SIGNIFICANCE OF THE ACCURACY OF BUILDING HEAT DEMAND ESTIMATIONS FOR THE PLANNING OF HEATING GRIDS

Master Thesis in Urban Planning by

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1 INTRODUCTION

Estimation of building heat demand has been performed for decades, to evaluate policies for energy efficiency measures in the building sector (e.g., the IKARUS project, (Stein & Wagner, 1999)) and for the purposes of district heating planning. The advent of electronic cadastres in the last years has allowed doing this with geographic information systems (GIS) and georeferenced data which is an important step in supporting the local planning of heat supply, esp. heating grids.

Nowadays, many municipalities in Germany and other European countries are creating heat demand maps (cadastres) to support the planning of heating grids, which are seen as a key element in the transformation of the energy sector and whose feasibility depends on distances and spatial heat demand densities. The city of Hamburg is about to publish a heat demand cadastre (estimated date of completion is beginning 2017) with the same aims, mainly: supporting the planning of heating grids and targeted building retrofitting in order to meet CO_2 emission reduction goals.

There are two predominant methods in Germany – and most European countries – for assessing urban heat demand. One is to resort to building typologies with characteristic heat demand figures (kWh per square metre floor area and year) reported in the literature (for example see Loga et al (2015)). Building types are allocated to buildings, based on their characteristics, and the heat demand is calculated with the specific heat demand figure multiplied with the floor area of the building. The other method is to assess the nature of the building shell and then perform a static heat balance, calculating heat energy demand based on geometry and heat transmissivity of the building shell, assuming normed user behaviour and particular types of heating systems. In fact, both methods are related, in so far as information about building shell materials and heating systems are taken again from building typologies.

These methods yield point estimates for building heat demand, but point estimates are, almost by definition, wrong. There is so much detail that can vary for the individual building that a typology could not possibly cover all combinations of characteristics (building geometries, wall and window areas and transmissivities etc.), which leads to discrepancies between the estimated demands and the observed demands (calculated for example for individual buildings after they have been more closely inspected on site, rather than estimated with a typology).

Furthermore, the estimates that result from such computations can also differ markedly from observed consumption. The reasons being similar - variability of building shell materials, but in this case, variability also in heating equipment (boilers, type of heating etc.) and, of course, user behaviour. Typologies make use of standard or “norm” users, while in reality the building users could differ in their occupancy patterns, ventilation behavior and preferred indoor temperature which contributes to the problem. Therefore, heat demand estimations are prone to errors and for the purpose at hand – the planning of heating grids – these errors need to be analysed.

2 OBJECTIVE

When creating heat demand maps, a lot of effort is put into determining heat demand as single point estimate of amount of heat per year (MWh/a) or characteristic heat demand values indicating amount of heat per square meter of building floor area per year (kWh/m^2*a) but possible error intervals around these point estimates are seldom given. However, it is to be expected that these possible errors could influence the planning of heating grids, which relies on heat demand estimations.

On the other hand, since heating grids connect multiple buildings, the aggregated heat demand rather than the demand of the individual building is what is more important.

The objective of this thesis is to first analyse the possible relative error of a point estimate of heat demand at an aggregated level and then put this error in the context of heating grid planning. Thus, the following question was formulated:

What relative errors of heat demand estimations at an aggregated level can plausibly be expected and how important are they for the planning of heating grids?

Although the non-residential building stock plays an important role in heating grid planning, in order to keep the scope manageable, only the residential building stock is analysed in this thesis.

3 METHODOLOGY

The approach I adopt is quantitative and in part stochastic. In a first step, I perform a large scale heat demand estimation for the entire residential building stock of the city of Hamburg at an aggregated level in order to mirror the approach usually adopted for heat demand cadastres. However, in order to estimate possible errors, I modify the approach. Rather than using single, typology-based specific energy demand values for each building, I use a building typology merely to connect the digital cadastre with a dataset containing a large sample of 7700 building energy certificates[i] each including a unique calculated value for heat demand for the corresponding building. Each building in the digital cadastre thus receives a type from the typology and each building in the more detailed dataset of

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[i] The City of Hamburg promotes energy efficient refurbishments of its building stock by subsidising the energy certification of buildings and subsequent efficiency retrofit measures. Energy certificates contain detailed information about building geometry, building shell and heating technology of the individual building they are awarded to.

energy certificates also receives a type from the same typology. These types then connect the two datasets. Since typologies cannot include thousands of types for practical reasons, a single type in the typology corresponds to more than one building in the certificates dataset and therefore for each building polygon multiple possible values for heat demand are obtained – each corresponding to the unique value for any given building in the certificates dataset that is of the same type. In this way, a range of possible heat demand values, rather than a single value, is obtained for each building type and via the connection to the ALKIS - for each building in the cadastre. This range gives some insight into the possible error at the building level - taking an average or median of these possible values and analysing the spread (in the statistical sense: the deviation) around this number is an indication of how good the point estimate is – accuracy at the building level.

In a second step, in order to estimate the accuracy at an aggregated level, the buildings are grouped spatially in small groups of approx. 12 buildings on average per group. The logic behind the aggregation is that of “street fronts” – buildings within the same urban block and overlooking the same street form one group. A Monte Carlo simulation is then performed that stochastically iterates over the datasets and gives a range of heat demand values (in MWh/a) for each of these groups. The reason for such a simulation is that it is to be expected that at the aggregated level, the total heat demand would be more stable than for each individual building, since some estimations may be higher, others lower and thus some averaging effects could be observed. The computed distribution of values (based on the iterations) at the aggregated level is then used to calculate a point estimate for each group together with a relative error.

Lastly, in order to put the error in the context of heating grids, for each of the building groups a small theoretical heating grid is modelled which allows the calculation of the linear heat density (the ratio between heat demand and the length of the pipelines needed to connect the buildings) for each group. In this way, the relative error of the heat demand estimation could be transferred to one of the main parameters used for the evaluation of the plausibility of heating grids and the effects of the errors on the planning of grids could be analysed.

4 DATA SOURCES

This chapter presents the two main datasets used for the analysis. All additional sources are compiled as references and presented as in-text citations and as a bibliography at the end of the thesis.

4.1 ALKIS – the Electronic Cadastre

The Hamburg digital cadastre (*Allgemeines Liegenschaftskataster Informationssystem*) referred to as "ALKIS" in this thesis, is the official cadastral map of Hamburg. Although the ALKIS is part of a standardized cadastral system used throughout Germany and the term can actually refer to the digital cadastre of any German city, the term is used to designate the Hamburg cadastre specifically.

The ALKIS consists of a large number of objects (mostly geographic vector data and attributes). Of these, I mainly use the building footprints, represented as two-dimensional polygon geometries, together with their attributes. The attributes describing each building polygon are for example: building use, construction year, construction type etc. The ALKIS is freely available for download from the Hamburg Transparency Portal (*Transparenzportal Hamburg*) and can be manipulated in the GIS (Geographic Information System) software "QGIS", which is open-source. The version of the ALKIS used in this thesis is from the first quarter of 2017.

4.2 Building Energy Certificates

As mentioned in chapter Methodology, a considerable amount of this thesis is based upon a dataset of approx. 7700 building energy certificates originally compiled for a large scale heat demand estimation of Hamburg in 2009-2012 and more recently provided to the GEWISS Project in Hamburg[i]. The dataset includes a relatively detailed description of the energetic properties of buildings of various types and sizes, including specific useful heat demand for space heating as calculated with the German DIN-4108-6 and, in part, measured heat consumption (available for approx. 1500 buildings). The original source of the certificates is the IFBHH (*Hamburgische Investitions- und Förderbank*) which is in charge of the *Hamburg Energiepass* – the system of building energy certification in Hamburg.

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[i] See http://www.eneff-stadt.info/de/planungsinstrumente/projekt/details/geographisches-waermeinformations-und-simulationssystem/

5 ESTIMATING RESIDENTIAL HEAT DEMAND

The first step is to estimate the heat demand of the Hamburg residential building stock. As described earlier, one of the most common ways of estimating residential heat demand in Germany is to use a building typology which contains specific heat demand values (in kWh/m^2*a) for various building types. These types are allocated to a digital cadastre which includes all buildings in a target geographic area and thus the heat demand of every building can be estimated, given the building's floor area and the allocated specific value. The geographic scope I chose is the entire residential building stock of the city of Hamburg, by using the Hamburg ALKIS.

The typology used is the IWU Typology (see below), which is one of the most famous and widely used building energy typologies in Germany. Other typologies include the "Ecofys typology" (Hermelink, et al., 2011), the "Blesl Typology" (Blesl, et al., 2007) or the "*Schleswig-Holstein* Building Typology" (Walberg, et al., 2012). The reasons for choosing the IWU Typology are, firstly, its transparency and the availability of very well-described documentation and, secondly, its wide use in Germany. A downside to it is that it is not Hamburg-specific, a fact that can be offset by the use of Hamburg-specific energy certificates (further discussed in Chapters Data Sources and Accuracy at the building level). A comparison of these typologies is not in the focus of this thesis, but can be found elsewhere (Muñoz Hidalgo & Peters, 2015).

5.1 Difference between Heat Demand and Heat Consumption

An important point has to be made prior to any discussion of heat demand estimations – the difference between "demand" and "consumption".

"Heat Demand" is a computed value representing the amount of heat energy that a building would require given some standard conditions (for example constant indoor temperature of 20°C or 19°C and air change rates[i] of 0.6 h^{-1}). There are a couple of standard ways of calculating this value in Germany – DIN 4108-6 for residential buildings and DIN 18599[ii] for all others. The IWU Typology (discussed below) used a slightly modified calculation that produces results very similar to the DIN 4108-6 calculations (Loga, et al., 2015, p. 58). Heat demand can represent a couple of different values – useful heat demand for space heating (*Nutzwärme*), useful heat demand for domestic hot water, final energy (energy that enters the building prior to conversion into useful energy) and primary energy (energy contained in raw fuels including the energy needed for extraction and supply to the building).

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[i] The amount of times per hour that the complete volume of air is exchanged in a room or building.
[ii] DIN 18599 is sometimes used for residential buildings as well, it is considered the more detailed one.

Whereas heat demand derives final energy from useful heat via a calculation, “Heat consumption” is measured final energy. It includes transformation losses, if the heat generation is done in house, as for example with a gas-fired boiler. It also includes distribution losses, in so far as they are not radiated into heated space and also heat losses for hot water storage and others.

The two measures - demand and consumption - differ mostly because of the user behavious such as window opening and thermostat setting and internal gains, since “standard” or “normed” values are used for computing demand whereas consumption is usually individual.

5.2 IWU Typology

The „IWU“ (*Institut Wohnen und Umwelt*) Building Typology is a German residential building typology describing the heat demand properties[i] of common types of residential buildings in Germany (Loga, et al., 2015). Due to its central part in this thesis and numerous references to it, it will be referred to simply as the “IWU Typology” and is briefly described here.

The energetic properties of residential buildings in Germany vary considerably, however, attempts at heat demand estimations have resulted in the formulation of building typologies, which, by combining similar buildings into energetic types, try to simplify the vast number of different buildings into classes with relatively similar characteristics[ii]. The logic behind the classification lies, for energetic building typologies in general, and for the IWU Typology in particular, in three main domains – the construction epoch (when was the building built, usually grouped in decades or epochs, e.g. 1930-1940), the construction type (e.g. single-family house, multi-family house), and the renovation level (an assumption for the level of refurbishment that a building underwent).

Buildings built in the same epoch can be assumed to be made of similar materials (the typical materials for a certain epoch) and thus to have similar energetic properties, mainly heat transmissivity of the building shell. An additional connection between energetic characteristics and construction epoch is the legislative framework that was in force at the time of construction – for Germany, a major factor was the oil crisis in the late 1970s which led to the introduction of “*Wärmeschutz*” (heat protection) legislation, to which buildings constructed after this period had to adhere (Loga, et al., 2015, p. 11).

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[i] Demand for space heating and hot water, thermal transmissivity coefficients of the building shell, heating systems and other physical properties connected with heat demand. Additionally, consumption corrected values are also available in the typology – these are computed using coefficients derived from empirical consumption data.

[ii] How similar could these be within a class itself is further analysed in thesis.

On the other hand, different construction types – single-family houses, row-houses, multifamily buildings and large multifamily buildings – also influence energetic properties due to a) their geometry[i] and b) other typical characteristics – unheated spaces, roof types, shared walls between buildings and others.

The IWU Typology combines the type and epoch and thus classifies buildings into 44 types:

Years	Epoch	Type				
		EFH	RH	MFH	GMH	HH
... 1859	*A*	EFH_A		MFH_A		
1860 ..1918	*B*	EFH_B	RH_B	MFH_B	GMH_B	
1919..1948	*C*	EFH_C	RH_C	MFH_C	GMH_C	
1949..1957	*D*	EFH_D	RH_D	MFH_D	GMH_D	
1958..1968	*E*	EFH_E	RH_E	MFH_E	GMH_E	HH_E
1969..1978	*F*	EFH_F	RH_F	MFH_F	GMH_F	HH_F
1979..1983	*G*	EFH_G	RH_G	MFH_G	GMH_G	
1984..1994	*H*	EFH_H	RH_H	MFH_H	GMH_H	
1995..2001	*I*	EFH_I	RH_I	MFH_I		
2002..2009	*J*	EFH_J	RH_J	MFH_J		
2010..2015	*K*	EFH_K	RH_K	MFH_K		
2016...	*L*	EFH_L	RH_L	MFH_L		

Table 1 Overview of the IWU Typology. EFH - single-family house. RH- terrace house (row-house), MFH- multifamily building, GMH - large multifamily building, HH - high-rise building (8 or more floors). Formatted by author, original source (Loga, et al., 2015).

It is evident from Table 1. that not all combinations of epoch and type occur in the typology – for example there is no GMH in epoch A and HHs are only in epochs E and F. I am unaware of the exact reason for this omission, however, it can be assumed that the reason is that there are only very few buildings with some combinations of epoch and construction type in Germany. On the other hand, the explanation for the lack of GMH and HH after 1984, 1978 respectively, could lie in the introduction of energy-efficiency legislation after the oil crises. The first Heat Protection Ordinance (*Wärmeschutzverordnung 1977*) actually prescribed different minimal transmissivity coefficients for buildings with different geometry – more energy efficient geometry had to adhere to lower transmissivity standards, so in the end, the overall energy efficiency of new (at the time) buildings

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[i] The energy efficiency of a building is, apart from other things, also based on its geometry. This is usually expressed with the Surface-Area-to-Volume ratio (*A/V Verhältnis*) that describes the ratio between the area of the outer shell of a building and its volume. The logic is that buildings that manage to close more volume with less outer shell area exhibit less thermal losses, since thermal losses permeate the outer shell. Generally, the lower this ratio the more efficient a building is and vice-versa.

levelled out. This would mean that after the late 70s, there might as well be no large difference between the efficiency of buildings regardless of their size, which would explain the presence of only MFH in these periods. The single-family houses and row-houses could have been left as types due to other specifics – different typical heating systems, roof types, floor layouts and thus different amount of residential area or in the case of row houses - shared-walls which also impact heat demand.

Nevertheless, for the purpose of using the energetic building types in combination with the ALKIS, a way had to be devised to fill these gaps, since the Hamburg building stock includes no small amount of buildings, which occupy the cells in the table for which there is no type. The way this problem is tackled is discussed in chapter Assign Types.

The typology makes use of one more criterion – the level of refurbishment defined as "baseline" ("*Ist-Zustand"*), "modernization package 1" ("*Modernisierungspaket 1"*) and "modernization package 2", referred to in this thesis as "baseline", "renovation level 1" and "renovation level 2". "Baseline" corresponds to the state in which most buildings are currently in[i]. For the estimation of this baseline condition the developers of the typology used a large sample of buildings in Germany in order to identify the typical characteristics of buildings. This means, that if, for example, buildings in epoch A were built originally with a specific type of windows that are no longer present and almost all such existing buildings have more modern windows, the baseline condition will include the newer improvements and not the original windows, see (Loga, et al., 2015, p. 33)

Renovation level 1 includes standard energy-efficiency measures which correspond (not strictly) to the German Energy Saving Ordinance 2009 (*EnEV 2009*) (Loga, et al., 2015, p. 34), while renovation level 2 - even better insulation and lower transmissivity coefficients (near passive house standards). In both levels of renovation the exchange of the heating system is assumed with again different levels of depth – for example, renovation level 2 measures include not only the exchange of a gas boiler, but the addition of a heat-recovery ventilation and solar thermal collectors for domestic hot water. For a complete description of all measures included in levels 1 and 2 see (Loga, et al., 2015, pp. 34,35).

The energetic properties of buildings according to the renovation level are described for all epochs and types until epoch J (2002-2009) (included) at the end of which the German Energy Saving Ordinance 2009 came into force. Buildings erected since then (epochs K and L - 2009-2016) already have to adhere to high standards of energy efficiency and also very few buildings built in this period would have undergone renovation so soon after construction, therefore for them three variations rather than "renovation levels" are given in the typology. These variations contain again different energy-

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[i] For reference year one should take the year 2010, when a sample survey was carried out, see (Diefenbach, et al., 2010)

efficiency values, for example in epoch K, variation 1 is the standard according to the German Energy Saving Ordinance, variation 2 has demand 30% lower (*KfW 70*) and variation 3 is 60% lower (*KfW 40*).

Taking into account this third classification component, the IWU Typology consist of 38 types with three renovation levels for each – baseline, renovation level 1 and 2 -- and 18 more types (epochs K and L) with variations, equalling a total of 132 types[i].

For each of these 132 types numerous characteristics are present in the typology including but not limited to:

- Typical floor counts
- Typical areas:

  Residential floor area (heated) (*beheizte Wohnfläche*) - the heated area used for residential purposes;
  Net floor area – the gross floor area minus the area of the walls (*Nettogrundfläche*);
  Gross floor area in accordance with the Energy Saving Ordinance (*Gebäudenutzfläche EnEv*);
- Transmissivity Coefficients (widely known as "U-values") – measures of the rate at which energy moves through certain objects.
- Specific useful heat energy demand for space heating in kWh/m^2*a applied to the residential floor area.
- Specific useful heat energy demand for domestic hot water in kWh/m^2*a. Although conceptually domestic hot water is more tied to number of persons, it is usually computed as a function of area instead, in order to standardize the demand calculation.
- Specific final energy in kWh/m^2*a – all buildings described in the typology are using a gas boiler as energy system, which is very common, although not ubiquitous in Germany.

All specific heat demand values are given for both a standard heat demand computation and after a correction applied for typical levels of consumption (*Typische Verbrauchsniveau*). Additionally, a measure for heat energy demand for space heating and domestic hot water in kWh/m^2*a including distribution and storage losses and taking into account hot water system contribution (emission to heated space) is also provided (*Wärmeerzeugung*). These values are also given as computed and consumption-corrected values.

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[i] It has to be noted that the typology includes some special and regional-specific types, not mentioned in this chapter, most of which are relevant for the former GDR (East Germany), these however are not relevant to Hamburg and for this reason were omitted. The special type is a "pre-fabricated" single family house which was also not used, since no viable way of assigning this type to the buildings in the ALKIS was found.

5.3 Connecting the ALKIS and the IWU Typology

After describing the characteristics of the IWU Typology, this chapter discusses the method used to allocate the IWU types to the residential building stock of Hamburg (ALKIS). It is based on a working paper "Assigning IWU Building Types to Buildings in the Hamburg ALKIS" by the Technical Infrastructure Systems Group at the HafenCity University Hamburg, see (Dochev, et al., 2017). The method was used, among other applications, in the construction of the heat demand cadsatre (*Wärmekataster*) of the Department for Environment and Energy of the city of Hamburg (*Behörde für Umwelt und Energie*).

