THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

SPATIAL ANALYSIS OF URBAN HOUSING STOCKS

MAGNUS ÖSTERBRING

Department of Civil and Environmental Engineering
Chalmers University of Technology
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CHALMERS UNIVERSITY OF TECHNOLOGY

SE-412 96 GOTHENBURG

SWEDEN

TELEPHONE +46 (0)31-772 1000

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Abstract

Urban building-stocks must be transformed in order to reduce energy and resource use to achieve climate change mitigation targets. As the rate of renewal in the building-stock is low, energy efficiency measures need to be applied when renovation is being done. In order to evaluate renovation potential of the existing building stock on an urban level, a local approach is needed to understand challenges and possibilities associated with the transformation of the building-stock. By incorporating building-specific information and also considering the building in its setting, a more holistic view can be achieved. For this purpose, available databases containing building-specific information has been gathered and processed for the multi-family building stock of the city of Gothenburg. The available data is used to describe the energy performance of the stock, future renovation needs and is used to create a description of the stock used as input for calculating the energy demand. This thesis with appended papers shows that available data sources can be used to describe the characteristics of the stock on a building level while considering the location and context. Building attributes such as year of construction, value year, property owner, geometric data and energy performance certificates is spatially linked as well as used in modelling the energy performance of buildings to provide detailed and valuable information to policy makers, urban planners and property owners.

Key words: Building-stock modelling, energy performance certificate, GIS, Multi-family buildings, Energy, renovation, refurbishment

Foreword

This thesis summarizes the work during two and a half years of studies at the division of Building Technology in the research group of Sustainable Building, Chalmers University of Technology. The work has been financed by the Swedish Energy Agency, the Climate-KIC, Chalmers and NCC Construction Sverige AB. This study has been made possible with the help of data supplied by the City planning office of the city of Gothenburg as well as Riksbyggen.

I would like to thank my colleagues at Building Technology as well as my colleagues at NCC for a good working environment and especially my supervisors, Holger Wallbaum and Christina Claeson-Jonsson who have supported me throughout this work. Special thanks go to Érika Mata, Liane Thuvander, Mikael Mangold and Filip Johnsson for all their invaluable help and expertise.

I would also like to thank my friends and family for their support.

List of Publications

This thesis is based on the following three peer-reviewed journal papers and one peer-reviewed conference paper:

I. **Österbring, M**., Mata, É., Thuvander, L., Mangold, M., Johnsson, F., & Wallbaum, H. (2016). A differentiated description of building-stocks for a georeferenced urban bottom-up building-stock model. Energy and Buildings, 120, 78-84.

II. Mangold, M., **Österbring, M**., & Wallbaum, H. (2015). Handling data uncertainties when using Swedish energy performance certificate data to describe energy usage in the building stock. Energy and Buildings, 102, 328-336.

III. Thuvander, L., **Österbring, M**., Mangold, M., Mata, E., Wallbaum, H., & Johnsson, F. (2015). Spatial exploration of the refurbishment dynamics of urban housing stocks. In Computers in Urban Planning and Urban Management CUPUM Cambridge.

IV. Mangold, M., **Österbring, M**., Wallbaum, H., Thuvander, L., & Femenias, P. (2016) Socio-economic impact of renovation and energy retrofitting of the Gothenburg building stock. Energy and Buildings, 123, 41-49.

Paper I is written by me in in collaboration with Érika Mata, Liane Thuvander, Mikael Mangold, Filip Johnsson and Holger Wallbaum. The paper covers my work with developing a methodology for describing urban housing stocks. I have developed the methodology, performed the analysis and written the main part of the paper.

Paper II is written by Mikael Mangold in in collaboration with me and Holger Wallbaum. The paper covers the Swedish Energy performance certificates and how to handle statistical errors regarding the heated floor area. I have done part of the writing and data analysis with Mikael Mangold.

Paper III is written by Liane Thuvander in collaboration with myself, Mikael Mangold, Érika Mata, Holger Wallbaum and Filip Johnsson and covers the use of available building stock information, and in particular the value year, to spatially explore the need for renovation in the urban housing stock. I have developed the concept and done part of the writing.

Paper IV is written by Mikael Mangold in collaboration with myself, Holger Wallbaum, Liane Thuvander and Paula Femenias and covers the socio-economic challenges of renovating the existing building stock based on value year and assumed service life of the buildings. I have developed the concept with Mikael Mangold and done part of the writing.

