B/C/D
1958 - 1978	E, F	*Freistehendes Einzelgebäude*	1100	≤2, else regarded as missing *Bauweise*	EFH_E/F
		Doppelhaushälfte	2100		RH_E/F
		Reihenhaus	2200		
		Freistehender Gebäudeblock	1100	≤5 6,7,8 >8	MFH_E/F GMH_E/F HH_E/F
		Haus in Reihe	2300		
		Gruppenhaus	2400		
		Gebäudeblock in geschlossener Bauweise	2500		
		Missing Bauweise	-	1,2 3,4,5 6,7,8 >8	EFH_E/F MFH_E/F GMH_E/F HH_E/F
1979 - 2016	G, H, I, J, K, L	*Freistehendes Einzelgebäude*	1100	≤2, else regarded as missing *Bauweise*	EFH_G/H/I/J/K/L
		Doppelhaushälfte	2100		RH_G/H/I/J/K/L
		Reihenhaus	2200		
		Freistehender Gebäudeblock	1100	any	MFH_G/H/I/J/K/L
		Haus in Reihe	2300		
		Gruppenhaus	2400		
		Gebäudeblock in geschlossener Bauweise	2500		
		Missing Bauweise	-	1,2 >2	EFH_G/H/I/J/K/L MFH_G/H/I/J/K/L

Table 6 Overview of assigning IWU archetypes based on "Bauweise", epoch and number of floors

4.2.4. Reference areas

After we assign the IWU and VDI archetypes to each building polygon, we have to estimate the reference area to calculate the total heat demand. Residential archetypes of IWU have the residential floor area as reference area. The VDI archetypes use the heated gross floor area (*"beheizbare Bruttogrundfläche"*) [8]. Note that there is another German term that can also be translated as *heated gross floor area - Nutzfläche EnEV* according to the German Energy Saving Ordinance *EnEV*. According to it the *Nutzfläche EnEV* is calculated using the entire heated volume (measured from the outside) of the envelope of a building and then multiplying with 0.32[2]. Although *"Nutzfläche"* means "useable" area, per definition, it is very similar to the *"beheizbare Bruttogrundfläche"* for the majority of buildings. The difference is in that one is volume-based (*Nutzfläche EnEV*), the other area-based. This can lead to large discrepancies with buildings with atriums or similar non-standard volumes. Since we use a two-dimensional cadastre, we can only estimate both the volume and the floor area based on footprint and floor count. Therefore, for our purposes, we cannot differentiate between *Nutzfläche EnEV* and *beheizbare Bruttogrundfläche* and take them as equivalent and equal to the *heated gross floor area*.

For both sets of archetypes, we first estimate the *heated gross floor area* by multiplying the floor count with the footprint areas. For residential buildings we also mirror heated attics, since they are not included in the floor count. To estimate the area of heated attics, we list the roof forms which **could** have a heated attic - Table 7. Flat roofs and more uncommon types (domes) are not considered.

English Term	**German Term**	**Roof Type Code**
Gable/Saddle Roof	*Satteldach*	3100
Hip Roof	*Walmdach*	3200
Half-hip Roof	*Krüppelwalmdach*	3300
Mansard Roof	*Mansardendach*	3400

Table 7 Overview of roof types that could be "heated".

Then, from these four roof types different rules are defined to estimate if they are heated. The Mansard Roof we consider always heated. This is an assumption based on the fact that Mansard roofs were generally invented in order to provide living space beneath the roof shell. Similarly, the Half-hip Roof we also always consider heated. For the other two types – Gable/Saddle Roof and Hip Roof a reference to the IWU Typology is made [7]. We consider a building polygon with Gable/Saddle Roof as having a heated attic, if the IWU archetype of the building polygon is listed in the typology description as having a heated attic ("EFH_A","EFH_B","EFH_C", "EFH_D", "EFH_E", "RH_B", "RH_C", "RH_D", "RH_E", "MFH_A") [7].