5.3.1 ALKIS Building Uses Included in the Analysis

The first step in the assigning process is to formally describe what a "residential building" is. The specific definition of "residential" can vary from source to source[i], but for the purpose of this thesis the best choice would be to mirror the definition of "residential" as it is described in the IWU Typology. IWU used their typology on the German Census for a country-wide estimation and analysis, and when they assigned their types to the buildings in the Census, they used the following definition: "Residential buildings, that is, buildings for which the residential floor area is at least as big as other areas, excluding dormitories, "other buildings with residential floor areas" as well as "inhabited shelters" (*bewohnte Unterkünfte*)" (Loga, et al., 2015, p. 17).

In order to filter out all buildings that do not fall into this definition, the ALKIS use code definitions were used (Table 2.). The building uses are grouped in a general "residential group", however, some of the described uses do not fall under the residential use as defined in the previous paragraph.

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[i] For example dormitories are counted as residential buildings, according to German Census, while the IWU Typology excludes them.

ALKIS Name	ALKIS Code	Included as residential in this thesis	Description in ALKIS
Wohngebäude	1000 (G)	Yes	*'Wohngebäude' ist ein Gebäude, das zum Wohnen genutzt wird.*
Wohnhaus	1010	Yes	*'Wohnhaus' ist ein Gebäude, in dem Menschen ihren Wohnsitz haben.*
Gemischt genutztes Gebäude mit Wohnen	1100	Yes	*'Gemischt genutztes Gebäude mit Wohnen' ist ein Gebäude, in dem sowohl gewohnt wird, als auch Teile des Gebäude zum Anbieten von Dienstleistungen, zur Durchführung von öffentlichen oder privaten Verwaltungsarbeiten, zur gewerblichen oder industriellen Tätigkeit genutzt werden.*
Wohngebäude mit Gemeinbedarf	1110	Yes	-
Wohngebäude mit Handel und Dienstleistungen	1120	Yes	-
Wohn- und Verwaltungsgebäude	1121	Yes	-
Wohn- und Bürogebäude	1122	Yes	-
Wohn- und Geschäftsgebäude	1123	Yes	*'Wohn- und Geschäftsgebäude' ist ein Gebäude, in dem gewohnt wird und in dem sich ein oder mehrere Geschäfte befinden, in denen Waren zum Verkauf angeboten werden.*
Wohngebäude mit Gewerbe und Industrie	*1130*	No	Not included, since the change of the energetic properties of the buildings due to the secondary use may be too great
Wohn- und Betriebsgebäude	*1131*	No	
Wohn- und Wirtschaftsgebäude	*1222*	No	

Table 2 Building Use Codes included in the IWU Type Assigning. Original Source: (Dochev, et al., 2017)**. Definitions source:** ***ALKIS GeoInfoDok v6 Objektkatalog*****.**

The table shows that some mixed-use buildings where taken as residential - this complies with the definition of a “building with at least half of the area used for residential purposes”, since the “dominance” principle[i] is also used for the ALKIS. Other mixed-use buildings were filtered out, due to the possibility that non-residential functions, although using less area, might distort heat demand to a large extent (for example use code 1130 *Wohngebäude mit Gewerbe und Industrie* might include energy intensive industry, which will greatly influence heat demand).

It has to be noted that this filtering is generally based on many assumptions and constitutes a “best guess”, provided the available information. It resulted in a total of approx. 200 000 residential buildings[ii] in Hamburg.

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[i] A building’s main function is the predominant function – predominant in sense the most area is used for it.

[ii] For the purposes of the thesis, small auxiliary buildings of less than 30 m^2 gross floor area are also excluded.

5.3.2 Interpolating Missing Construction Years

A second important step for the assigning of IWU Types is the calculation of the construction epoch. The buildings in the ALKIS, include a building's construction year as an attribute ("*Baujahr"*) which can be used to classify the building in question into the construction epochs of the IWU Typology. However, this attribute carries a value for only 50% of the residential buildings. In order to be able to assign the types to all buildings, I made an estimation of the missing construction years based on methods developed previously by the Technical Infrastructure Systems Group at HCU (Dochev, et al., 2016). I tested two variations for spatial interpolation of the missing construction years[i]. In order to measure their accuracy, they were applied to the buildings with known construction years as though they were unknown and a success rate was noted (if a building's interpolated year is in the same epoch as the "real" construction year, as noted in the ALKIS, the interpolation is described as successful). It is then assumed that the "real" success rate for the buildings with unknown construction years should be similar.

5.3.2.1 Spatial Interpolation Using Similar Neighbour

The first method tested makes use of a building's area-to-perimeter ratio together with the number of floors in order to find, for each building, a neighbour building which has the most similar characteristics. The construction year of this neighbour building is then taken for the building in question. Figure 1 illustrates the area-to-perimeter ratios. The underlying logic is that similar buildings close to each other could probably have similar construction years.

Figure 1 Example of Area-to-Perimeter ratios for buildings in Hamburg. The figures inside the building polygons indicate the building's Area-to-Perimeter ratio (in m²/m).

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[i] Both methods made use of a python script, run in the QGIS python environment. Source: (Dochev, et al., 2016)

The amount of floors of each building is used so that initially only neighbours with the same amount of floors are taken into account. If no neighbour in the defined number of neighbours has the same number of floors, this criterion is neglected and only the area-to-perimeter ratio is taken.

The neighbour count is a parameter that can be specified in the algorithm, so that different values can be played through. The results are presented in Table 3.

Neighbours (k)	Buildings with correctly estimated epoch ("correct" in the sense of: matching the ALKIS information)	Buildings with construction years given in the ALKIS	Percent "correct"
30	53659	107444	50%
20	55435		52%
10	57448		53%
5	59425		55%

Table 3 Results of the Spatial Interpolation of construction years using similar neighbour.

5.3.2.2 Spatial Interpolation using average values for neighbours

The second method takes the average of the construction years of the k-nearest neighbours as the construction year for the building in question. Again, the amount of neighbours (k) is a setting for which different values were compared. The results from this method, using a varying number of neighbours, are presented in Table 2.

Neighbours (k)	Correctly estimated	Total buildings with known construction years	Percent "correct"
30	29119	107444	27%
20	31138		29%
10	38882		31%
5	46192		43%

Table 4 Results of the Spatial Interpolation of construction years using average values.

5.3.2.3 Conclusion

Both of the presented methods do not exceed 60% accuracy, with the "Spatial Interpolation using similar neighbour" method having the highest accuracy – 55%. This method seems superior to the other one, with the worst result for the former being better than the best result of the latter. Still some other measures of accuracy may reveal other results – for example, for the wrongly estimated buildings - a measure of how many epochs is the difference between the estimation and the real construction epoch could show that averaged out construction years tend to introduce a smaller amount of correctly estimated buildings, but closer estimations for the wrongly estimated ones.

Improvements in the similarity estimation of the first approach may increase performance. On the other hand, the "Spatial Interpolation using average values for neighbours" may be improved by using average construction year of buildings of similar type.

A rate of 55% for 50% of the buildings (the other 50% have construction year entries in the ALKIS) equals around 75% correct construction years in the whole dataset, which is deemed satisfactory. The possible discrepancy that this 25% incorrectness could project on the heat demand estimations is neglected on purpose in order to focus the analysis on the discrepancy stemming from the typology approach rather than from the incompleteness of the ALKIS. The latter is indeed a problem for heat demand estimations, but pursuing this question in greater detail is beyond the scope of this thesis. Nevertheless, I am working on this in another context.

5.3.3 Estimating Renovation Levels

The third component of the IWU Typology classification is the renovation level. It is actually the most problematic one, since no exhaustive source of data on this subject exists in Germany. Estimating how a building looked like at the time of construction and how most buildings currently look like (represented by the baseline condition of the IWU Typology) is plausible, however, the operational life of buildings is decades long, in which time, many different actors played roles in the refurbishment and renovation and a lot of uncertainty lies therein. This uncertainty between the "baseline" condition and the documented characteristics is further discussed in the chapter Accuracy at the building level, where the energy certificates dataset is compared with the IWU "baseline" condition.

For the large scale estimation for Hamburg and the Monte Carlo Simulation in chapter Accuracy at an aggregated level which involves the Hamburg ALKIS, assumptions had to be made for the renovation level of each building polygon.

Firstly, with the introduction of the German Energy-Saving Ordinance 2009 the obligation to increase energy-efficiency when a building is refurbished or modified was introduced. The Hamburg ALKIS construction year attribute includes not only the year of construction, but also, the year in which a significant change in the building took place. "Significant change" is defined as a change in the building characteristics which implies a change in the cadastre, mainly addition of floors, or change in the building footprint in any direction larger than 50 cm. This means that if such modification of a building took place after 2009, according to the Ordinance 2009, it should have had measures for the increase of energy efficiency implemented. This assumption is not true if taken the other way around – if a building was not modified, this does not mean that it was not refurbished, it just means that this refurbishment was not mirrored in the cadastre, since it did not fall under the conditions described above. For these reasons, all building polygons with an additional entry in the construction year attribute in the period 2009-2017 are considered as renovation level 1[i], with the understanding that this might underestimate the number of refurbished buildings.

Secondly, the addresses of all buildings with energy certificates are known and a connection with the ALKIS could be made – these were all considered as renovation level 1, which corresponds to what is generally noted in the energy certificates. It must be noted that herein lies another assumption - the energy certificates include a "current state" and proposed measures for a future "refurbished state". Generally, the IFBHH (see chapter Building Energy Certificates) provides financial aid for the implementation of this "refurbished state", the exact extent of these measures can, however, vary from what is noted in the energy certificate. Therefore a building with an energy certificate, most likely did undergo refurbishment, the extent of which may not be exactly as it is written in the certificate. For the purpose of this thesis this is neglected and these buildings are all considered as adhering to renovation level 1.

In total approx. 10 000 building polygons are thus classified as renovation level 1. This amounts to around 0.5% of the total building stock. However, different Germany-wide sources indicate a wide range of possible percentages – from ~20% to around ~30-60%. Such a large discrepancy can be attributed less to the specifics of Hamburg and more to different definitions of "renovation" and to different totals that these percentages correspond to. It can be safely assumed that almost all buildings in Hamburg and in Germany built more than two-three decades ago have undergone **some** changes. According to (Selk, D.; Gniechwitz, T.; Steffens, A., 2009), around 70% of buildings in epochs up to 1984 have undergone measures for the increase of energy-efficiency (partial insulation and/or heat system exchange). Of course this definition of "renovation" is not the same as the defined "renovation level 1" of the IWU Typology, which corresponds to Energy-Saving Ordinance 2009 standards. According to a sample study of IWU (Diefenbach, et al., 2010) around 20% of all buildings in Germany have insulation added after their completion (the insulation was not part of the original construction process), which again cannot be directly transferred to the Hamburg building stock if the levels are defined as the ones in the IWU Typology. The varying definition of "renovation" and the spatial patterns of these renovations are at the root of the heat demand accuracy problem, with heat demand/consumption discrepancy adding yet another layer of uncertainty.

Therefore the 0.5% of buildings considered as "renovation level 1" is most probably lower than the real number of renovated buildings. Nevertheless it can be assumed that Ordinance 2009 standards would have rarely been applied to buildings prior to 2009, therefore the larger part of renovations (the cited 20% to 60% renovated buildings) can be considered as modifications of the "baseline" IWU

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[i] They could, theoretically, be renovation level 2, this is deemed unlikely however and no further work is done to try to distinguish between level 1 and level 2.

level (this level already assumes the lack of original heating systems and some older window types). To what extent are buildings in Hamburg a modification of the "baseline" level is analysed in chapter Accuracy at the building level.

The 0.5% buildings with renovation level 1 are my "best guess" for the amount of buildings with Ordinance 2009 standards with the full awareness that this number might be higher.

5.3.4 Assigning Building Types

The rules used for the assigning of each IWU type to the building polygons are summarized in Table 5. The logic behind the table is discussed elsewhere (Dochev, et al., 2017), but a summary is provided here.

The ALKIS includes an attribute named "*Bauweise*" which approximately translates to "construction type". However, the "*Bauweise*" is somewhat different from the already introduced term "construction type" as in "single-family house", "multifamily house" etc. The reason for this is that although some of the properties of "*Bauweise*" are signals for one of the types mentioned above, others are signals for the relation between building and plot or between buildings and not the type of the building itself. For example a "*Gruppenhaus*" (a type of "*Bauweise*") has a formal definition:

"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" (Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland, 2015).

Another problem with the "*bauweise*" is that some building polygons in Hamburg do not strictly adhere to this specification, for example, the majority of polygons with "*Gruppenhaus*" as "*Bauweise*" in the Hamburg ALKIS have 3 or 4 floors and not "up to 2½" as is the official description[i]. This leads to an ambiguity which has to be overcome. Additionally, some buildings do not have this attribute at all.

A further problem is that, despite the fact that the IWU Typology describes typical floor areas for the different types of buildings, attempting to assign types based on floor areas (residential, gross or net) is also a less than ideal approach. The root of this problem lies in the definition of a "building", where building sections are sometimes considered different buildings, sometimes not. Figure 2, an excerpt of the ALKIS is in an example for this – the thick black borders indicate different buildings and no clear pattern can be distinguished for the number of sections in the building. This means that

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[i] Reasons for this discrepancy are most probably rooted in the migration from the older Hamburg GIS system to the unified ALKIS system.

depending upon where the border of the building is defined in the ALKIS the floor areas change significantly from building to building, although these buildings may be of the same type.

Figure 2 Example of different definitions of building sections in the ALKIS.

In the end, the most robust indicator for the construction type of a building was found to be the floor count, the typical value of which is described for each type in the IWU Typology (Loga, et al., 2015, pp. 13-15, 104). In the few cases where a building's floor count signals two possible types, not only one, the floor count of the exact reference building used in the IWU Typology is taken. For example, the difference between Multi-Family Building (MFH) (3 to 5 floors) and Large Multi-family Building GMH (5 to 8 floors) in epochs E and F is problematic for buildings with 5 floors, since they could be assigned both types. In this situation the reference buildings in the typology for MFH_E and MFH_F have 4 floors, while for GMH_E and GMH_F have 8 floors and it was assumed that the properties of a 5-floor building would be closer to a 4-floor building rather than to an 8-floor one and the type assigned is MFH.

The last problem addressed here is the missing types for GMH buildings and high-rise buildings (HH) in epochs after E and F and the lack of type row-house in epoch A. There are two general ways in which one can classify these buildings into the other types – by construction type or by epoch. This means that HHs in later periods are either assigned values for HHs in earlier periods or values for MFH in the same period. I adopted the latter approach since epochs after F (1978-) coincide with the introduction of the Energy-Saving Ordinance of 1977 which, as described in chapter IWU Typology, most probably led to a levelling out of the energy efficiency of different buildings, which would mean that after this period larger buildings potentially had similar efficiency[i] and can be classified into a single MFH type.

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[i] In the sense of heat demand per square meter – more "geometrically" efficient buildings were to adhere to lower transmissivity standards and the other way around, so in the end the overall efficiency most probably levelled out.

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 5 Overview of IWU Types Assigning based on "*Bauweise*" and number of floors. The "*bauweise*" code 2300 – *Haus in Reihe* is not present in the Hamburg ALKIS. Source: (Dochev, et al., 2017)

5.3.5 Estimation of Residential Floor Area

The last step in the heat demand estimation is the calculation of the gross floor area used for residential purposes ("*Wohnfläche"*), referred to as "residential floor area". This is necessary since the specific heat demands defined in the IWU Typology and also the values given in the energy certificates apply to this area and not the gross floor area (GFA) of a building but, on the other hand, the ALKIS indicates only the latter. Therefore, in order to compute the total heat demand of a building (as in MWh/a) in the ALKIS, the GFA[i], calculated as number of floors times footprint area has to be converted to residential floor area.

This is done using coefficients taken from the German "*VDI-3807 Blatt 1*" (Verein Deutscher Ingenieure, 2013, p. 18) – 0.59 GFA and 0.71 GFA for multifamily and single-family houses respectively. The construction types EFH and RH are considered "single-family" with a coefficient of 0.71 and the other types are considered "multifamily" and being assigned a 0.59 coefficient.

An additional point to consider is the heated attics and their respective areas. These types of residential floor areas are not uncommon in Hamburg, but they cannot be mirrored in the GFA of a building, since attics are not considered complete floors and are not included in the floor counts. In order to tackle this, the roof form attribute of the ALKIS is used and for roof types, considered suitable for residential purposes an addition to the GFA is made. For more details on this see (Dochev, et al., 2017).

This calculation implies the assumption that more attics are heated than not-heated which is based on the increasing population of Hamburg and the resulting pressure on the housing market. In order to avoid gross overestimation the area of the attics is taken with a coefficient of 0.5.

5.4 Results of Connecting ALKIS and IWU typology: An Overview

The assigning of IWU types produced a building count for each IWU type in Hamburg, which is summarized in Figure 3. Not surprisingly, the majority of buildings are single-family and row-houses in almost all periods.

However, the building counts can be somewhat deceiving when it comes to the total heat demand, since the size of buildings plays an important role. Summarizing the same buildings into types and depicting the square meters of residential floor area (Figure 4) shows that in almost all epochs the majority of residential floor area is in the MFH type (typically between 3 and 5 floors).

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[i] The calculation of the GFA itself can be problematic for buildings with multiple sections with different floor counts that all have the same footprint. This may lead to gross overestimations of the GFA and therefore of the total heat demand. This was tackled by filtering out buildings for which this was estimated to be the case. The amount of these buildings is relatively small and does not influence the bigger picture of Hamburg. For more details see chapter "Geometry Correction" in (Dochev, et al., 2017).

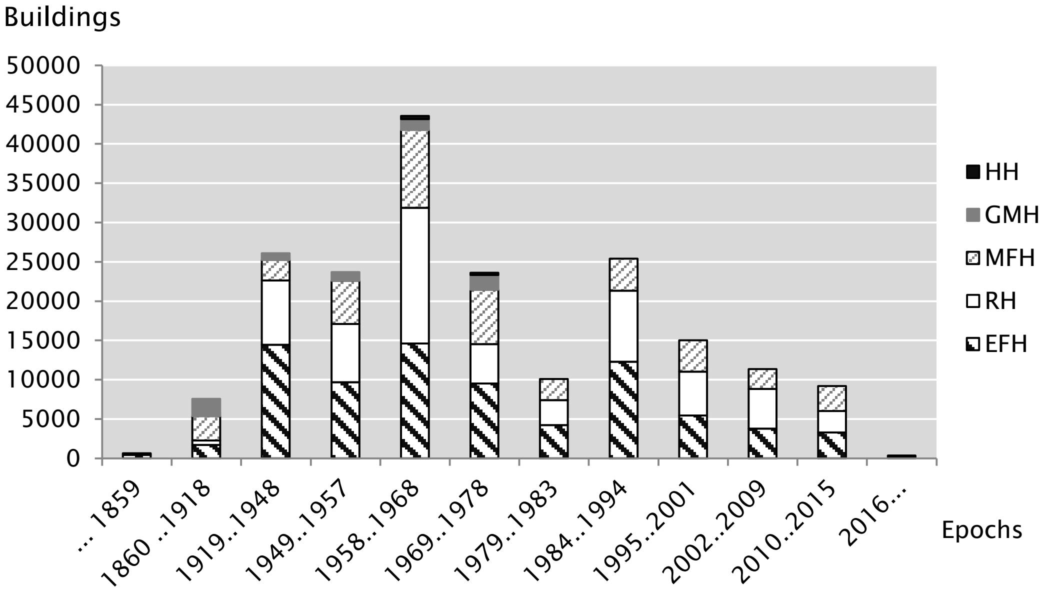

Figure 3 Number of buildings in Hamburg according to the IWU Typology (Result of the Assignment Process described in Section 5.3).