The following peer-reviewed journal paper and peer-reviewed conference paper are not included in the thesis but are mentioned here for further reading:

V. Mangold, M., **Österbring, M**., & Wallbaum, H. (2015). A review of Swedish residential building stock research. International Journal of Environmental Sustainability.

VI. **Österbring, M**., Mata, É., Johnsson, F., & Wallbaum, H. (2014). A methodology for spatial modelling of energy and resource use of buildings in urbanized areas. In World Sustainable Building Conference WSB14 Barcelona.

Contents

Acronyms and nomenclature

Acronyms

BSM – Building-stock modelling

DHW – Domestic hot water

EEM – Energy efficiency measure

EPC - Energy performance certificates

GIS – Geographic information systems

HFA – Heated floor area

MFB – Multi-family building

MHP – Million homes programme

SH – Space heating

1. Introduction

Buildings account for about 40 % of the final energy use and 36 % of CO_2-emissions in Europe (BPIE, 2011). At the same time, they provide a possibility for cost-efficient energy efficiency measures (EEM) (IPCC, 2014). The European Energy Performance of Buildings Directive defines efficiency standards for both new and existing buildings targeting these efficiency opportunities (EU, 2010, EC, 2002). The Swedish government has similarly set policy which strives for substantial reductions in energy use by 2020 and 2050 (SOU 2005, Swedish Government, 2009). In order to encourage energy efficiency in buildings, energy performance certificates (EPC) were introduced in Sweden in 2006 as a result of the EU energy efficiency directive (EC, 2002). On a municipality and city level, more ambitious targets on energy savings have voluntarily been adopted. The city of Gothenburg has implemented such targets and aims to reduce energy consumption in residential buildings by 30 % by 2020 compared to 1995 levels (City of Gothenburg, 2009). For developed countries it is estimated that most of the buildings that will be in use in 2050 have already been built (U.N.E.P sbci, 2009) and the renewal rate of the Swedish residential stock is only 0.6% (Boverket, 2014), which implies a need for EEM in the existing stock if the above-mentioned targets are to be met.

In order to evaluate renovation potential of the existing building stock on an urban level, a space and context specific approach is needed to understand challenges and possibilities associated with the transformation of the building-stock. By using building-specific information and considering the building in its setting, a better overview can be achieved. In Sweden, there are several data sources available with attribute data on buildings such as EPC, the building and property register as well as cadastral maps. One important thing to note about the Swedish EPC is that they contain information on measured energy performance and not calculated energy performance. As these datasets contain information on spatial location, it is possible to combine the different data sources for individual buildings using geographic information systems (GIS). Since the property register also contain information about ownership, it is possible to not only aggregate building information to spatial units such as districts or neighbourhoods but also for individual property owners. Furthermore, information regarding the economic extent of past refurbishment activities is known which better enables the analysis of future renovation need.

The data gathered on a building level can then be further used to create a building stock description used to model the energy performance of the building-stock, and since the Swedish EPC contain measured energy use it can also be validated at any spatial scale. Building-stock modelling (BSM) can be used amongst others to assess the energy demand of the existing stock which enables the possibility to prioritize what measures to apply and where they would be most effective. Much work have previously gone in to develop the energy simulation in BSM but little work has been done taking advantage of the building-specific information that is available. Instead, representative buildings based on average data is often used which limits the accuracy with increased spatial resolution of the results and hence limits the target group of such models to a planning or policy level.

1.1 Purpose

The purpose of this study is to describe the renovation need and challenges for the urban housing stock of the city of Gothenburg using available data sources for Sweden, to evaluate the building-specific information that is available and to use the available information to create a building-stock description that enables energy performance modelling on a building level.

The multi-family building (MFB) stock in the city of Gothenburg is used as a case study for describing the composition of the stock and the MFB portfolio of a property manager is used to evaluate the results of the description used in the energy model. In this work, MFB are defined as buildings with 3 or more apartments.