All residential buildings for which the attic is thusly considered heated receive an additional area of 75% of the footprint area. This is 25% less than an additional floor to compensate for the reduced volume beneath the roof shell and possible false assumption whether the attic is heated. Expressed

2 Or in a more complicated way for more extraordinary floor heights – outside the 2.5-3 metre range. This is however neglected for the purpose of this paper.

as a formula this amounts to (1) for residential buildings with heated roofs and (2) for all others (including non-residential).

$$(1)\ A = a * (f + 0.75)$$
$$(2)\ A = a\ *\ f$$

where:
A – heated gross floor area
a – footprint area
f – number of floors

After we estimate the heated gross floor area, we apply the coefficients for share of residential area (Table 2) and tackle residential and non-residential buildings differently. Non-residential buildings use the heated gross floor area as reference area, therefore we do not calculate further. Residential buildings use the residential floor area as reference area and use the coefficients in Table 8 to convert heated gross floor area to residential area. For mixed-use buildings we take the non-residential share of the area as it is, and apply the conversion coefficients only to the residential part of the area. The numbers in Table 8 are based on our analysis of a sample of buildings with energy certification, where both areas are noted.

Construction type (IWU Typology)	**Conversion coefficient**	**Note**
EFH	*0.77*	Equals the average ratio for all the reference buildings in the *IWU* typology with this construction type (all *EFH*s and *RH*s respectively)
RH	*0.81*	
MFH	*0.8*	The average ratio is 0.84. However 4% were removed since some "purely" residential buildings according to the *ALKIS* actually have non-residential uses within them which leads to an overestimation of the total living space.
GMH	*0.8*	
HH	*0.8*	

Table 8. Overview of coefficients used for converting heated gross floor area to residential area

4.2.1. 3D Data and building parts

There are two issues with using the floor count and the footprint area for estimating gross floor area. Firstly, the floor height is relevant for heat demand, since the same gross floor area can have different total volumes based on how high each floor is. This is somewhat tackled by the archetype approach and the reference buildings behind it. It can be argued, that given that the specific heat demands assigned to the polygons come from a reference building, the floor heights would be implicitly in the archetype. IWU simulated the reference buildings with measured floor heights from construction plans, therefore the reference building has a "typical" floor height encoded in the specific heat demand of the archetype.

A bigger issue is the presence of buildings with multiple "bodies" with different floor counts, all within the same building footprint. In this case the maximum floor count is usually found in the ALKIS for the given polygon. This leads to large overestimations of building volume. An example is presented in Figure 1. Interestingly, official 3D data for Hamburg [11] even in the second level of detail (LoD2), which includes roof forms, also fails to tackle this problem.

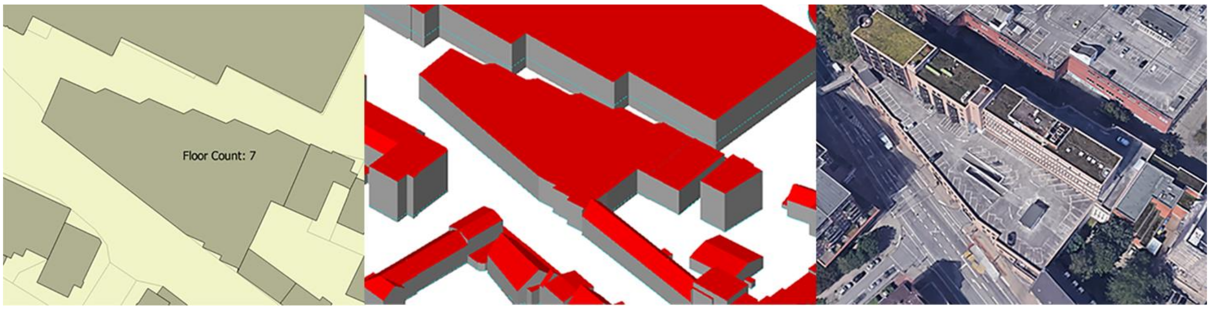

Figure 1 False volume estimations. Left to right: ALKIS, 3D model (LoD2) and Google Earth.

Using 3D data has the advantage of more precise volumes of simpler buildings, however simpler buildings are the ones where using floor count and footprint is most plausible. In a way 3D fails where needed most – complex and extraordinary buildings. For this reason we do not use 3D data for our model currently.

However, the 2D ALKIS actually provides for such situations, where additional cadastral objects "building parts" describe higher, lower or overarching building bodies within the same building (Figure 2).