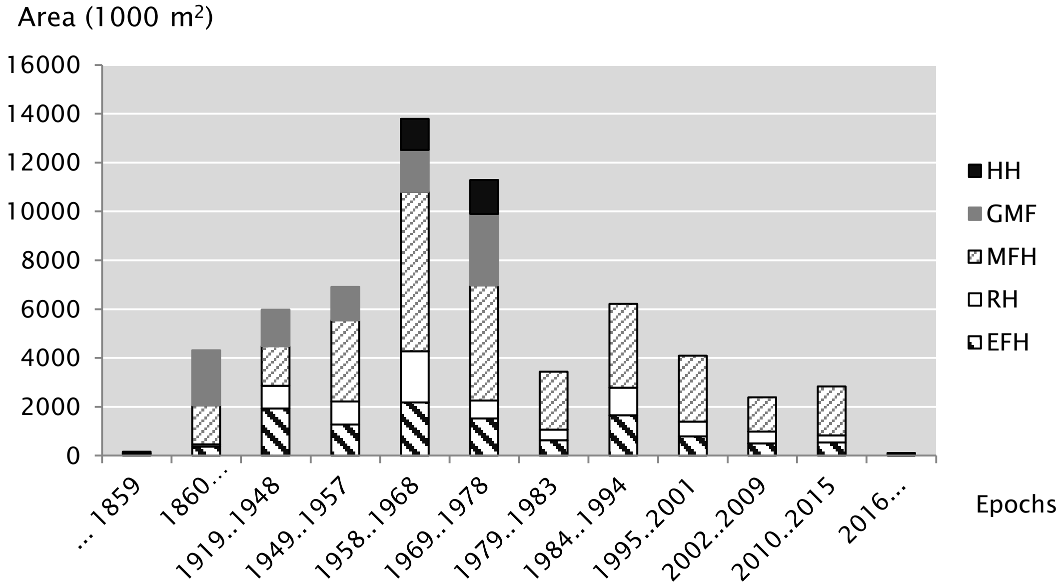

Figure 4 Residential floor area classified into IWU types. (Result of the Assignment Process described in Chapter Assigning Building Types). The lack of GMH and HH types after 1978 is due to the lack of such a type in the typology which resulted in the grouping of GMH and HH built after 1978 into the MFH type.

It has to be noted, that for epochs after E (1969-1978) all multifamily buildings, regardless of size are classified into the MFH type, therefore the lack of GMH and HH after this epoch is not due to their lack in reality, but due to the IWU Typology classification and the choice of how to tackle types, that are not present in the typology.

6 ANALYSIS OF THE HEAT DEMAND ACCURACY

For the purpose of this thesis “accuracy” is used in the context of the possible error of a point estimation. If a given building is assigned a single point value as an estimate for the specific heat demand then accuracy of this point value can be assessed by examining its variability observed in reality. If observed values in reality do not stray much from this point estimate (which can be taken from a typology or be a mean or a median of observed values) then the estimation can be considered accurate – the point estimate mirrors well the observed values. If, on the other hand, the observed values stray to a large extent from the point estimate, then the estimate is less accurate.

For example: Using the IWU Typology, a building polygon is assigned a type EFH_C with a specific heat demand of 163.8 kWh/m2*a. However, in the Energy Certificates dataset there are 904 buildings which have this type based on construction type and year of construction. These 904 buildings exhibit a variety of specific heat demand, ranging from 100 kWh/m^2*a to 500 kWh/m^2* based on the characteristics of these individual buildings and their “on site[i]” evaluation as noted in the certificate. Since no typology can plausibly cover all possible observable values, taking only the minimum and maximum (as described above) may lead to the wrong conclusion – there might be a couple of extreme cases, but most of the 904 certificates might actually have a demand close to the point estimate. Therefore the accuracy is assessed by examining the distribution of observed values around the point estimate.

In order to obtain such distributions, the IWU Typology is used to link building certificates and ALKIS polygons. For each ALKIS polygon an IWU Type is assigned using the procedure described in chapter Connecting the ALKIS and the IWU Typology. Additionally, using the same procedure an IWU Type is assigned to every building in the building certificates dataset – this is possible due to the large amount of data for each building and the available building address, which allowed connection with the ALKIS and for the same method to be applied.

The accuracy estimation is then performed for individual buildings and for aggregated groups of buildings separately in the following chapters.

For the accuracy at the building level, the spread[ii] of the values found in the building certificate dataset for each IWU Type is analysed together with a comparison of the average and the median values for each type and values found in the IWU Typology for the corresponding type. This is done for both heat demand and consumption (more clearly defined in the next chapter).

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[i] The analysis of the building was performed on site, taking account all the specifics of the individual buildings

[ii] In the statistical sense – distribution of values

For the accuracy at an aggregated level a Monte Carlo Simulation is performed in order to derive a spread of values stemming from the building certificates for groups of buildings.

In both cases, I assume that the 7700 building certificates are a relatively good sample that manages to cover the variability in heat demand/consumption in reality. Analysis of sample bias would be beneficial, is however out of the scope of this thesis.

6.1 Definition of Used Values

As pointed out at the end of the chapter IWU Typology, heat demand and heat consumption can mean a variety of computed or measured values. Therefore it is necessary to define the values which are used, together with the original source and any modifications applied (Table 6).

For the purposes of the accuracy estimation, under “heat demand” is understood the useful heat demand for space heating, calculated with a standard procedure of static heat balancing In the case of the IWU Typology, this measure is computed with a modification of the standard DIN 4108-6 method and in the case of the building certificates with the DIN 4108-6 itself. It is deemed appropriate to compare heat demand computed with slightly different methods, due to the high correlation between results produced with them. (Loga, et al., 2015, p. 82).

Under “heat consumption” is understood the useful heat for space heating and hot water, including system losses without the conversion losses. In order to derive this, I adjusted the building certificates with coefficients in order to take out the conversion losses. These values are presented in Table 7. The reason for this exact formulation of heat demand and heat consumption lies in their respective usage.

Useful heat demand for space heating, calculated with a standard procedure is an indication of the energy-efficiency of a building shell, converted into energy, i.e. kWh/m^2*a. This measure cannot be observed in the real world in the form of a gas or district heating bill. It is purely theoretical. A heating bill (for example a gas or heating oil, or district heating bill) always includes the losses of the technical heating system (energy conversion and distribution) as well as the behavior of the users, who set their thermostats and ventilate their dwellings in different fashions. The reason for analysing useful heat demand is that it yields insight into the efficiency of the building, resulting from building physical parameters. In doing a static heat balance computation, the building shell is the thing that is diverse with the other parameters being kept constant – standard hot water consumption as in 5 kWh/m^2*a residential area, standard air change rate and indoor temperature and standard values for conversion losses. This means that measures of inaccuracy for this simpler theoretical heat demand are basically measure of inaccuracy of the estimation for the building shell condition.

The defined heat consumption is what is most likely to be of interest for the planning of heating grids. The efficiency of the building shell, although important, is just one of many variables which lead up to the district heating bill, which in the end is the deciding parameter for the economics and therefore the planning of grids. The conversion losses had to be taken out since they would not be present if a district heating grid is constructed (most conversion losses will take place at the heating grid source, conversion losses at the transfer station in the building will occur, but are also offset with a coefficient for consistency). All other parameters – user behavior, system losses and hot water together with the building shell – will be mirrored in the energy certificate values for consumption and their combined variability at the building level, and, more so, at an aggregate level (for groups of several buildings) is what is important for heating grids.

Term	Description	Source	Note	Modified for the purpose of the thesis
Heat Demand	Annual Useful Heat Demand for space heating (*spezifischen Jahresheizwärmebedarf*) in kWh/m²*a	7700 building certificates	Based on the standard DIN 4108-6 calculation.	No
		IWU Typology	Calculated with IWU method. Uncorrected for typical level of consumption	No
Heat Consumption	Heat Consumption including useful heat, hot water and system losses, excluding energy conversion losses In kWh/m2*a	1500 Building certificates	Hot water included[i]. Conversion losses offset with coefficients according to heating system.	Use of coefficients for offsetting conversion losses, based on literature values
		IWU Typology	Calculated as demand with IWU method and including domestic hot water and system losses. Corrected for typical level of consumption.	No

Table 6 Definition of the terms “Heat Demand” and “Heat Consumption”

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[i] The inclusion of hot water is assumed for at least the majority of certificates.

The used coefficients (Table 7) for offsetting conversion losses were taken from (Schild, et al., 2010, p. 117). The choice for the specific system is based on (Diefenbach, et al., 2010, p. 9). The exact type of the heating system in the energy certificates which include consumption values is not known and is assumed based on the energy source (Table 8). While this could lead to some bias in the estimation, it is unlikely to influence the spread of the values, since the same coefficient is applied to all consumption values of the same energy source type.

Type of system	**Building Usable Area**		
	150m²	**500m²**	**2500m²**
Low temperature Boiler 1987-1994 *(Niedertemperatur-Kessel)*	$\frac{1}{1.19}$	$\frac{1}{1.15}$	$\frac{1}{1.13}$
District heating transfer station *(Fernwärme Übergabestation)*	$\frac{1}{1.02}$	$\frac{1}{1.02}$	$\frac{1}{1.02}$
Electric storage heater *(Nachtspeicherheizung)*	$\frac{1}{1.12}$	$\frac{1}{1.12}$	$\frac{1}{1.12}$

Table 7 Coefficients used for offsetting conversion losses according to the type of system. Based on data provided in (Schild, et al., 2010)

Type of Energy Source	**Number of energy certificates**	**Assumed heating system**
Erdgas	873	*Niedertemperatur-Kessel 1987-1994*
Flussiggas	3	
Braunkohle	6	
Steinkohle	30	
Heizöl	165	
Nahwärme	16	*Fernwärme Übergabestation*
Fernwärme	276	*Fernwärme Übergabestation*
Strom	100	*Nachtspeicherheizung*
Unknown, assumed *Erdgas*	219	*Niedertemperatur-Kessel 1987-1994*

Table 8 Assumptions made for the heating systems in the energy certificates, based on energy source

6.2 Accuracy at the Building Level

In order to be able to compare the spread of the heat demand values in the Energy Certificates database with the IWU values, the current state (prior to future measures described in the certificate) of the buildings in the Energy Certificates database was compared with the IWU renovation levels in order to filter out buildings which are already renovated, for analysing them together with less renovated ones would not be appropriate. This resulted in the filtering of two buildings – the transmissivity coefficients of the building shell of these buildings were above the coefficients defined in the IWU Typology as “renovation level” 1. What is left are all the buildings in the energy certificates dataset that do not reach the transmissivity coefficients of “renovation level 1”. Therefore, the spread of values presented in this chapter applies to buildings which are considered “baseline” (compare Section 5.3.3. Estimating Renovation Levels).

It has to be noted that some IWU types are not represented in the energy certificates dataset and cannot be analysed in this chapter (EFH, RH and MFH in the more recent epochs K and L, corresponding to 2010-2015 and after 2016). Additionally, some building types have a very small sample size for heat demand and even smaller for consumption (since the consumption data is available only for a part of the dataset). The sample size is taken into account when discussing the spread of values and noted in the diagrams. In addition, the Appendix at the end of this thesis summarizes all the types and the respective counts and percentages.

At this point I distanced myself from inferential statistics on purpose and present an analysis of observed distributions. Applying confidence intervals (parametric or non-parametric) to the observed means, medians and percentiles would allow the formal (in the statistical sense) transferring (*inferring*) of these values to the whole building stock but would unnecessarily complicate the analysis. The produced spread was so great that an exact calculation of confidence intervals seemed unnecessary and only taking into account the sample size as a signal for reliability of the conclusions seemed satisfactory. Furthermore, the accuracy at the building level is not the main focus of the thesis.

The analysis of the distribution for heat demand for single-family buildings (EFH and RH) in the sample (Figure 5) exhibits some positive skew with light tails. The interquartile range is around 100 kWh/m^2*a, which, given the general range of heat demand values of between 50-300 kWh/m^2*a, appears relatively high. Maximum values reach up to 600 kWh/m^2*a in the case of EFH_C and EFH_D, which with a median of around 250 kWh/m^2*a, is a magnitude of +100% of the third quartile. Nevertheless, with the 85th Percentile being at around 370 kWh/m^2*a, using a median value for each type, one could cover ~50% of the sample data with +/- 50 kWh/m^2 and ~70% with +/- 100 kWh/m^2*a.

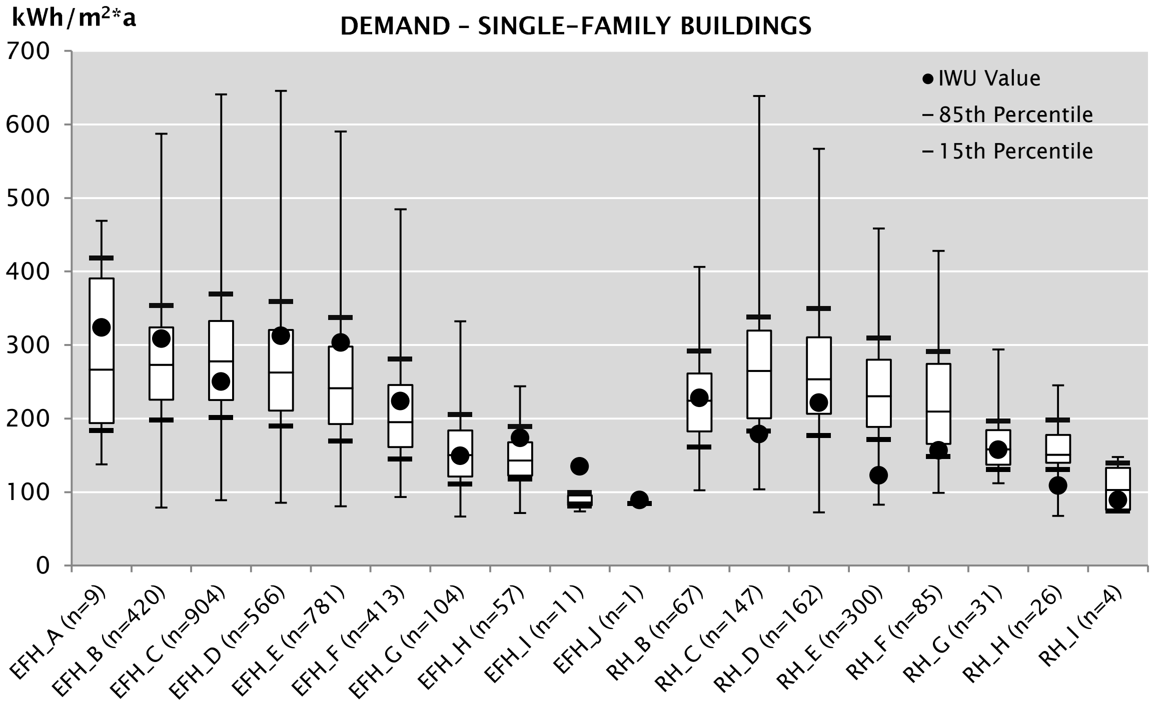

Figure 5 Distribution of heat demand of single-family residential buildings in Hamburg, classified into IWU types. Extreme values removed using the outlier labelling rule with g=3, see (Hoaglin, et al., 1986)**.**

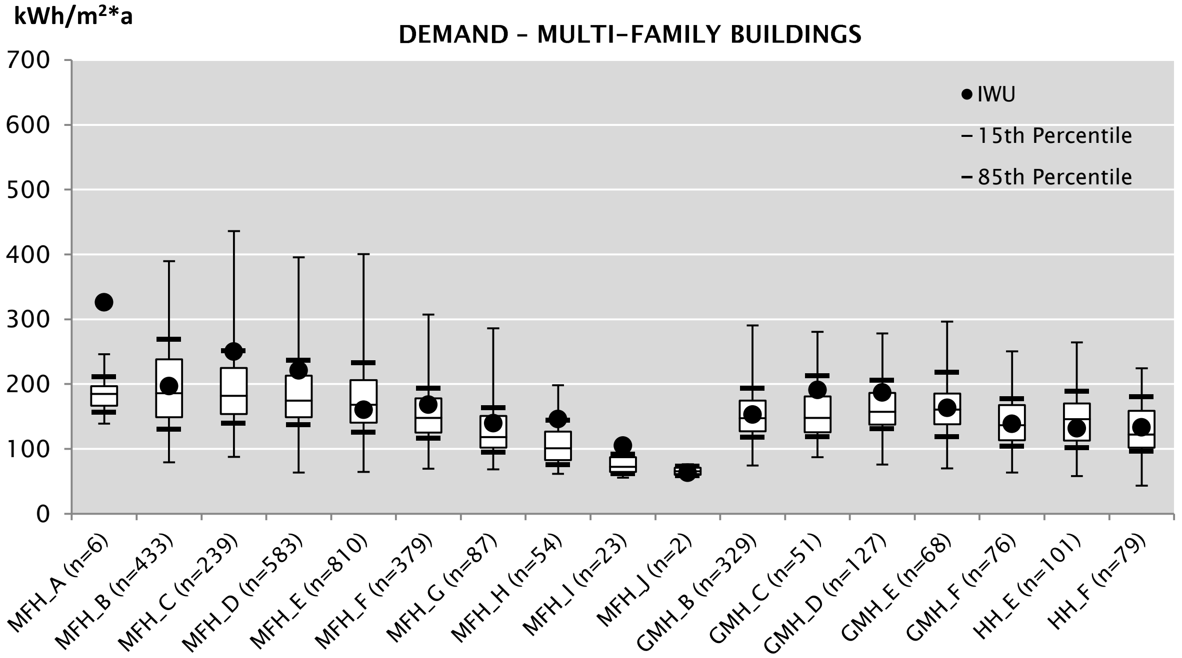

Figure 6 Distribution of heat demand of multifamily residential buildings in Hamburg, classified into IWU types. Extreme values removed using the outlier labelling rule, g=3, see (Hoaglin, et al., 1986)

Multifamily buildings in the sample (Figure 6) exhibit generally smaller interquartile ranges and more stable results, although again positively skewed. In the "baseline condition" median values vary between 100 and 200 kWh/m^2*a with interquartile ranges of 50 kWh/m^2*a on average. Maximum values reach up to 430 kWh/m^2*a, however the 85th Percentile values do not exceed 270 kWh/m^2*a which suggests that values as high as 400 kWh/m2*a are more of an exception. Overall, using median values one could cover around half of the spread with +/-30 kWh/m^2*a. The range between the 15th and 85th Percentiles is, on average, 100 kWh/m^2*a which implies that for most types the values are +/-50 kWh/m^2*a of the median.

Comparing the IWU specific energy demand for the different types with the values of the Energy Certificates database shows rather ambiguous results. Multifamily buildings in Hamburg are generally more efficient[i] than their typology counterparts, mostly in periods C and D (1919-1957), where median values and even the interquartile range is below the IWU values. In the case of single-family row-houses (RH), however, the values for the IWU Typology are lower than the median and interquartile ranges for periods C through F, and H.

This prompted an investigation into the two main factors influencing heat demand[ii] - the building shell transmissivity coefficients (*Wärmetransferkoeffizient*) and the Surface-to-Volume ratios (Figures 7 and 8).