1.2 Methodology

The methodology used throughout this thesis is based on three steps: desk research, data acquisition and processing as well as evaluation for case studies. The steps are briefly described in this chapter. They are described in greater detail in their associated chapters and the attached papers. Throughout this thesis, the MFB stock of Gothenburg and particularly the part of the stock managed by Riksbyggen is used as the case study. The reason being that this work is conducted in Gothenburg and is supported by the city of Gothenburg and Riksbyggen (by supplying building-stock information)

Desk research

An expanded literature review on the state-of-the-art of spatial BSM based on what has already been done in paper I is conducted with a focus on the visualization of results and building-stock information. The intended stakeholders, the parameters visualized and the spatial scale and method used to visualize are reviewed. This is described in chapter 2.

Data acquisition and processing

In chapter 3, the available building-stock information available in Sweden and how it is processed to describe the characteristics of the MFB stock of Gothenburg is done as an overview to the data used in Paper I-IV. In particular, the focus is to spatially describe the energy performance of the stock, to highlight ownership distribution and previous renovation activities or lack thereof.

Case study evaluation

Two case studies are used. In the first case study, an expanded description of the methodology presented in Paper I including errors in the EPC is shown for the case of the portfolio of a property manager. In the second case study, available building-stock information for the city of Gothenburg is visualized aiming at stakeholders involved in urban and energy planning as well as property owners and managers.

2. Building-stock modelling

To address the challenges of the stakeholders involved in the transformation of the building-stock, building-stock models have been used to calculate the energy demand of the existing building-stock (Ascione et al., 2013, Fabbri et al., 2012) as well as to evaluate its potential developments (Mata et al.,2013, Sartori et al., 2009). The bottom-up methods for describing and simulating the energy performance of building-stocks (Swan and Ugursal, 2009, Kavgic et al., 2010) have evolved from being used on a country level to be applied at urban scale by incorporating GIS. Using GIS has several advantages as it facilitates merging of several databases and further enhances analysis and communication by spatially differentiating and visualizing results. The energy performance modelling has similarly become more sophisticated to the point where the fields of BSM and building energy simulation are merging (Reinhart and Davila, 2016). While the spatial resolution has increased and the energy models become more advanced, the input used for these models have seen little development and are still largely based on using representative buildings which are used to scale results to the desired level of output. Such descriptions loose accuracy with increased spatial resolution and commonly results are only presented at aggregate levels for districts or entire cities and not on a building level (Reinhart and Davila, 2016). The scaling of representative buildings to account for the energy performance of the entire stock is based on the assumption that buildings with a similar year of construction have a similar energy performance. The older the stock that the representative building is aiming to describe, the more problematic this assumption becomes as renovations have been applied to a varying degree and the energy performance may have changed significantly from its original state (Eriksson, 1993, Aksoezen et al., 2015). Some models have gone further and has started incorporating building specific data, most commonly taking advantage of 3D city models based on LIDAR data (Steadman et al., 2013) or by analysing differences in digital terrain models and digital elevation models (Mastrucci et al., 2015) as well as using building-specific data from EPC to better describe the technical characteristics of individual buildings (Österbring et al., 2016). This development allows for the possibility of visualizing and communicating results on a building level as well as allowing results to be aggregated arbitrarily to suit communication with stakeholders that previously have not been reached.

As the representative description of buildings limits the accuracy to higher levels of aggregation, stakeholders operating at a planning or policy level are commonly targeted by BSM. However, a few exceptions can be found where other potential stakeholders have been identified. It has been suggested that EPC data can be used by construction companies to assess the size of the renovation market (Gangolells et al., 2016) and (Fonseca and Schleuter, 2015) points to the possibility to use results for educational purposes. However, the author has not found any mention of studies using BSM to target property owners and managers who are essential to the urban transformation process. As such, the intended stakeholders for BSM varies but can generally be divided into three broad categories; urban planners, energy planners and governmental bodies needing policy support.

To support these stakeholders, base-line models have been used to assess the current energy performance of cities and districts to highlight areas where interventions should be prioritized on both energy demand side (Caputo et al., 2013) and supply side (Nielsen and Möller, 2013). Similarly, to assess the technical potential of specific technologies, specific measures have been investigated to evaluate the potential to reach environmental targets using EEM (Nouvel et al., 2015), the potential development of renewables (Theodoridou et al., 2012) and potential expansion and optimal layout of district heating networks (Fonseca et al., 2016). While these models tend to focus on the technical potential, other models have developed more dynamic scenarios as to describe the change of the stock over time. The basis of these scenarios range from assumptions on a fixed rate of technology implementation to agent-based models or other decision models based on economic (Petrovic and Karlsson, 2014) or socio-economic feasibility (Delmastro et al., 2015).