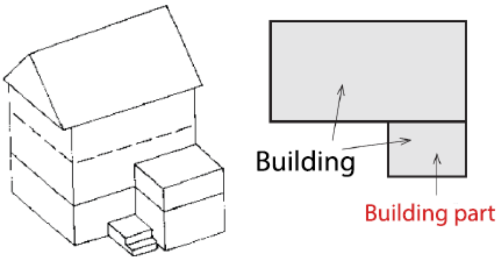

Figure 2 Example of "building parts" in the ALKIS. Adapted from the official documentation of the ALKIS [12]

Building parts have a separate floor count. We use this to either increase (higher building part - "*Hoehergeschossiger Gebaeudeteil (nicht Hochhaus)*" or "*Hochhausgebaeudeteil"*) or decrease (lower building part "Geringergeschossiger Gebaeudeteil") the heated gross floor area. In this way we correct for the over- or underestimation of the gross floor area due to different heights within the same building footprint.

Note that, regrettably, "building parts" are not always consistently noted in the ALKIS of Hamburg and there are buildings with different floor counts that are not properly described. The quality of this aspect of the ALKIS seems to be regional specific. We analysed the ALKIS buildings in the "Moabit" neighbourhood of Berlin, for example, and found it to be more complete with respect to building parts. The Berlin ALKIS is available from the Berlin geoportal [13].

4.2.1. Renovation levels

The issue of a building's renovation level is one of the most difficult due to the lack of data. Although the building archetypes are based on the state a building is to be found "currently" (actually the IWU sample is from 2010, the VDI most probably prior to that - 2007), there are probably many buildings with much higher energy efficiency. Using the ALKIS we cannot model this and expect the model to overestimate the heat demand.

5. Results and plausibility

5.1. Reference Area plausibility

As a major correlator to total heat demand, we first check the plausibility of our reference area estimations. For the residential floor area this is possible using census data. We sum up all areas of the buildings according to "city quarters" (*Stadtteil*) which is an official administrative division. Hamburg is divided into approximately 100 such quarters. At this level of aggregation census data on total residential floor area is available from the Hamburg statistics office [14]. A correlation analysis of our estimation of the residential floor area and the census data (Figure 3) produced a very good fit.

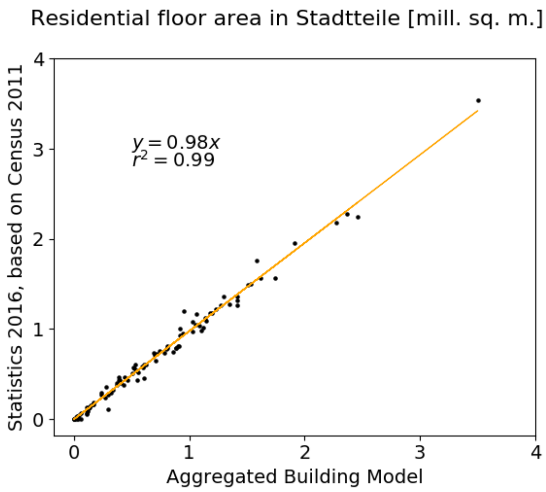

Figure 3 Correlation between estimated residential floor area and official statistics at the "Stadtteil" level (an administrative division of Hamburg)

Validating the non-residential floor area at these scales is not possible, since there are no official statistics on this (as far as we know).

5.2. Heat Demand estimation plausibility

A good estimation of the living space is necessary for the estimation of the total heat demand, nevertheless the latter is of more importance for the purposes of this paper. We check model plausibility at three different scales: city, neighbourhood and building.

5.2.1. City-scale plausibility

Since Hamburg is a city-state within the German Federation, state-level data is equivalent to city-level data. The Hamburg Statistics Office publishes a state-level energy balances for different years [15–17]. We look at the years 2014-16, the three most recent for which data is published. The statistics office derives this data from measurements from energy providers. Public bodies usually use this data for reference for policy analysis and CO_2 target tracking. However, the data differentiates and cross-tabulates between fuel-type and user-type, but not usage. This means the total amount of kWh used by households, commercial and business sector and industrial sector in Hamburg is present in the statistics. The fuel-type (gas, district heating, electricity, oil etc.) used for this energy is also present. The end usage (space heating, domestic hot water, cooking, appliances etc.) is not. Since we model only heat demand, we need to estimate how much each of the user groups uses for this purpose. For this we use a national split estimated and published by the *Working Group on Energy Balances* (Energy Balances Group) [18]. This is a German association including energy industry and research institutes. According to their publication from 2017, on average, households in Germany use 70% of final-energy for space heating and 14% for domestic hot water. The second group (commerce, services, business) 49% and 5% respectively and industry - 6% and 1%. Using the statistics for years 2014-16, we first calculate the kWh used for space heating and hot water for each year using the above split. We then correct the space heating for weather conditions using degree days. In the end we average the consumption for the three years.