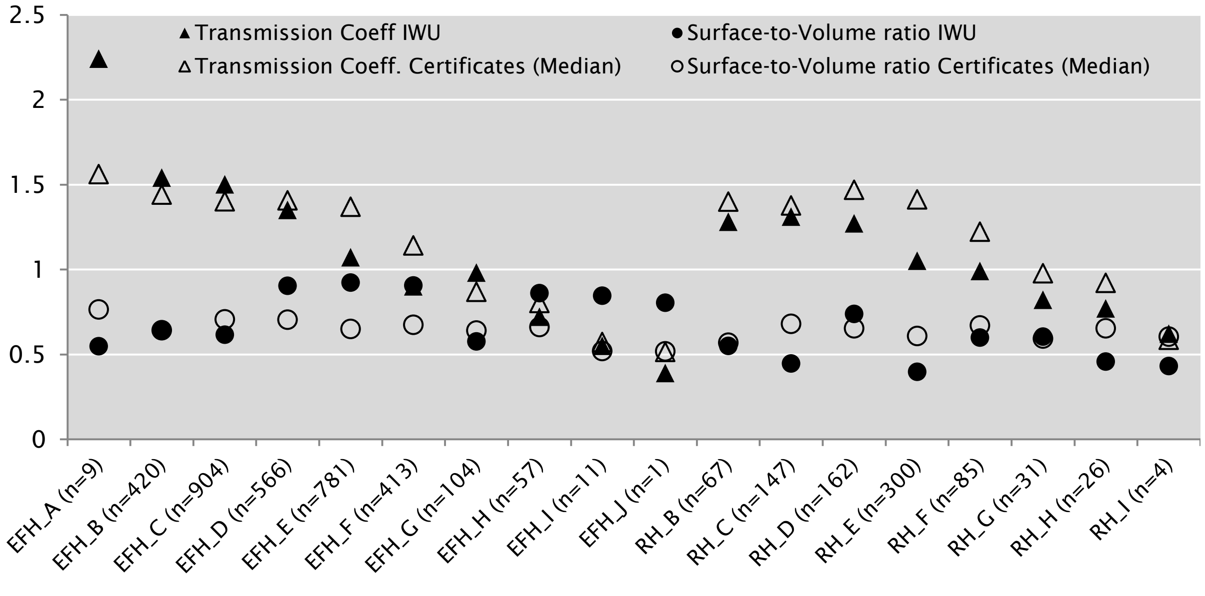

Figure 7 Overview of transmissivity coefficients for single-family buildings (computed as weighted average values for all areas of the building shell) and Surface-to-Volume ratios.

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[i] Since this is calculated useful heat demand under standard conditions, values can be interpreted as energy-efficiency of the building shell.

[ii] As defined in the beginning of the chapter.

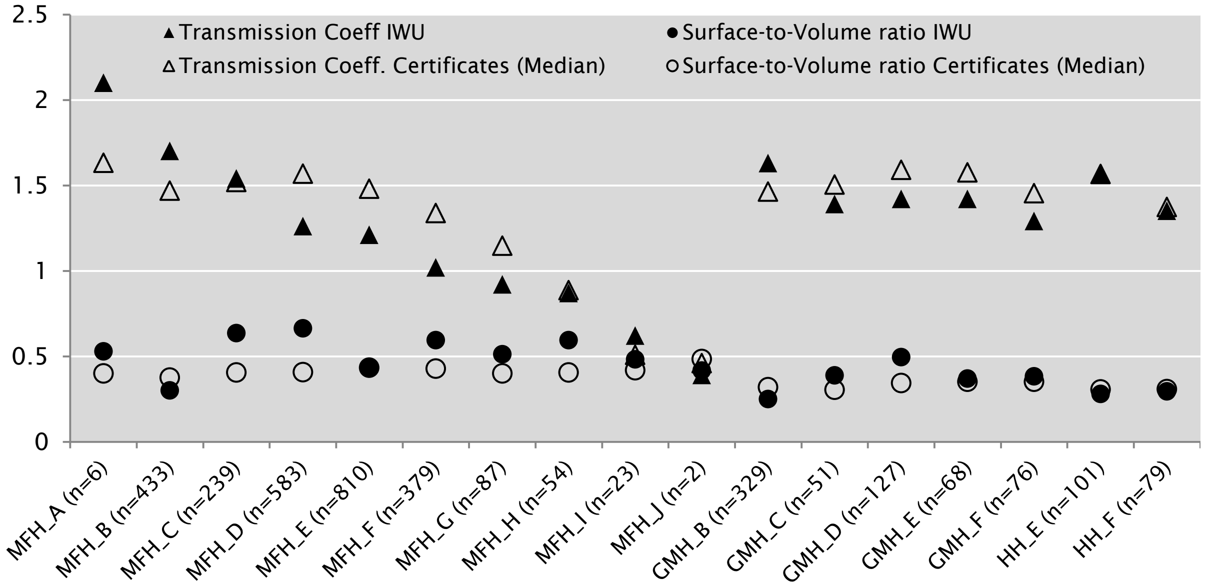

Figure 8 Overview of transmissivity coefficients for multifamily buildings (computed as weighted average values for all areas of the building shell) and Surface-to-Volume ratios.

The data shows that row-houses in the Energy Certificates dataset are not only less energy efficient regarding their building shell, but also have generally larger Surface-to-Volume ratios which together result in higher heat demand. Detached single-family houses exhibit a larger mix, with some having larger transmissivity, but lower Surface-to-Area ratios, resulting in an overall balance and values for heat demand closer to the IWU estimates. The case with the multifamily buildings is a clearer example of the same "balancing-out effect" - IWU values for transmissivity are generally lower, implying better quality building shell of the IWU reference buildings, but values for Surface-to-Area are higher, meaning less efficient geometry.

Breaking down the heat demand into these two components shows the complexity of heat demand estimations even before taking the heating system efficiency, hot water usage and the user behaviour into account. The observed balancing-out effects hint at the presence of perhaps similar, but more subtle and difficult to pinpoint effects when analysing heat consumption (Figures 9, 10).

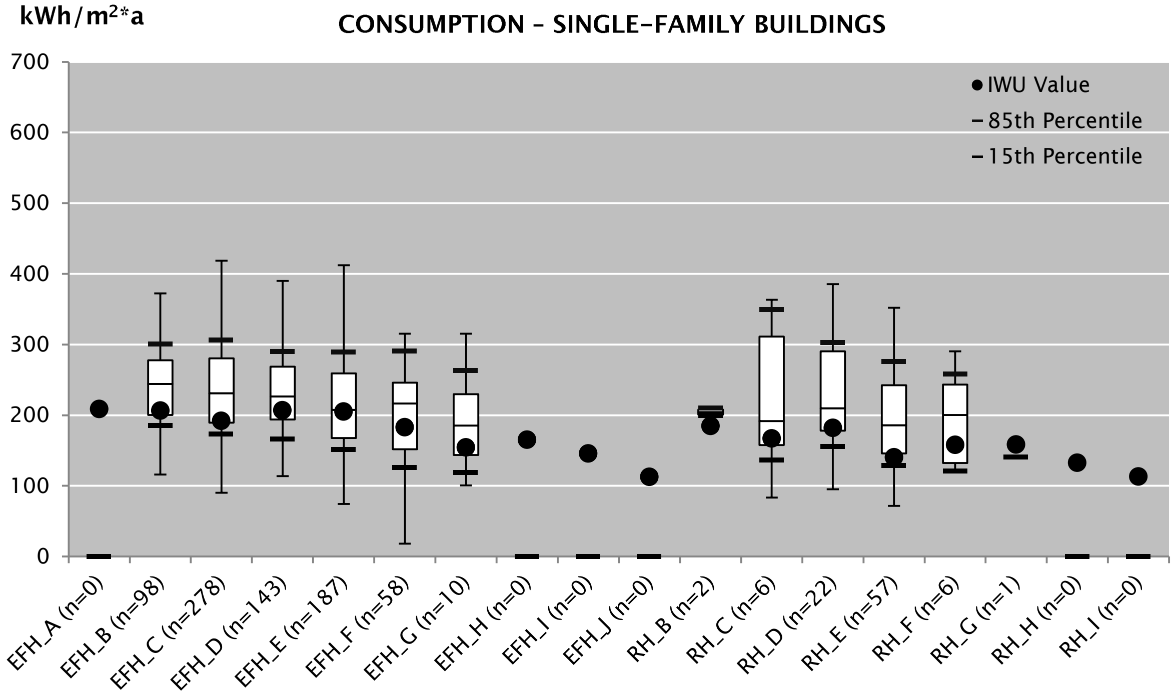

Figure 9 Distribution of heat consumption of single-family residential buildings in Hamburg, classified into IWU types. Extreme values removed using the outlier labelling rule, g=3, see (Hoaglin, et al., 1986).

Although with a significantly smaller sample size, the analysis of the consumption could be considered for some of the types – EFH_B, C, D, E and F and RH_D and RH_E. The straightforward comparison of the values for consumption (Figure 9) and demand (Figure 5), however would be inappropriate, since consumption values include hot water and system losses (without conversion losses) while the demand values are explicitly only useful heat. Nevertheless, the fact that even with the addition of hot water and system losses consumption is still lower than the theoretical demand is a sign of the discrepancy between demand and consumption, the latter tending to be lower than the former.

The analysis of consumption for single-family houses exhibits stable results with the interquartile range being on average ~80 kWh/m^2*a and the range between the 15th and 85th percentile on average ~130 kWh/m^2*a. Median values lie close to the middle of the quartile- and 15th and 85th percentile ranges hinting at distributions with some normal properties. Based on this data, if one takes median values for each type with +/- 40 kWh/m^2*a one could cover around 50% of the observed values and 70% with +/- 65kWh/m^2*a. While single-family buildings exhibit rather high maximum values, the multifamily buildings have at most 320kWh/m^2*a and narrower quartile ranges (~53 kWh/m^2*a) and 15th to 85th percentile ranges (~80kWh/m^2*a) suggesting perhaps averaging out effects of user behaviour. Of course, the sample size is very small for some of the types which renders the results less reliable.

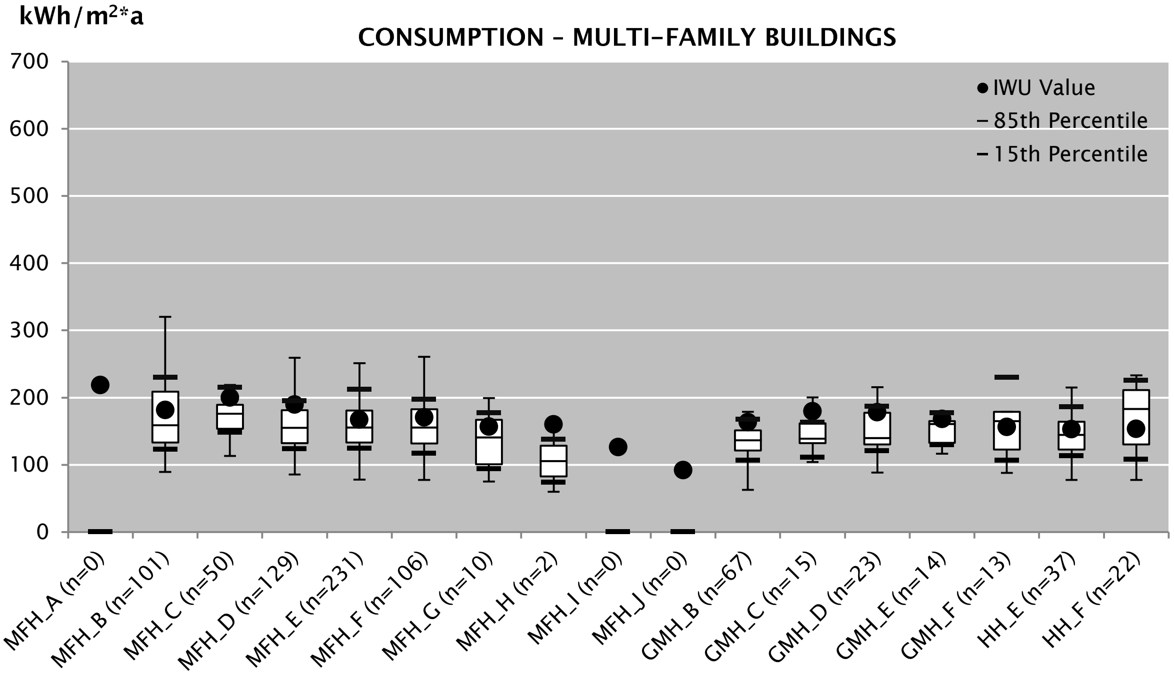

Figure 10 Distribution of heat consumption for multifamily residential buildings in Hamburg, classified into IWU types. Extreme values removed using the outlier labelling rule, g=3 (Hoaglin, et al., 1986).

In conclusion, the analysis suggests that the accuracy at the building level is questionable – point estimates (median) could deviate with +/- 50 kWh/m^2*a up to +/- 100 kWh/m^2*a in many cases. Larger deviations were observed, but are more of exceptions. Heat demand tends to vary more than heat consumption and smaller buildings tend to vary more than larger ones. Additionally heat demand exhibits positive skew with light tails that is not so evident when it comes to consumption.

IWU values for demand systematically underestimate the demand of row-houses, which can be attributed to both geometry and generally less energy efficient building shell. Breaking down demand into geometry and building shell quality shows that in many cases the buildings in Hamburg exhibit compacter geometry, but lower efficiency compared to the IWU reference buildings which levels the resulting demand and produces specific heat demand closer to the IWU estimate. IWU values for consumption are also closer to the median estimation compared to demand.

A tendency could be observed of the interquartile and inter-percentile ranges for demand being lower for newer buildings, which can be attributed to the more variability of renovations that older buildings underwent. For consumption this pattern is more subtle, suggesting that the user behaviour decreases usage at the higher levels or maybe heating systems cannot deliver the theoretical demand. The medians tend to decrease through the decades, but the pattern is rather subtle for demand and difficult to analyse for consumption due to smaller (or non-existent) sample sizes in newer periods.

6.3 Accuracy at an Aggregated Level

Although the analysis at the building level showed a relatively wide range of possible values for the specific heat demand and consumption within each type, for the purposes of this thesis, these values are to be viewed in the context of heating grid planning.

In the usual case, the specific heat demand (or consumption) measured in kWh/m^2*a of an individual building is, in itself, not of prime concern for heating grid planning. It is the total demand of all the potential consumers (buildings) in MWh/a that is relevant (on the demand side) for the economic plausibility and for the macroscopic[i] dimensioning of heating grids (Schuchardt, 2015). Therefore, when estimating the accuracy of heat demand estimations in the context of heating grids, the accuracy for the total MWh/a of groups of buildings rather than the specific heat demand for individual ones is what is more relevant. For this purpose, the entire ALKIS dataset is aggregated into building groups.

6.3.1 Building Aggregation

The aggregation method used for this step of the analysis is based on the working paper "Aggregation approaches for GEWISS – "Street front*"* aggregation*"* (Dochev, et al., 2017) and was also used for the construction of the Hamburg Heat Demand Cadastre (*Wärmekataster*)[ii] that is about to be published by the Hamburg Department for Environment and Energy (*Behörde für Umwelt und Energie*) in the spring of 2017.

The aggregation logic is that since technical infrastructure, in general, follows the street network of a city, the grouping of buildings, which are supplied by this infrastructure, should adhere to the spatial layout of the street network. On the other hand, the urban block (*Baublock*) is a relatively established aggregation level at which data for official purposes are collected, for example for the five yearly Census. Therefore, an aggregation that takes into account the urban block is advantageous for the analysis as it offers for example sociodemographic data at congruent area units. Combining the two approaches produces the "Street-front" aggregation – splitting the urban block into parts, each overlooking the nearest street (Figure 11). The "Street-front" aggregation is performed using the name of the street on which the building is located, derived from the address attribute in the ALKIS together with the urban block identification number, obtained from the urban block dataset of Hamburg[iii]. The aggregation produced approx. 17.000 groups (groups are also referred to as "clusters" in the context of the Hamburg Heat Demand Cadastre), with most groups having between 5 and 20 buildings

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[i] Matching the heat demand of the supplied buildings and the heat source.

[ii] We are obliged to Frau Lubow Deck and Herr Arne Werner (from *Behörde für Umwelt und Energie*) and Herr Axel Orth (from *Landesbetrieb für Geoinformation und Vermessung*) der Freien und Hansestadt Hamburg who served as sparring partners in the development of this aggregation method.

[iii] Available freely from the Hamburg Transparency Portal.

(Figure 12). A small amount of buildings (900) are in groups with just one building which would mean that their distribution of values after the Monte Carlo Simulation would approximate the distribution for this IWU Type in the energy certificates.

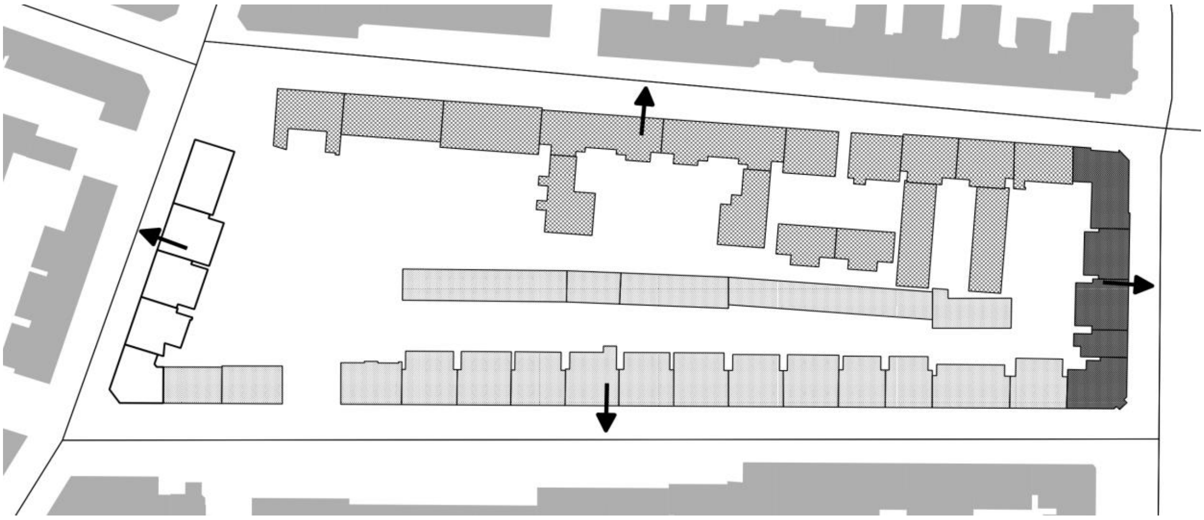

Figure 11 Example of "Street-front" aggregation. Different colours depict the different aggregated groups.

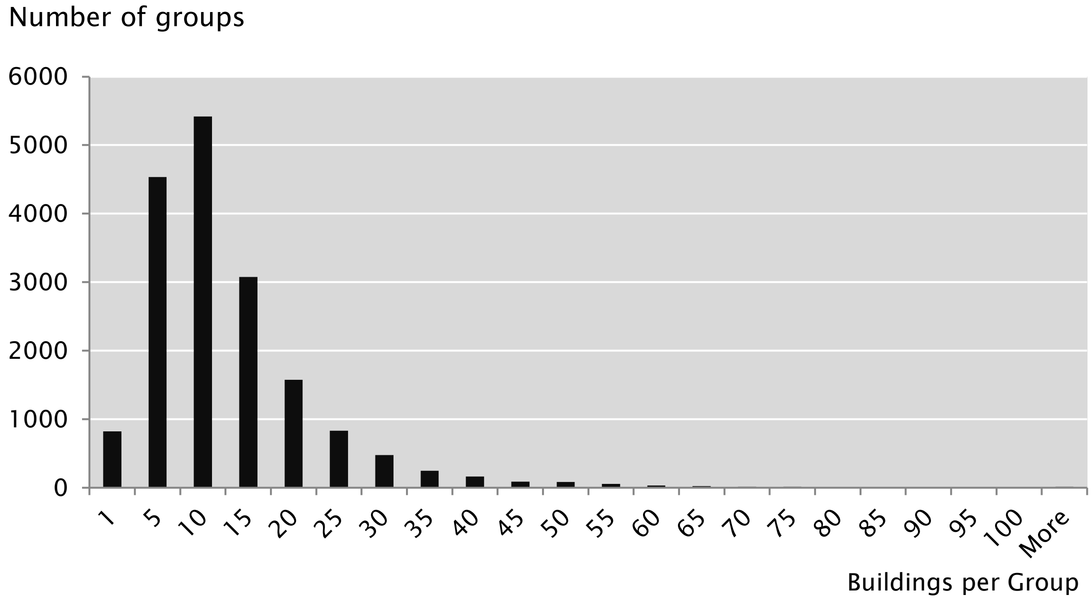

Figure 12 Frequency distribution of the number of buildings per group after the "Street Front" aggregation.