While many papers mention the ability of these models to provide decision support, it is often not explicitly stated which stakeholder the results are aimed at but rather broadly refers to support policy, urban planning and energy planning. Furthermore, it is not stated how the spatiotemporal visualization of results are adapted to meet the requirement of the intended stakeholder. Table 1 shows a review of contemporary studies on a city level with a focus on the intended stakeholder, the spatial visualization of results and parameters visualized.

Table 1 – Contemporary studies on a city level with intended stakeholder, parameters and visualization included.

Name	City	Stakeholder	Parameters investigated	Level of visualization	Parameters visualized
Fonseca and Schlueter (2015)	Zug	Educational, urban and energy planning	Power	City (districts in 2D), buildings for 4 districts (3D).	Peak space heating demand, energy reduction potential, GHG reductions, Occupancy type
Fonseca et al (2016)	Zug	Energy and urban planning	Energy and power	Buildings in a district (3D)	Solar potential, infrastructure layout and optimization (pipes),
Nouvel et al (2015)	Rotterdam	Policy support	Energy	City (districts in 2D), buildings in a district (3D)	Gas consumption intensity (2D), Heating savings potential (3D)
Pittam et al (2014)	Corke	Policy support	Energy and CO2	Buildings in a district (2D)	Distribution of archetypes and house types
Mastrucci et al (2015)	Esch-sur-Alzette	Urban planning	LCA	City (buildings in 2D)	GWP
Singh et al (2013)	Liege	Policy support	Energy	City (districts in 2D)	Distribution of buildings with shared facade
Mikkola and Lund (2014)	Helsinki	Energy planning	Power	City (districts in 2D)	Floor area, peak heating load, peak heating load
Delmastro et al (2015)	Turin	Energy planning	Energy and cost	District (buildings in 2D)	DH network layout
Caputo et al (2013)	Milan	Energy planning and local administration	Energy	City (districts in 2D)	Energy consumption for heating, lighting and equipment, DHW, cooking
Ascione et al. (2013)	Benevento	Energy planning	Energy	District (buildings in 2D)	Energy label
Fabbri et al (2012)	Ferrara	Urban planning	Energy	District (buildings in 2D for historical city center)	Energy label
Heiple and Sailor (2012)	Houston	Modellers	Energy	District (density map in 3D)	Power demand
Steadman et al. (2014)	London	Policy	Energy	City (districts in 2D)	Exposed surface area, building volume, wall to volume ratio
Tanikawa & Hashimoto (2009)	Mancheste r	Urban planning and waste management	Material stock	District (buildings in 3D)	Building typology
Taylor et al. (2014)	Leicester	Policy	Energy	District (buildings in 3D)	Energy
Perez et al. (2013)	La Chaux-de-Fonds, Neuchatel and Martigny	Energy management	Energy	City (buildings in 2D)	Construction period
Theodoridou et al. (2012)	Thessaloni ki	Energy policy and planning	Energy	City (buildings in 3D and blocks in 2D)	Solar potential, DHW from solar (both in 3D), C02 emissions per block

To reach the intended target audience, results are commonly visualized on different scales depending on the purpose, but typically consist of a country (Petrovic and Karlsson, 2014), regional (Nielsen and Möller, 2013) or city level (Mikkola and Lund, 2014), with city based models in addition often including a more detailed view of a particular district or neighbourhood (Dall'O' et al., 2012). For country and regional levels of visualization, results are commonly aggregated to and visualized in 2D for statistical zones (Steadman et al., 2014) or zones defined by the authors to be homogenous as to the urban typology and as such fit the representative buildings used to describe the stock (Pittam et al., 2014). On a city level, either zones or individual buildings are used to visualize results in 2D, depending somewhat on the scale of the city in question. Representations of results on a district or neighbourhood level commonly use 2.5D or 3D models of buildings where a higher level of detail is used when more detailed information on roof structure is needed, typically for investigation of solar energy potential (Theodoridou et al., 2012, Jakubiec and Reinhart, 2013).