We consider that our heat demand estimation for the residential gross floor area in Hamburg corresponds to the heat consumption of households in the statistics. Similarly, we consider our heat demand estimation for the non-residential gross floor area as comparable with the consumption of the user group "commerce, services, business" and "industry". Note that we model only space heating and domestic hot water. Also, for this comparison we used "useful heat" for residential buildings. Comparing final energy would be more appropriate, however information on types of heating systems is not available for the whole city and therefore we couldn't model final energy. For non-residential buildings the specific heat demand of the archetypes is consumption-based - the mode of a sample distribution - therefore it averages over the losses of the different heating systems of the sample.

Heat Demand of Hamburg [GWh]	Source	Households	CBS*	Industry	Total
Space Heating (weather corrected)	Statistics Office*	8584	6066	549	15199
Domestic Hot Water		1605	517	50	2172
Space Heating + DHW		**10189**	**7182**		**17371**
Space Heating (Useful Heat)	Model	**9559**	**9314**		**18873**

Table 9 Comparison of total estimated heat demand using our model and energy statistics. CBS: "commerce, business and services".

The results in Table 9 show that the model is overall plausible. However, since the model does not account for recent renovations, but uses useful energy instead of final energy (for residential buildings), the apparent good fit is most probably due to the two effects averaging themselves out. The non-residential heat demand is consumption-based and as expected is overestimated in the model. This can be due to the presence of recently renovated buildings, but also due to an overestimated reference area (we could not validate the reference area of non-residential buildings).

5.2.1. Neighbourhood scale plausibility

As second plausibility check we use an energetic planning report, for a part of the Bergedorf neighbourhood in Hamburg [19]. The report gives 38.8 GWh as measured heat consumption for the whole territory of the neighbourhood (~0,3 km^2, secondary urban centre with a mixture of residential and non-residential buildings). For the same territory our model gives a value of 41.1 GWh. No distinction is made between residential and non-residential consumption in the report, so we cannot validate separately.

5.2.2. Building scale

Lastly, we compare our estimation of heat demand for seven non-residential building complexes in Hamburg (Table 10). Out of data protection reasons we name the complexes A to F. Each complex has between two and seven buildings. The uses vary between educational buildings, sport facilities, small-scale production facilities and large manufacturing plants.

	Measured from energy audit			**Estimated by model**		
Building Complex	Heat Consumption [MWh]	Useable Area [m2]	Specific Consumption [kWh/m2]	Heat Demand [MWh]	Heated floor Area [m2]	Specific Demand [kWh/m2]
A	2097	15691	133,7	1788	16059	111,4
B	1160	5850	198,3	1140	8124	140,3
C	224	1018	219,6	60	600	100,3
D	532	3300	161,1	318	3225	98,7
E	388	4650	83,5	614	6556	93,6
F	*12767*	*85331*	*149,6*	*25127*	*339558*	*74,0*
Total (excluding F)	4401	30509	144,2	3920	34564	113,4

Table 10 Comparison between measured consumptions and floor areas and model estimations for six building complexes in Hamburg. For the total we exclude complex F since it is an outlier when it comes to size.

This comparison shows that there are discrepancies at the building level, not only in terms of specific heat demand but also floor areas. In some cases errors in area and specific heat demand cancel each other out and the total demand is close to the actual consumption (A, B). In other cases the specific heat demand is close, but the area estimation leads to large discrepancies (E). Complex F has a hugely overestimated floor area, however the useable area noted in the energy audit has in places large floor heights – more than 20 meters. Our heated floor area always assumes a standard floor height therefore it is not comparable. Summing up all demands and areas for complexes A to E shows that on average the estimation is plausible although far from precise. We exclude complex F, since it is two orders of magnitude larger than the rest and it has to be viewed separately or it will overshadow all other examples if aggregated with them.

Overall the model performs well at the city and neighbourhood scales with discrepancies in range of 20%. This is similar to other such models in the literature [2].

6. Discussion and Outlook

We set out to describe the details and pitfalls that we observed while applying the archetype approach to urban heat energy modelling. (to be continued…)

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