This aggregation level may still be a bit low with respect to the planning of heating grids. Even heating grids that may be regarded as "small" may serve dozens of buildings. However, the reason for estimating the accuracy at a somewhat lower level is to allow more flexibility and complement the Heat Demand cadastre of Hamburg, the purpose of which is not only the planning of heating grids. A coarser aggregation was needed for this thesis (see Chapter Planning of Heating Grids) but nevertheless the error estimations were performed at a lower level adopting a more conservative approach – the assumption being that the level of accuracy increases as aggregation gets larger, therefore errors should be larger at lower levels.

6.3.2 Monte Carlo Simulation

The reason for the use of a Monte Carlo Simulation is that each building group contains different numbers and different types of buildings, each with a different distribution of values contained in the energy certificates dataset. Simple sum of minimum values or of maximum values for each type would imply that all buildings in a group are either very efficient or very inefficient which is unlikely. On the other hand, taking average values for each type and summing those would imply that there is a perfect distribution of the variability contained in each IWU type and any group can be approximated with the average values for each of the types, which again is unlikely. One can argue that the reality is somewhere in between, some groups of buildings probably include types buildings, the demand of which does not vary much within the type, while others are likely more "mixed" – with large differences of demand even within the IWU type. In order to analyse this mixture of possibilities I performed a stochastic analysis in the form of a Monte Carlo Simulation.

It has to be noted that in some cases of IWU types, either no buildings or very few buildings in the energy certificates are present for a given type (see Appendix). For the buildings with no corresponding type in the energy certificates, the respective IWU value for demand and consumption[i] is taken for consistency. Generally, heat demand is well covered in the certificates with only newer buildings (after 2010) not being present. For heat consumption approx. 1500 certificates are available and 16 IWU types are not covered – again mainly more recent buildings - after 1995 (epochs I,J,K,L).

The simulation (implemented in the Python language and available on github[ii]) iterates over the building groups. In each iteration (p) each building (i) is assigned a random specific heat demand value for its type from the certificates dataset[iii] (D_{ip}). This value is then multiplied with the residential

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[i] Heat demand as in useful heat demand for space heating and consumption as the consumption corrected heat demand values for space heating and hot water with system losses included.

[ii] https://github.com/ivandochev/Master-Thesis-HCU/blob/master/MonteCarlo%20Simulation.py

[iii] Or from the IWU Typology, if the type is not present in the typology.

area of the building (A_i), and the resulting yearly heat demand per building is summed over all buildings in the group (n) which equals S_p, the total heat demand for the group in iteration p:

$$S_p = \sum_{i=1}^{n} D_{ip} A_i$$

where:

$i = 1, \dots, n$ building in the group
D_{ip} = the specific heat demand/consumption in kWh/m^2*a for building i in iteration p
A_i = the residential area of the building i, remaining constant in each iteration
S_p = the sum of the total demand of the group for iteration p

Since some buildings (approx. 10 000) were classified as renovation level 1, for these buildings the corresponding value from the energy certificates dataset is for the demand of the renovated state noted in the certificate. In the case of consumption these buildings are assigned the IWU value for consumption-corrected demand of renovation level 1.

The iteration count is set at 500 iterations, which produces 500 different values for S_p for heat demand and another 500 for consumption. The results of the two sets of 500 runs can be summarized by a frequency distribution of S_p for every group. An example of one such distribution is given in Figure 13 (bin-width in the example 20 MWh/a). A total of approx. 17000 such distributions (one for each group) are generated for heat demand and heat consumption respectively.

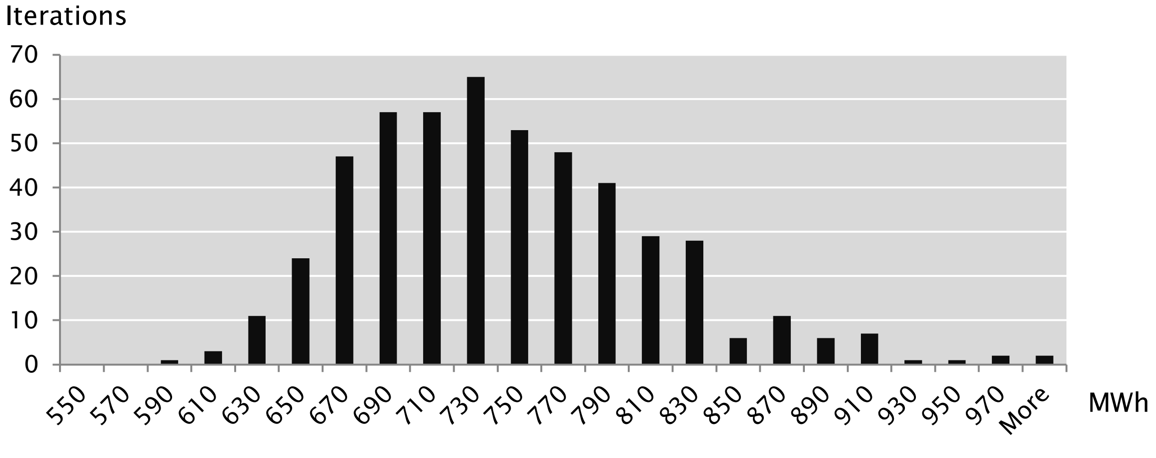


Figure 13 Example distribution of heat demand values obtained for a group of buildings with the Monte Carlo Simulation.

6.3.3 Analysis of Results

Given the results of the Monte Carlo simulation, a measure of accuracy for the heat demand estimations at the aggregated level can be obtained by exploring the spread of values around a measure of central tendency. If the spread is narrow, then most of the iterations resulted in values that are relatively close to each other, which means that when using the measure of central tendency the error is likely to be small – as small as the spread around the central measure. Of course in order to compare the errors for groups of different size and demand the errors are relativized, which results in a point estimate (the measure of central tendency) and relative errors as percentages of this point estimate.

Firstly, a comparison between the sum of all means and medians together with the sum for the corresponding IWU values is made so that the relationship between the totals for the entire Hamburg building stock can be analysed and serve as a plausibility check. The results are relatively stable - around 10 TWh/a. Values for the averages are slightly higher than the medians, which implies positive skew in the simulation distributions. IWU value for demand is higher while for consumption lower than the simulated results. It has to be noted that comparing consumption and demand would be inappropriate since consumption values include hot water and system losses while demand covers only useful heat for space heating.

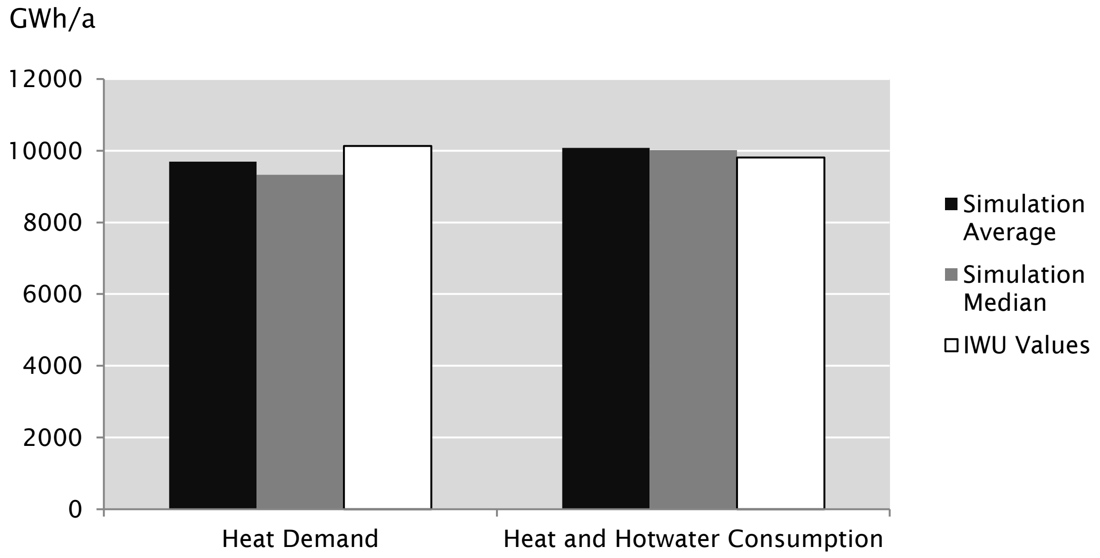


Figure 14 Comparison between total heat demand and consumption per annum for the residential building stock of Hamburg. Values from the Monte Carlo Simulation are given as sums of averages and sums of medians from the iterations.

Secondly, for the error estimation the distributions of all building groups have to be analysed as opposed to only their respective sums. However, due to their large number of around 17000 groups, analysing each one individually is not possible. Therefore descriptive statistics of these distributions have to be viewed, again, as a distribution.

In order to obtain a better understanding of this large amount of distributions, firstly the number of unique values in each one was counted (Figure 15).

Since the simulation iterated at random between the available certificates for each type, a small number of unique values can result from two situations – either a) there were many values obtained from the building certificates all of which were the same so no matter which one the iteration picked it lead to the same result; or b) there was a very small number of building certificates which corresponded to the buildings in the group and each time the same certificates were picked. As presented in Chapter Accuracy at the building level the values in the certificates vary to a large extent, but there are some types, for which the sample is actually very small, which means that the resulting small number of unique values for given groups can be attributed to small number of certificates, rather than to small variability in those certificates per type. For this reason, an arbitrary value of a minimum of 5 unique values was set for each group. Groups with less than that amount are used further in the analysis, but the relative errors obtained are considered “unknown” and only a point estimate is made. The possible maximum number of unique values is 500, since this is the number of iterations set in the simulation.

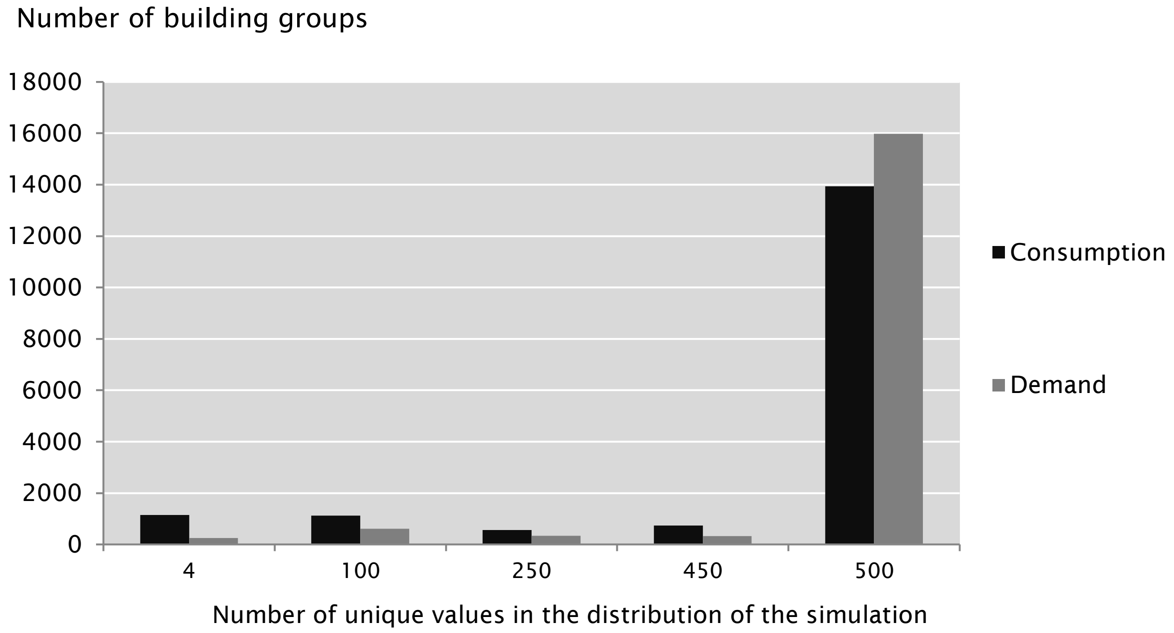


Figure 15 Number of building groups according to the amount of unique values in each. A small number indicates a small sample of building certificates, which renders the error estimation less plausible

Figure 15 shows that for most of the building groups a rather rich variability is obtained from the simulation, with values for consumption being lower, which is due to the overall smaller sample size of the consumption values (1500 as opposed to 7700 certificates for demand). In total, around 1000 building groups for consumption and around 200 for demand have less than 5 unique values and error estimations for them are not made – these are considered “unknown”. The figure also shows that choosing a different limit for the “unknown” group anywhere between 5 and 450 values does not influence the results too much, since by far the largest amount of groups has more than 450 unique values.

The rich variability of values, however, does not indicate much about their nature. The Yule-Kendall (Yule, 1912, p. 150) skewness coefficient is robust, quartile-based measure of skewness which shows that most of the 17000 groups exhibit positive skew (Figure 15) and most probably their distributions depart from normality.

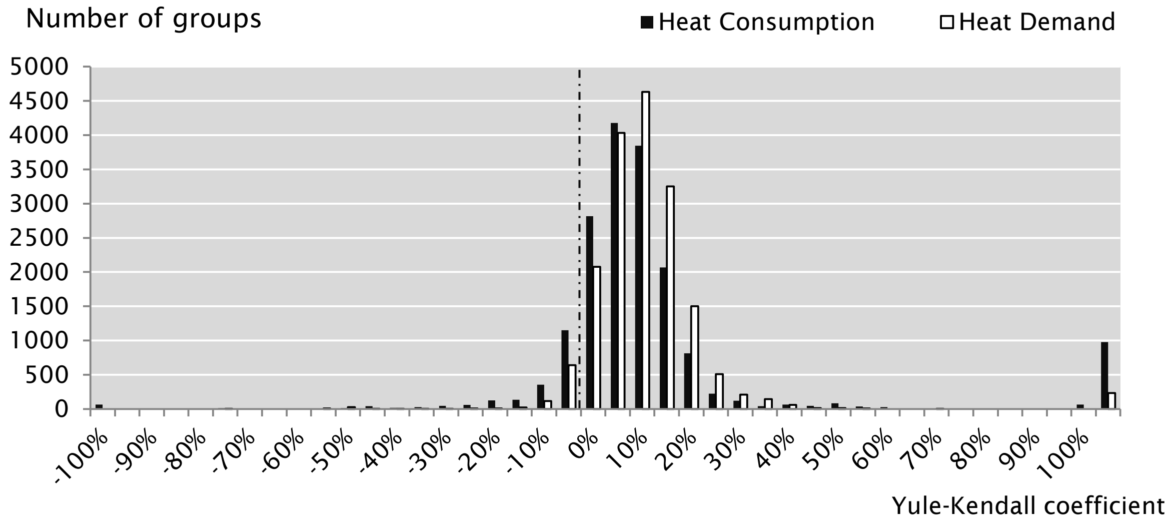


Figure 16 Number of groups according to the Yule-Kendall Skewness coefficient. Positive values indicate positive skewness.

Although the degree of non-normality differs, and some groups could potentially be analysed with the standard measures (mean and standard deviation), for the purpose of analysing the whole dataset and the ability to compare between groups, the non-parametric, measures of median and percentiles are used as descriptive statistics.

A common measure for relative dispersion is the coefficient of variation, defined as the ratio between the standard deviation and the mean. Since, under conditions of normality, the area of +/- 1 standard deviation under the curve encompasses around 66% of the distribution, a non-parametric alternative would be to use 15th and 85th percentiles and the median, encompassing 70% of the values in the distribution. However, the median may not be in the middle of this inter-percentile range and therefore two values for errors (*relative error above* and *relative error below*) were defined as:

$$E_a = \frac{P_{85} - M}{M} \qquad E_b = \frac{M - P_{15}}{M}$$

where:

$E_a =$ Relative error above (above median)
$E_b =$ Relative error below (below median)
$P_{85} =$ 85th Percentile
$M =$ Median
$P_{15} =$ 15th Percentile

These relative errors are used for the accuracy assessment. Considering that the "true" value for the demand and consumption of each group is unknown, the Monte Carlo Simulation delivers a range of possible values (based on the certificates). If the median is taken as a point estimation in the middle of these possible values, it is likely (70% of simulation outcomes) that the true value is within the defined inter-percentile range and if E_a and E_b are low, that would mean that this range is small and the "true" value probably does not deviate much from the point estimation, therefore the estimation is relatively accurate.

The calculation of the relative errors is performed for each group and summarized in Figures 16 and 17 for heat demand and heat consumption respectively. The results show that most errors tend to be in the 5-20% range. For heat demand, the errors below tend to be lower than the errors above, which can be attributed to the positive skewness of the distributions, which, on the other hand, is most probably a result of the skewness observed in the building level analysis. This is not exactly the case with consumption, where the difference between the "relative error above" and "below" is more subtle. This complies with the results obtained at the building level, where the skewness for consumption was also less evident.

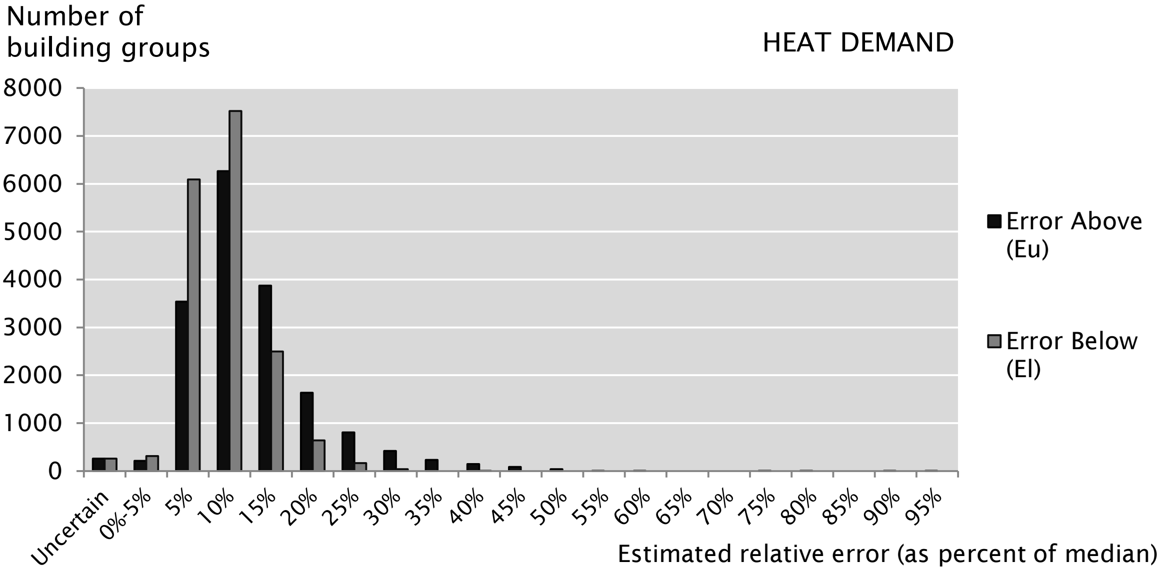


Figure 17 Frequency distribution of estimated relative errors for heat demand, as percentages above (E_a) and below (E_b) the median. Data grouped in 5% bins.

Due to the larger sample of certificates, the "unknown" relative errors for heat demand (the ones for which no plausible distribution could be obtained) are also relatively low. Heat consumption, on the other hand, shows slightly lower relative errors (more groups in the 5-10% range), however the estimates for consumption have to be regarded as generally less reliable due to the sample size.

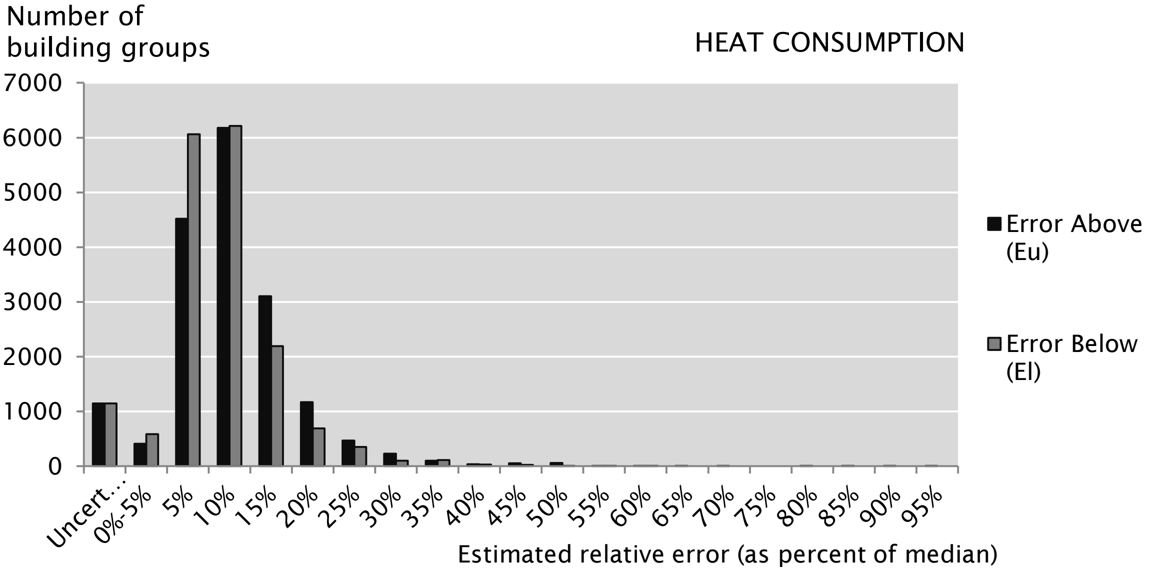


Figure 18 Frequency distribution of estimated relative errors for heat consumption, as percent above (E_u) and below (E_l) the median. Data grouped in 5% bins.

Finally, in order to produce a better overview, the average between the upper and lower errors (E_u and E_l) was taken and the values for consumption and demand were compared (Figure 18).

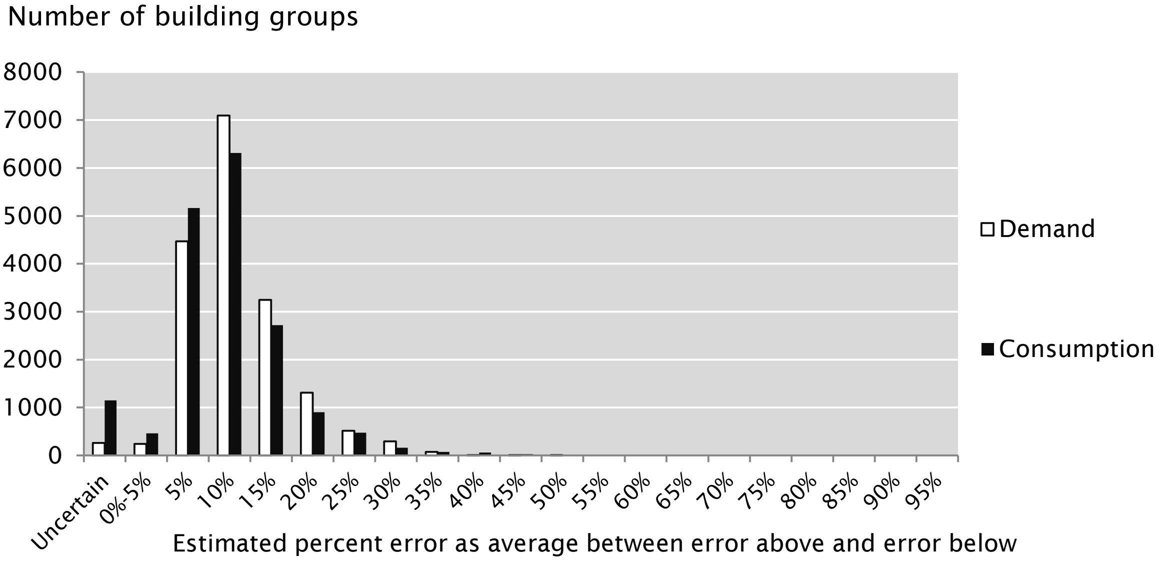


Figure 19 Frequency distribution of the average between error above and error below median (E_a and E_b) for demand and consumption respectively. Data grouped in 5% bins.

The comparison shows that for almost all groups the average relative error is between 5% and 20%. A significant amount of groups (approx. 11000 for both demand and consumption) exhibit a relative error of up to 15% which can be considered a good accuracy. Nevertheless, errors of up to 65% were observed which emphasizes the differences between the estimations for different groups.

In order to analyse these differences the average between error above and below is classified into three bins – 0-10% error, 10-20% and above 20% and each group is visualized spatially (Figure 20). The observed spatial pattern shows that lower relative errors are to be found in the outer parts of the city, while higher ones in the more central parts. The most common errors of 10-20% are relatively equally dispersed. The reason for the higher relative errors in the central parts is most likely due to the buildings' age. More central parts tend to include older buildings, which most probably underwent various renovations and retrofits through the decades and therefore have more variability in their current (baseline) state. This can be seen also at the building level (Chapter Accuracy at the building level). Additionally, this pattern could be influenced by the number of buildings in the groups – more central parts of the city include fewer buildings per group (the buildings are larger and the street pattern is denser) which results in reduced averaging out effects since the iterations include fewer distributions.

Generally, most of the errors are in the 5% to 20% range, however, although in fewer iterations, the Monte Carlo Simulation also produced estimates outside of the taken interval – 15th to 85th Percentile. Therefore it can be concluded that for the majority of groups it is likely that the errors are confined to this (up to) 20% error range, but larger errors could be observed. This can happen mostly if locations with strong spatial autocorrelation, for example dense clusters of very well renovated buildings, are not modelled as "renovated", but rather taken as "baseline" renovation. Then, the real demand (and consumption) might indeed deviate with more than 20% from the estimate, since the assumed averaging out effects will not be present. In other words, the presented relative errors can be considered plausible if renovation levels are at least partially modelled – large groups of renovated neighbouring buildings are not completely overlooked and the right renovation level is assigned for at least some of them to avoid high spatial clustering of "wrong" renovation levels. In the concrete case, I attempted to model the renovation levels, classifying approx. 10 000 buildings as renovation level 1, therefore this is already mirrored to some extent in the simulation, but as stated in chapter Estimating Renovation Levels this estimation is a form of a best guess.

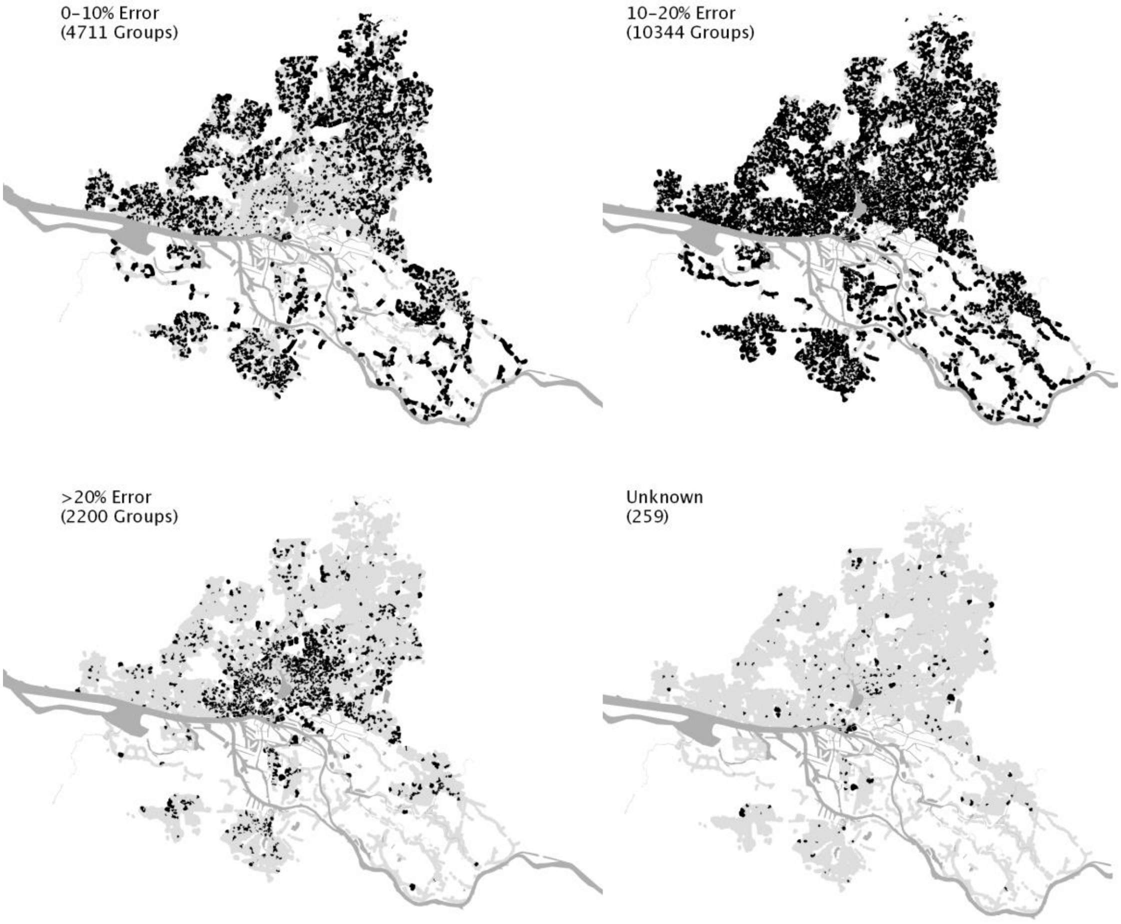


Figure 20 Spatial pattern of the estimated relative errors for heat demand. Average Values between relative error above and below median. Patterns for consumption are similar.

7 PLANNING OF HEATING GRIDS

After the relative errors for all building groups were obtained, the inevitable question arises of what is their practical significance. A 20% error in some cases is disastrous, while in others - acceptable. Therefore the estimations have to be put in context – in this case, the context of heating grid planning. The planning of heating grids is a complex topic and the decision for a heating grid is usually based on a variety of factors, many of which are non-technical – political will, motivation of building owners, current energy prices and others. Analysing the estimated relative errors in this context is a topic on its own, nevertheless I made an attempt to do this, by relating the relative errors to one central magnitude of heating grid planning – the linear heat density (LHD - *Wärmebelegungsdichte*).

7.1 Linear Heat Density

“Heat density” in general can refer to several calculated values used for the analysis of heating grid potential. One such density measure is the heat density in MWh/ha (Hausladen & Hamacher, 2011, pp. 48,49). A more concrete, but more difficult to compute density measure is the Linear Heat Density in MWh/meter pipeline length (Nast, et al., 2009, p. 185):

$$LHD = \frac{Q_a}{l}$$

where:

Q_a = Total heat demand of all consumers in MWh/a

l = Total length of heating grid in meters, supply and return pipes counted as one.

The LHD is used as an indicator for the overall economic feasibility of a heating grid. The larger this ratio, the more efficient the heating grid, since it transports more heat across shorter distances, thus reducing grid losses and investment costs for pipelines. Although the more straightforward measure of heat density (MWh/ha) is easier to compute, the LHD is a more precise and more “finely grained” value. In general, both densities can be used in grid planning for assessing the viability of grids, but since the LHD performs better at finer scales, and the scale of the building groups is relatively fine, I deem it the better measure for the purpose at hand.

The LHD in itself is by no means enough to evaluate the economics of a specific grid, but it is one of the first indicators computed at the start of grid planning in general and is therefore an important factor for decision support.

Hence I take LHD as the context into which I place the relative errors obtained by the Monte Carlo simulations so that their importance for grid planning can be meaningfully analysed. By transferring the relative errors of the heat demand and consumption estimations onto the LHD, a measure of the error of the LHD is obtained. Comparing these estimated values with general rule-of-thumb threshold values for the LHD allows a conclusion to be drawn as to how important the estimated error is. If for large number of building groups, the estimated relative errors influence the LHD to such an extent as to render the plausibility of a grid questionable (for example the error below results in a too low density while the error above for plausible density), then the estimation and its error do (or should!) affect grid planning: Depending upon where in the computed interval lies the true value, the plausibility of a potential heating grid changes.

While the heat demand and consumption estimations are based on the types of buildings, the LHD requires grid lengths, which are most dependent upon local context and urban form – street, plot and building layout. Groups of buildings of the same type could potentially have different densities, based on their positions in their respective plots, based on the street layout and the possible routes for a pipeline or simply based on the distance between the buildings. Therefore, in the context of heating grids, estimating the LHD will enable an even more localized analysis, which explores the more complex relationship between the characteristics of groups of buildings and their spatial relationships.

7.2 Hypothetical Heating Grid Construction

Since the purpose of this analysis is not to plan concrete grids, but to explore the effect of the errors on grid planning, I created a simplified model by regrouping all of the 17000 small building groups, resulting in more compact structures ("re-aggregated building groups") for each one of which I computed a separate small hypothetical grid. These hypothetical grids should be interpreted as integral parts of potential grids, rather than complete district heating grids in themselves, though that may also be possible.

By constructing these hypothetical grids, I obtained a measure of grid length for each aggregated building group, which I used for computing different values for LHD for this group - a point estimate using the median demand or consumption, respectively, together with the relative errors.

7.2.1 Types of Grid Layouts

In order to construct the hypothetical grids in a plausible fashion, I did a literature search to find out about standard grid layout. These are my findings:

Firstly, the layout of the main pipeline of district heating grids is generally split into three types – radial (*Strahlennetz*), circular (*Ringnetz*) and multi-circular (*Maschennetz*) (Dötsch, et al., 1998, p. 37), presented in Figure 20. According to the *Fraunhofer Institut* (Dötsch, et al., 1998, pp. 37,38) and Kaltschmitt el al (2012, pp. 734,735) the circular layouts tend to be more flexible, since more heat sources can be connected. However, in practice, for smaller grids often the radial layout is preferred over the circular layout, as the latter is generally associated with greater pipeline lengths.

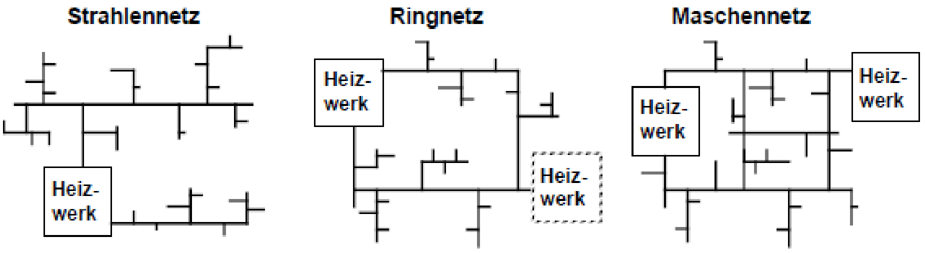
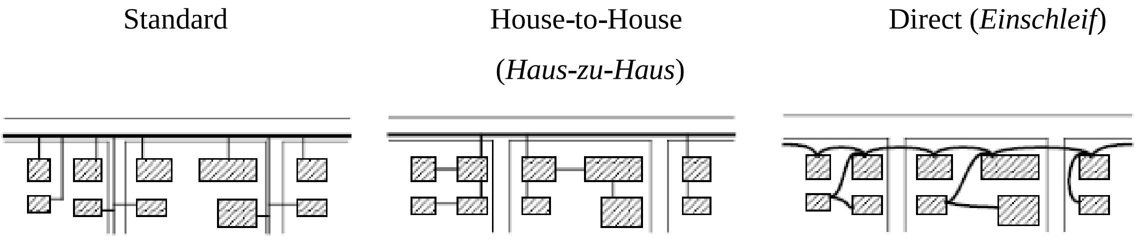


Figure 21 Types of main pipeline layouts. Source: (Dötsch, et al., 1998, p. 37)

Secondly, the type of service connections (how are buildings connected to the main pipeline – *Hausanschluß*, Figure 21) is generally categorized again into three categories – “standard” (*Standard-Trassenführung*), “house-to-house” (*Haus-zu-Haus Trassenführung*) and “direct” (*Einschleif-Trassenführung*) (Dötsch, et al., 1998, p. 37).


Standard

House-to-House (*Haus-zu-Haus*)

Direct (*Einschleif*)

Figure 22 Types of service connection layouts. Source: (Dötsch, et al., 1998, p. 37)

According to the *Fraunhofer Institut*:

> The most widely adopted layout is the “standard” layout (*Standard-Trassenführung*), where a main pipeline is placed in non-private areas, usually streets, and all consumers are directly attached to this main pipe. The second form is the “house-to-house”, which bundles buildings together and only one of them is connected to a main pipe. The advantage of the standard layout is that it is more flexible - the grid can be more easily expanded - and that service connections do not traverse private property (except the property which this pipe supplies). The advantage of the “house-to-house” layout is that it tends to have shorter pipe lengths, but, as opposed to the standard layout, is less flexible and right of

> passage permits for the infrastructure have to be obtained from plot owners. The most common way to approach the decision for a service pipeline layout is to get a mixed-form, which can benefit from the advantages of both types (Dötsch, et al., 1998, p. 38).

Similarly, Kaltschmitt el al (2012, pp. 734,735) also state that the exact layout is chosen according to local conditions which usually results in a mixture of "standard" and "house-to-house" connections.

7.2.2 Algorithm

Against this background, I had to devise a strategy on how to model, in a plausible way, the layouts of all grids corresponding to the building groups.

Since the scale of the hypothetical grids is rather small (~20 buildings) and the radial grid layout for the main pipeline is preferred for small grids, the hypothetical grids can be simplified into single radial-based grids. The geographic location of the main pipeline of these grids can then be approximated by the street network since main pipelines generally follow publicly accessible spaces.

Going back to the original building aggregation logic – "street front" aggregation – the building groups were defined by the street each building overlooks and the urban block in which it resides. If the hypothetical grids are to be modelled according to a radial layout, with the main pipeline following the street network, then the building aggregation already supports this – the buildings in the groups are nearest to the same street and therefore a main pipeline for each group can be approximated without the need to regroup the buildings. Furthermore, the fact that the groups are restrained by the urban blocks (no group contains buildings from more than one urban block) means that, in most of the cases, the buildings overlook not only the same street, but the same street segment[i]. This narrows down their possible length and results in more compact grids (Figure 23).

However, a problem arises – the building groups overlook the same street segment, but each segment is generally overlooked by two groups. Constructing a hypothetical grid for each of the two groups separately would greatly overestimate the pipeline lengths when viewed at a larger scale, since it can be assumed, that if a heating grid is placed along a given segment, buildings from both sides will be connected. If two groups on two different sides of the same street are viewed separately, then the street segment length would be counted twice –once as part of the grid of the one group and once as part of the grid of the other. Then calculating the LHD for these two groups, although correct for each group separately, would be wrong when viewed practically - given the chosen radial logic of the theoretical grids it is more practical to connect all plausible grid users to each main pipeline, which in this case would mean to connect buildings from both sides of the street.

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[i] Defined as the part of the street between two intersections.

This problem is easily overcome by grouping the building groups together into new aggregation units according to the street segment. In this way the resulting "re-aggregated" groups together with their corresponding street segment approximate a small heating grid, or a better-defined part of one, which is the goal of the modelling (Figure 23).

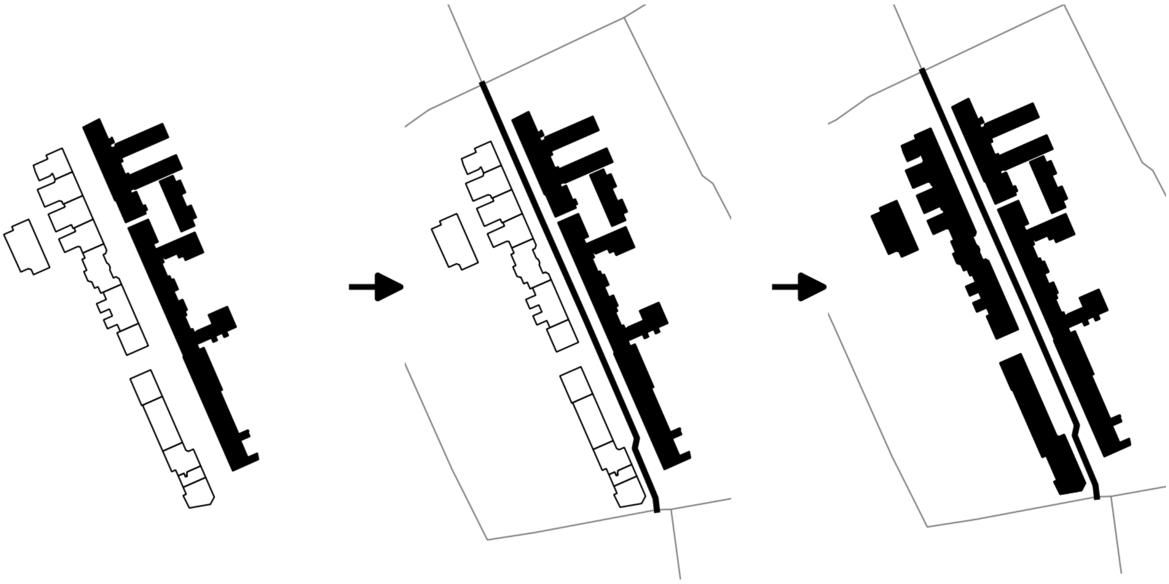

Figure 23 Re-aggregation of building groups in order to prepare grid modelling.

After this regrouping the number of the new "re-aggregated" groups is approx. 11000, which is more than half of the original number of building groups. The reason for this is that not in all parts of Hamburg the urban fabric is the same as in the above example, so some groups do not get re-aggregated, since they are the only ones overlooking a certain street segment – for example there are non-residential buildings or green areas on the other side of the street.

The thus derived groups are considered the building stock for approx. 11000 small district heating grids. These grids per definition already have a main hypothetical pipeline associated with them – the nearest street segment. In order to approximate a realistic grid, however, the service connections have to be modelled and added to the street segment geometry.

For the computation of the service connections I prepared a Python script[i] which uses a modified version of a Python numpy implementation (Mueller, 2012) of a minimum spanning tree algorithm (MST) (Prim, 1957).

The script iterates over all building groups, then for each re-aggregated group adds the street segment as the base geometry for the new grid. In a second step, a minimum spanning tree graph[i] is

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[i] https://github.com/ivandochev/Master-Thesis-HCU/blob/master/Hypothetical%20Heating%20Grids.py

constructed that connects all buildings together with each other or directly with the street segment depending upon their location. In this way the resulting grid is an optimal graph connecting all buildings in the group with the main pipeline – each building is either connected directly to the main pipeline or with another already connected building. This approximates the "mixed" type of service connection layouts described in the previous chapter.

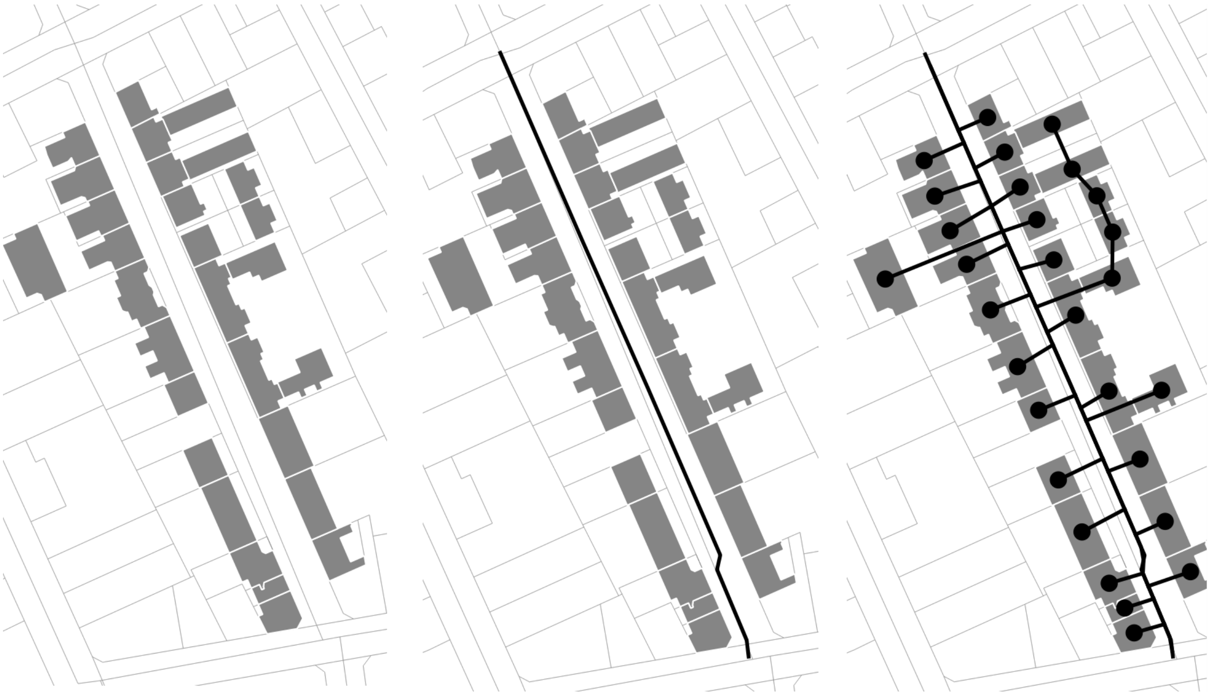

Figure 24 Example of the theoretical grid construction algorithm. Each individual group is taken, then a street segment forms the base geometry and for the grid and in a second step a weighted minimal spanning tree is created connecting all buildings.

Since the algorithm takes the locations of the buildings and the corresponding street segment as input and constructs the grid based on this, each grid layout is unique and based upon the local conditions. This follows the logic described previously that the exact service connection layout in reality is chosen according to local conditions usually resulting in a mixture of "standard" and "house-to-house" connections. However, optimal solutions are rarely possible in real conditions. For example, it may be difficult to obtain the passage permit for the infrastructure. In order to reflect this, the algorithm weighs the distances between buildings and gives preference to the direct connection with the main pipeline (street segment) over the house-to-house connection even if the former is longer. The weighing was arbitrarily set at 0.6 which means that distances between buildings and the street segment are considered (weighted) 60% shorter than their true length so that preference is given to

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[i] A minimum spanning tree (MST) is a graph (*G*) containing a specific subset of the edges of a fully connected edge-weighted graph (*F*) such that all nodes in *F* are present and connected in *G* without any cycles and with a minimum possible total edge weight. In many cases the weights are lengths in two-dimensional space which results in a MST with a minimal total edge length.

them. This results in a suboptimal graph with more standard connections but still making use of house-to-house connections for buildings which are too far from the street segment (even after distances are weighted). The results of the algorithm for different local conditions and urban forms are presented Figure 25.

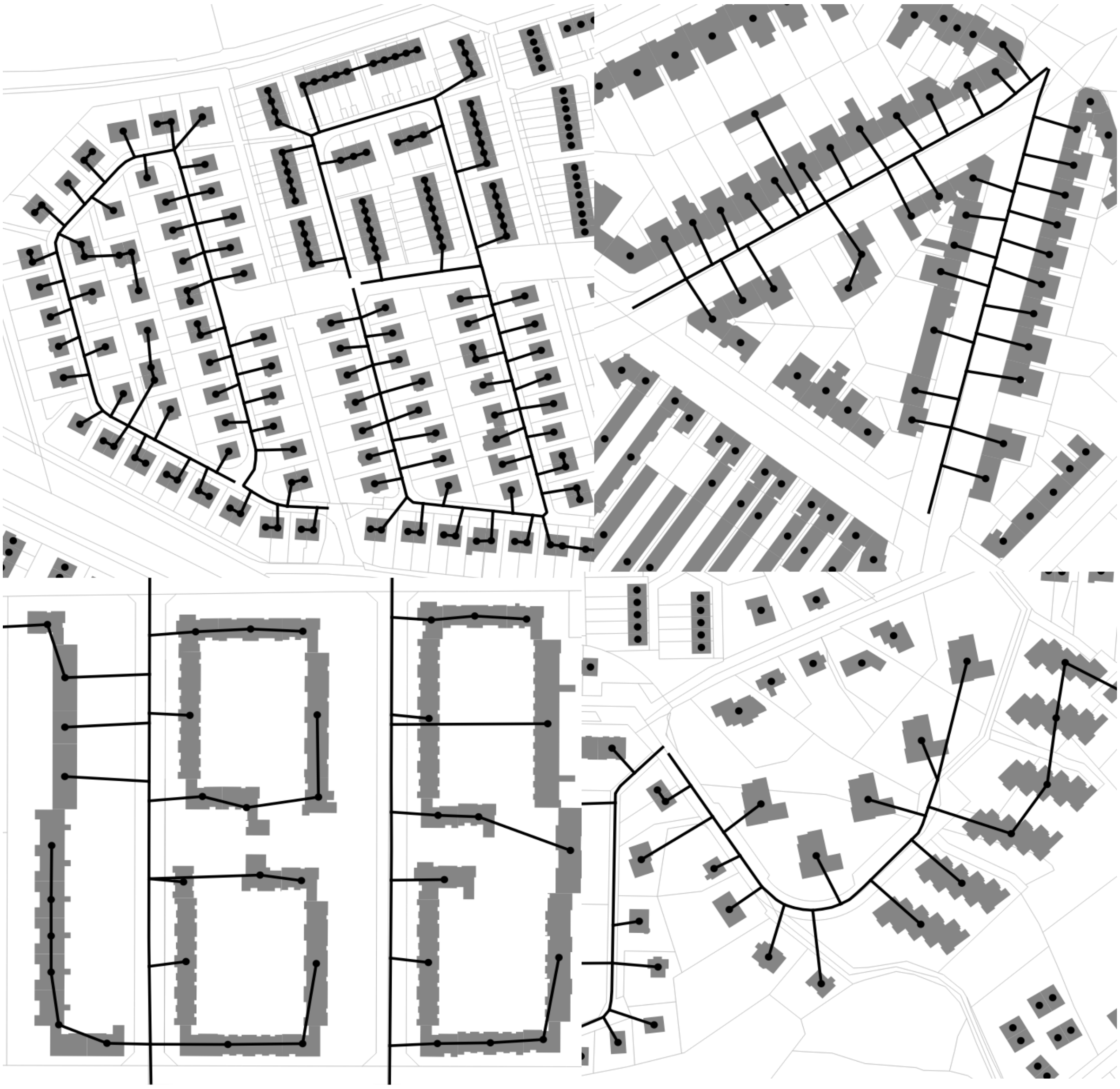

Figure 25 Examples of the generated theoretical grids for different locations and urban forms.

8 ANALYSIS OF THE LINEAR HEAT DENSITY

In the last part of this thesis, the results from the error estimation and the Linear Heat Density (LHD) computation are brought together and analysed. It has to be noted that this is exploratory, it uses simplifications of reality. For example, non-residential buildings are excluded; the calculated grid lengths are taken as fixed, although they could potentially vary depending upon some local conditions which were not modelled (e.g., plot layout); and some used thresholds are taken as binding, while in reality they are mostly for orientation.

The construction of the hypothetical grids allowed the estimations of the LHD for the whole Hamburg area using the median values from the Monte Carlo Simulation and the hypothetical grids (Figure 26, 27). At this point only values for consumption are taken, since they include hot water and the LHD is usually computed with the total heat demand including domestic hot water.

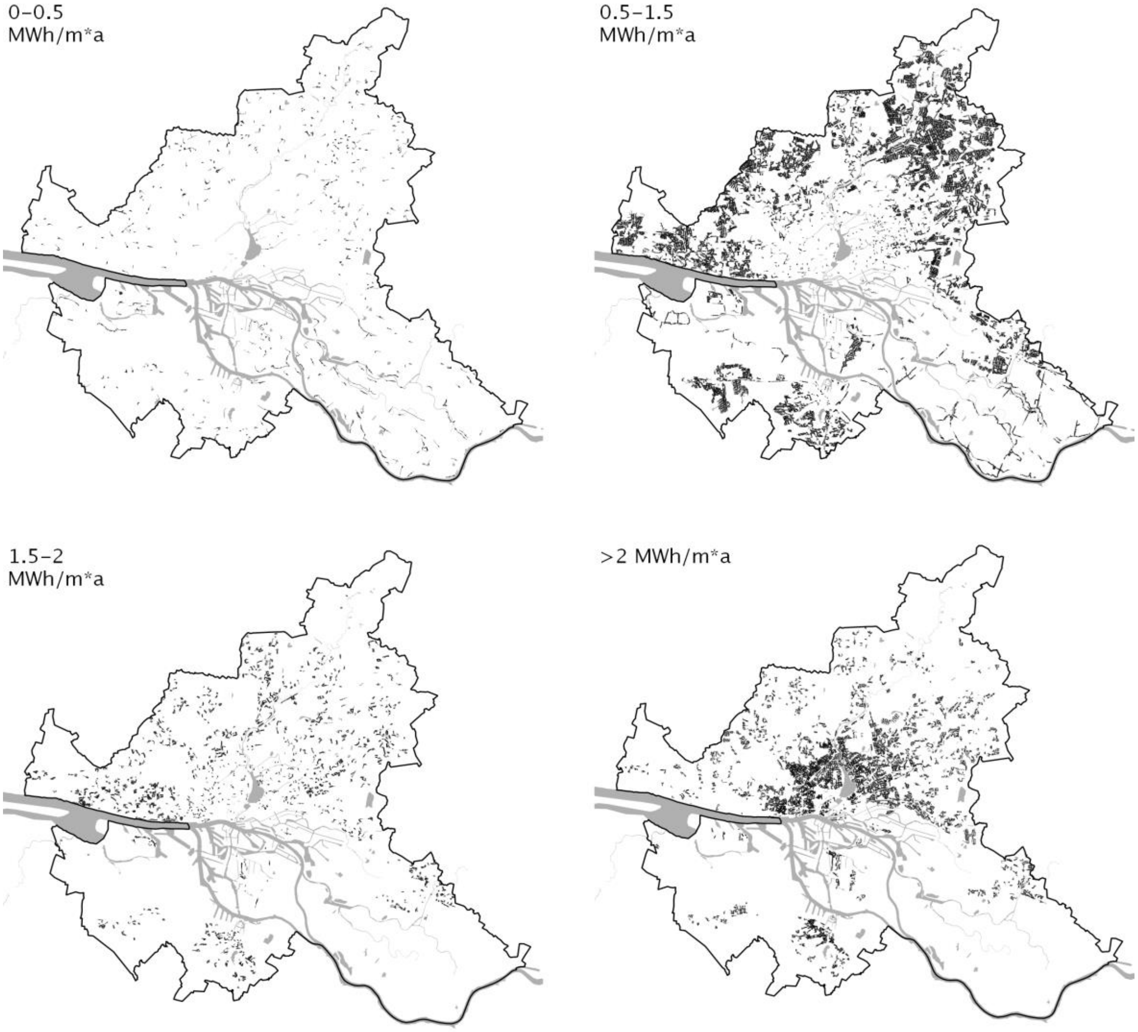

Figure 26 Overview of the Linear Heat Density in MWh/m*a of all hypothetical heating grids in Hamburg. Computed with median values for consumption from the Monte Carlo Simulation and the lengths of the hypothetical grids.

The spatial pattern of the LHD follows the urban density, which is not surprising. However, what is more interesting are the locations and the demand in the lower intervals, especially the 0.5-1.5 MWh/m*a.

The LHD has some fixed values which are used as “thresholds” for economic feasibility. One such threshold value is 1.5 MWh/m*a. An example of its use can be found in the German federal state of Bavaria, where for the purpose of supporting heating grids and biofuels, the state government provides financial aid for small heating grids. A minimum of 1.5 MWh/m*a LHD is a requirement (Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie, 2015). Additionally, Nast et al (2009, p. 185) also use the 1.5 MWh/m*a value and state that grids with lower LHD tend to have considerably higher grid losses.

Another value - 0.5 MWh/m*a - is the minimum LHD eligible for feed in-tariffs and preferential financing according to the German Combined-heat-and-power Act (*KWK-Gesetzes*) since 2008 (Wolff & Jagnow, 2011).

Looking at the estimated LHDs and the total demand located in the hypothetical grids (Figure 27), it turns out that a considerable amount – 3379 GWh/a (approx. 33% of Hamburg’s estimated heat demand) is actually in the the interval between 0.5 MWh/m*a – 1.5 MWh/m*a. This means that around a third of the total residential heat demand is in areas, where heating grids could be considered viable and eligible for financial aid but are below the usual threshold for economic feasibility.

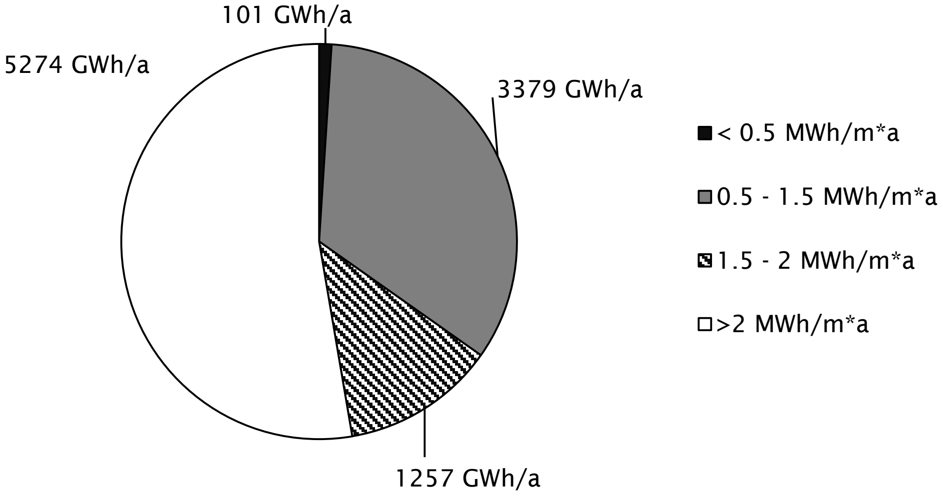

Figure 27 Shares of estimated heat consumption of the Hamburg’s residential building stock in different classes of Linear Heat Density (calculated for the hypothetical heating grids)

However, the presented values were calculated with single point estimates for heat consumption – the median - obtained from the distribution of the Monte Carlo Simulation, which as presented in previous chapters, has around 5%-20% relative error in most cases. Taking this into account (Figure 28) shows that the percent change in the lower intervals (below 0.5 and 0.5 – 1.5) is rather minimal +/- 5 percent points. This means that even if there is a systematic bias in heat demand estimations and all groups of buildings are actually below or above the estimations (but within the limits of the estimated relative errors), this will not influence the viability of grids on the large scale. This can be attributed to the urban densities - the size of buildings and their spatial constellations seem to play a more important role for heating grid feasibility than the error in heat demand estimations.

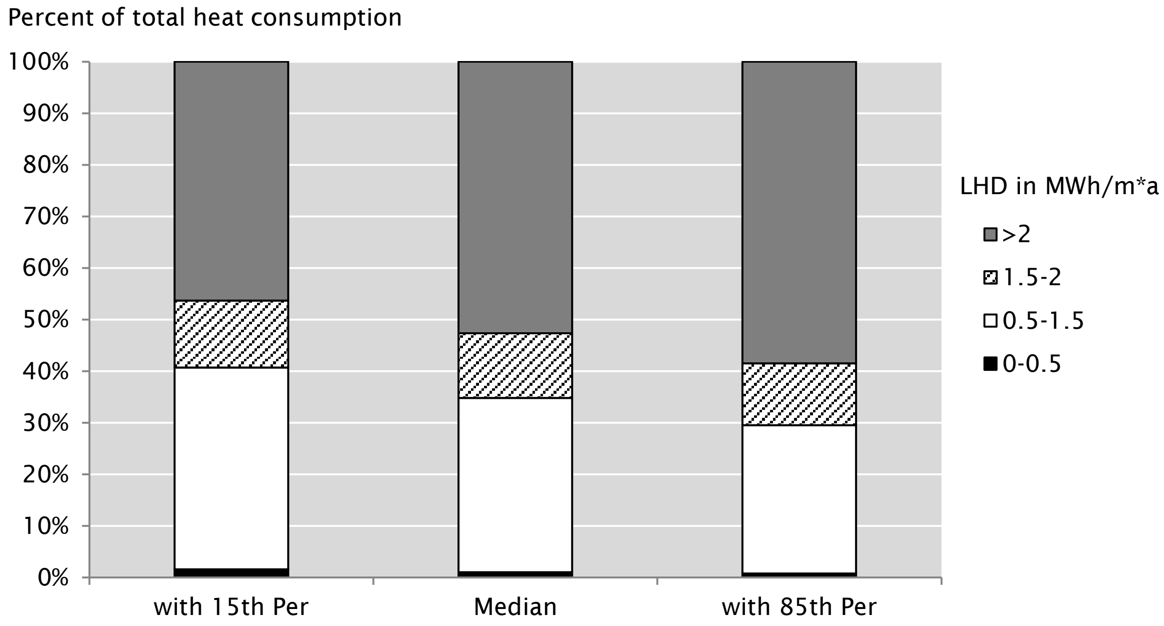

Figure 28 Variability of the LHD when calculated with the median, the 15th Percentile (the error below) and the 85th Percentile (the error above).

Additionally, analysing only the relative errors for the hypothetical grids in the aforementioned interval of 0.5 MWh/m*a to 1.5 MWh/m*a shows that approx. 50% are with average errors of 5-10%, while the other 50% are in the 10-20% range. Errors above 20% are observed for only 168 theoretical grids (out of 5411 grids in this LHD interval). Therefore the grids in the more questionable LHD interval of 0.5-1.5 do not exhibit especially larger errors and many are actually below 20% (Figure 20 actually showed a likely reason - the larger errors are in denser areas).

Lastly, the grids for which, due to the relative errors, it becomes uncertain whether the critical values of 1.5 and/or 0.5 are exceeded are analysed (Figure 29). There are 570 theoretical grids with a total consumption of 414 GWh/a[i] for which the point estimation (the median) is below 1.5 but the 85th Percentile (error above) is above. Therefore if one considers the 1.5 threshold as a strict prerequisite for financial aid (as in the example of Bavaria) these grids would potentially be excluded, while their consumption might actually be above the threshold – the uncertainty is due to the errors in the estimation.

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[i] Using the median values

On the other hand, the reverse situation – median is above, but lower error is below is observable for almost the same number of grids (565) with a very similar total consumption – 467 GWh/a. These are hypothetical grids the consumption of which might be below the 1.5 threshold and might be subject to increased grid losses after construction[i], although the point estimation in the process of planning was above (if we assume the median was used for the calculation of the LHD in the process of planning).

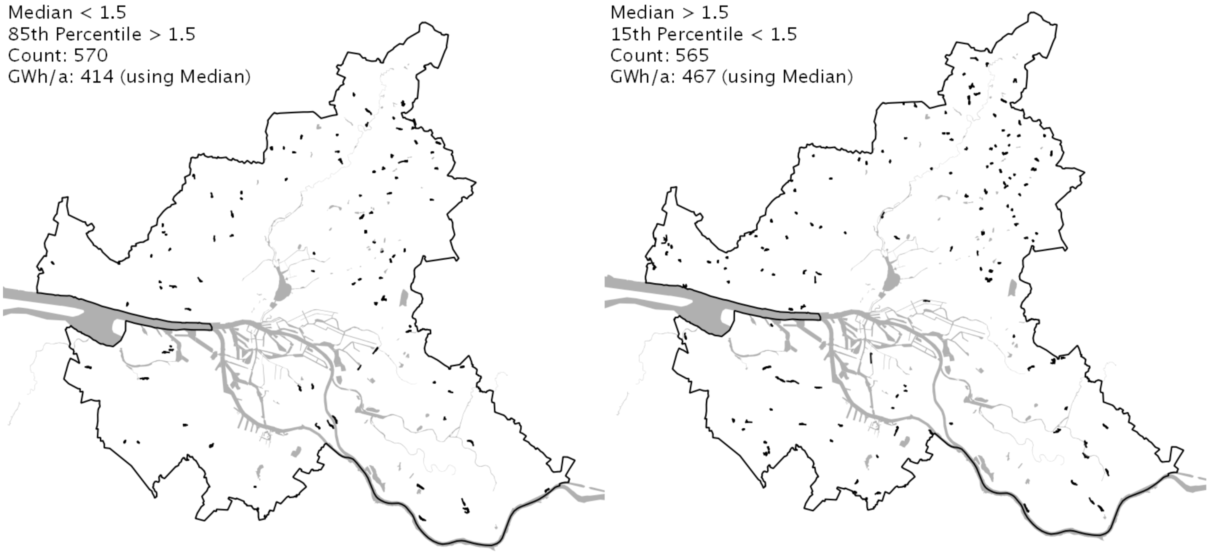

Figure 29 Hypothetical heating grids for which: Left – the Linear Heat Density using median is below the 1.5 MWh/m*a threshold while using the 85th Percentile is above 1.5; Right – LHD using median is above the threshold, while using the 15th Percentile is below.

For the 0.5 MWh/m*a threshold the analysis shows even lower numbers – an underestimation of the true consumption (median below, 85th Percentile above) influences only 98 theoretical grids, while an overestimation (median above, 15th Percentile below) 157 grids.

In both cases of thresholds, a relatively small number of grids corresponding to a low percent of the total heat consumption are affected by the errors in the estimations. Furthermore if the hypothetical grids are considered as parts of larger potential grids, then these errors will most probably be averaged out. The dispersed pattern (Figure 29) of the affected grids is also a signal for this – it is unlikely that a grid containing a number of hypothetical grids will include only the ones for which the errors influence the LHD thresholds and thus it is unlikely that this error could propagate to the combined grid.

Additionally, many heating grids include non-residential buildings, the more constant demand of which has positive effects on the economics and the operation of the grids and can offset these heat demand errors.

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[i] If we take the 1.5 as a strict threshold and see (Nast, et al., 2009)

In summary, the analysis showed that a significant percentage of the estimated heat consumption of Hamburg is in areas for which the LHD is in a more questionable (economic-wise) interval of 0.5-1.5 MWh/m*a. However, the errors in the estimations influence this percentage with only +/- 5 percent points. Furthermore, there are relatively few grids for which the errors could make a difference for reaching the thresholds of 0.5 and 1.5 MWh/m*a.

9 CONCLUSION AND OUTLOOK

The introduction of electronic cadastres and the availability of big data in recent years enabled more extensive and complicated heat demand estimations. In Germany, exhaustive datasets on energetic characteristics of buildings are rare and typology approaches based on sample data are what is typically used. Such approaches are prone to errors since typologies always constitute a simplification of reality and many times variability is hidden within each type.

This thesis presented an attempt at quantifying this error using a stochastic approach that takes into account the effects of aggregation on heat demand estimations. Using the IWU Typology as a connection between a digital cadastre and a sample of building energy certificates, a Monte Carlo simulation iteratively modelled the heat demand of groups of buildings taking into account the possible mix of building types and presenting a distribution of possible heat demand and consumption values at an aggregated level.

The analysis showed that even with relatively wide ranges of energetic characteristics at the building level (computed demands varying with up to +/- 100% within a single type) the mix of building types found in the case study city of Hamburg can offset these errors and more stable figures with lower errors of up to approx. 20% in most cases were estimated at the aggregated level. This holds true if no particularly high clustering of either more energy efficient or energy inefficient buildings is completely neglected while modelling the demand and averaging out effects when estimating demand are present. In other words, if renovation levels of buildings are at least partially modelled, the finer variability of demand/consumption will most likely be covered by a relative error of up to +/- 20%.

In a second step, an exploratory analysis into the effects of the errors on the linear heat density (a crucial parameter for the estimation of the economic feasibility of heating grids) was performed. Using a simplified model for the computation of plausible hypothetical small heating grids, grid lengths were estimated and linear heat densities (LHD) were calculated. This allowed the analysis of the computed LHD while varying the heat demand estimation according to the estimated relative errors derived from the Monte Carlo Simulation. Results showed that at the large scale, around 33% of the total estimated heat consumption for space heating and domestic hot water resides in buildings for which the LHD is below 1.5 MWh/m*a - a figure that is often used as a minimum threshold to make a heating grid worthwhile, or for the granting of financial aid (f. ex. in the German federal state of Bavaria). The estimated effects of the produced relative errors on these 33% are however low – +/- 5 percent points, so no large shifts of the potential for heating grids is observed. On the other hand, if the common threshold of 1.5 MWh/m*a LHD is taken as prerequisite for financial aid, then only about 5% (570 out of 11000) of the modeled grids are affected by the heat demand errors – the point estimation (median) is below, but the possible error could mean that the true values are above. Based on these values and the performed analysis it can be concluded that the accuracy of the heat demand estimations does not have large effects on heating grid planning with respect to the linear heat density. Although for some cases the errors might lead to a threshold value or a prerequisite for financial aid not being achieved, these cases are limited and also relatively dispersed spatially. If the computed hypothetical grids are considered as parts of larger grids rather than entire grids by themselves, it can be argued that even the small observed effects of the estimation errors would most probably be averaged out.

The performed analysis however was limited to the residential building stock. Further work is needed to include non-residential buildings which in many cases are very valuable for heating grids, due to their high and more constant demand. Their inclusion would allow a better mapping of the potential for heating grids and an analysis of whether the possible errors of the estimations of non-residential buildings are more important for grid planning than those of the residential building stock.

Of course, the topic of heating grid planning is far broader than the linear heat density. Errors in the assumptions behind the load curves and user patterns are very important, especially for smaller grids, where heat supply-security could become problematic (f. ex. in summer when the loads are low). On the other hand, the estimation errors could have an effect on a more concrete economic analysis of grids - returns on investment are a function also of the delivered heat.

The results of the thesis, while they should not be overstretched, seem to indicate that errors of demand estimations do not seem to influence the linear heat density to a large extent, but efforts of analysis should also be spend on those other topics.

BIBLIOGRAPHY

Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland, 2015. *AFIS-ALKIS-ATKIS Anwendungsschema.* [Online]
Available at: http://www.adv-online.de/aaa-Modell/binarywriterservlet?imgUid=dc860f61-34ab-4a41-52cf-b581072e13d6&uBasVariant=11111111-1111-1111-1111-111111111111#_C11588-_A11588_50133
[Accessed 22 3 2017].

Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie, 2015. *Richtlinien zur Förderung der CO2-Vermeidung durch Biomasseheizwerke (BioKlima).* Munich: Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie.

Blesl, M., Kempe, S., Ohl, M. & Fahl, U., 2007. *Wärmeatlas Baden-Württemberg: Erstellung eines Leitfadens und Umsetzung für Modellregionen.* Stuttgart: Institut für Energiewirtschaft und Rationelle Energieanwendung, University of Stuttgart.

Diefenbach, N., Cischinsky, H., Rodenfels, M. & Clausnitzer, K., 2010. *Datenbasis Gebäudebestand Datenerhebung zur energetischen Qualität und zu den Modernisierungstrends im deutschen Wohngebäudebestand,* Darmstadt: Institut Wohnen und Umwelt, Bremer Energie Institut.

Dochev, I., Seller, H., Muñoz Hidalgo, M. & Peters, I., 2016. *Spatial interpolation of building construction years (Working paper),* Hamburg: Technical Urban Infrastructure Systems Group, HafenCity University.

Dochev, I., Seller, H., Muñoz Hidalgo, M. & Peters, I., 2017. *Assigning IWU Building Types to Buildings in the Hamburg ALKIS (Working paper),* Hamburg: Technical Urban Infrastructure Systems Group, HafenCity University.

Dochev, I., Seller, H. & Peters, I., 2017. *Aggregation approaches for GEWISS - "Street front" aggregation (Working paper),* Hamburg: Technical Urban Infrastructure Systems Group, HafenCity University.

Dötsch, C., Taschenberger, J. & Schönberg, I., 1998. *Leitfaden Nahwärme.* Oberhausen: Fraunhofer UMSICHT, Fraunhofer IRB Verlag.

Hausladen, G. & Hamacher, T., 2011. *Leitfaden Energienutzungsplan.* Munich: Bayerisches Staatsministerium für Umwelt und Gesundheit (StMUG), Bayerisches Staatsministerium für Wirtschaft, Infrastruktur, Verkehr und Technologie (StMWIVT), Oberste Baubehörde im Bayerischen Staatsministerium des Innern (OBB).

Hegger, M. et al., 2014. *Energetische Stadtraumtypen.* Stuttgart: Fraunhofer IRB Verlag.

Hermelink, A., Manteuffel, B., Lindner, S. & John, A., 2011. *Flächendeckende Erhebung des energetischen Zustandes des hamburger Gebäudebestandes: Kurzdarstellung der Arbeitsschritte,* Hamburg: Ecofys Gmbh.

Hoaglin, D. C., Iglewicz, B. & Tukey, J. W., 1986. Performance of some resistant rules for outlier labeling. *Journal of American Statistical Association,* Issue 81, pp. 991-999.

Huenges, E., Kaltschmitt, M. & Wolff, H., 1999. *Energie aus Erdwärme.* Stuttgart: Deutscher Verlag für Grundstoffindustrie.

Kaltschmitt, M., Streicher, W. & Wiese, A., 2012. *Erneuerbare Energien Systemtechnik, Wirtschaftlichkeit, Umweltaspekte.* 5th ed. Berlin, Heidelberg: Springer Berlin Heidelberg.

Loga, T., Stein, B., Diefenbach, N. & Born, R., 2015. *Deutsche Gebäudetypologie Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden,* Darmstadt: Institut Wohnen und Umwelt.

Mueller, A., 2012. *Simplistic Minimum Spanning Tree in Numpy.* [Online]
Available at: http://peekaboo-vision.blogspot.de/2012/02/simplistic-minimum-spanning-tree-in.html
[Accessed 2 3 2017].

Muñoz Hidalgo, M. E. & Peters, I., 2015. *Allocating heat consumption of residential buildings in space with help of a filter array to determinate the building type in a digital cadaster.* Hamburg: Unpublished manuscript.

Nast, M. et al., 2009. *Evaluierung von Einzelmaßnahmen zur Nutzung erneuerbarer Energien (Marktanreizprogramm) im Zeitraum Januar 2007 bis Dezember 2008.* Stuttgart: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit.

Prim, R., 1957. Shortest Connection Networks and some Generalizations. *The Bell Systems Technical Journal,* 36(6), pp. 1389-1401.

Schild, K. & Brück, H., 2010. *Energie-Effizienzbewertung von Gebäuden Anforderungen und Nachweisverfahren gemäß EnEV 2009.* 1st ed. Berlin: Vieweg+Teubner Verlag | Springer Fachmedien Wiesbaden GmbH 2010.

Schuchardt, G., 2015. *Energetische Analyse von Nahwärmenetzen unter Berücksichtigung des mikroskopischen thermohydraulischen Netzzuständes.* Kassel: Dissertation, Fachbereich Maschinenbau, Kassel University.

Selk, D.; Gniechwitz, T.; Steffens, A., 2009. *Unsere alten Häuser sind besser als ihr Ruf Verbrauchsdatenauswertung – Wohngebäude; Untersuchung zur Ermittlung und Bewertung von Energieverbräuchen im Gebäudebestand.* Kiel: Arbeitsgemeinschaft für zeitgemäßes Bauen e.V.

Stein, G. & Wagner, H.-F., 1999. *Das IKARUS Projekt. Klimaschutz in Deutschland. Strategien für 2000 bis 2020,* s.l.: Springer-Verlag Berlin Heidelberg.

Verein Deutscher Ingenieure, 2013. *VDI 3807-1 Verbrauchskennwerte für Gebäude,* Düsseldorf: Verein Deutscher Ingenieure.

Walberg, D.; Gniewitz, T.; Schulze, T., 2012. *Gebäudetypologie Schleswig-Holstein / Leitfaden für wirtschaftliche und energieeffiziente Sanierungen verschiedener Baualtersklassen,* Kiel: Arbeitsgemeinschaft für zeitgemäßes Bauen e.V.

Wolff, D. & Jagnow, K., 2011. *Überlegungen zu Einsatzgrenzen und zur Gestaltung einer zukünftigen Fern- und Nahwärmeversorgung,* Wolfenbüttel/Braunschweig: online only at www.delta-q.de.

Yule, G. U., 1912. *An introduction to the theory of statistics.* s.l.:C. Griffin, limited.

APPENDIX

IWU Type	Total Buildings	Energy Certificates with Heat Demand		Energy Certificates with Heat Consumption	
	Count	Count	%	Count	%
EFH_A	462	9	1.95%	0	0.00%
EFH_B	1721	421	24.46%	98	5.69%
EFH_C	14464	904	6.25%	278	1.92%
EFH_D	9681	566	5.85%	143	1.48%
EFH_E	14623	782	5.35%	187	1.28%
EFH_F	9524	413	4.34%	58	0.61%
EFH_G	4229	104	2.46%	10	0.24%
EFH_H	12292	57	0.46%	0	0.00%
EFH_I	5432	11	0.20%	0	0.00%
EFH_J	3768	1	0.03%	0	0.00%
EFH_K	3278	0	0.00%	0	0.00%
EFH_L	126	0	0.00%	0	0.00%
RH_B	539	67	12.43%	2	0.37%
RH_C	8150	147	1.80%	6	0.07%
RH_D	7409	162	2.19%	22	0.30%
RH_E	17245	300	1.74%	57	0.33%
RH_F	4989	85	1.70%	6	0.12%
RH_G	3180	31	0.97%	1	0.03%
RH_H	9031	26	0.29%	0	0.00%
RH_I	5601	4	0.07%	0	0.00%
RH_J	5071	0	0.00%	0	0.00%
RH_K	2763	0	0.00%	0	0.00%
RH_L	141	0	0.00%	0	0.00%
MFH_A	203	6	2.96%	0	0.00%
MFH_B	3126	433	13.85%	101	3.23%
MFH_C	2636	239	9.07%	50	1.90%
MFH_D	5487	583	10.63%	129	2.35%
MFH_E	9913	810	8.17%	231	2.33%
MFH_F	6947	379	5.46%	106	1.53%
MFH_G	2694	87	3.23%	10	0.37%
MFH_H	4080	54	1.32%	2	0.05%
MFH_I	4000	23	0.58%	0	0.00%
MFH_J	2509	3	0.12%	0	0.00%
MFH_K	3136	0	0.00%	0	0.00%
MFH_L	111	0	0.00%	0	0.00%
GMH_B	2174	329	15.13%	67	3.08%
GMH_C	825	51	6.18%	15	1.82%
GMH_D	1122	127	11.32%	23	2.05%
GMH_E	1373	68	4.95%	14	1.02%
GMH_F	1847	76	4.11%	13	0.70%
HH_E	416	101	24.28%	37	8.89%
HH_F	292	79	27.05%	22	7.53%