There is a wide range of parameters visualized to support the different stakeholders targeted. While it is most common to present results as energy or power demand, some studies use geometric information or typologies to try and draw more general conclusions by first linking energy performance to such parameters. Typically, the parametric value is visualized by colour coding with a few exceptions where the areas are extruded and the height indicates the parametric value.

3. Building-stock information

To present results relevant to stakeholders such as building owners and managers on an individual building level puts high demands on data availability. For this thesis, data were retrieved from the Swedish Mapping, Cadastral and Land Registration Authority, the National Board of Building, Housing and Planning and the City planning office of Gothenburg.

3.1 Data sources

Table 1 shows the building specific databases available for the city of Gothenburg, at what level of aggregation they are available and the most relevant information they contain.

Table 2 - Building specific databases relevant for analysing the building stock, their level of aggregation and the identifier used to match them.

Database/Data owner	Aggregation level	N	Relevant information	Identifier
The property register (50A)	Building	153 000	Building type, construction year, value year and renovation year	Building ID, Property ID, mid-point coordinates
(42P)/Swedish Mapping, Cadastral and Land Registration Authority	Property	114 000	Property owner, % owned	Property ID
Gripen/National Board of Building, Housing and Planning	Building	6320	Energy use, HVAC systems, energy performance, heated floor area, number of stories, number of apartments	Building ID
Cadastral maps/City planning office	Building	178 000	2D, 3D (roofs)	Coordinates

The Swedish Mapping, Cadastral and Land Registration Authority supplied parts of the property register for the city of Gothenburg. Specifically, they provided the building register (50A) and the register of property owners (42P). The building register contains information on building type, year of construction, year of renovation and value year. The value year is of particular interest as it has several functions. It is a calculated on the year of construction and year of renovation and weighted depending on the economic extent of previous renovation measures. As such it can be used to assess the remaining life-time of a building and to assess the cost of previous renovation activities as has been done in Paper IV (Mangold et al., 2016). Table 2 describes how the Swedish Tax Office requires a renovation to be registered as a change in value year depending on the cost of the renovation in comparison with new building cost (Swedish Tax Agency, 2012).

Table 3 - Calculation of value year based on renovation cost according to the Swedish Tax Office

Renovation cost	Calculation of value year
Less than 20 % of new building cost	No change in value year
20-70 % of new building cost	The value year is set based on Equation 1
More than 70 % of new building cost	The value year is set to the year of renovation

$$\frac{(Value\ year - Construction\ year)}{Renovation\ year - construction\ year} = \frac{Renovation\ cost}{New\ construction\ cost} \qquad (1)$$

The National Board of Housing, Building and Planning supplied all EPC for the city of Gothenburg. The Swedish EPC are unique since they not only contain valuable information on characteristics of the buildings such as heating, ventilation and cooling (HVAC) system but also measured energy use for space heating (SH), domestic hot-water (DHW), and non-domestic electricity use. However, the Swedish EPC also suffers from some drawbacks. While the energy performance is given separately for SH, DHW and non-domestic electricity use, it is rarely measured as such but rather subdivided based on the energy expert issuing the certificate. Similarly, the heated floor area (HFA) is rarely measured but rather derived based on the living area. More information on the Swedish EPC and suggestions on how to overcome issues of deriving the HFA on a stock level have been done in previous work, see Paper II (Mangold et al., 2015).

From the City planning office, GIS shape files in 2D were provided for the footprints of the buildings as well as outlines of two different levels of statistical areas, Base areas and primary areas. Information on the 3D geometry of all roofs has also been provided but has not been utilized for other purposes than visualization. The datasets are combined based on the identifiers as follows. The EPC are connected to the property register using the building ID (50A) and the register of property owners is connected to the building register using the property ID. Coordinates is then used to connect these datasets to each individual footprint in the 2D-map of Gothenburg. As not all EPC contain the correct identifier, 5901 of the 6320 EPC are spatially linked to footprints. The HFA from the full set of EPC decreases from 17 500 000 m² to 15 900 000 m² for the information that can be spatially linked to individual buildings.

3.2 City of Gothenburg

The city of Gothenburg was founded in 1621 and is the second largest city in Sweden with about 550 000 inhabitants. The urban housing stock of MFB grew outwards until mid-1970s before densification started as described in paper III (Thuvander et al., 2015). Figure 1 shows the average energy performance for primary areas.

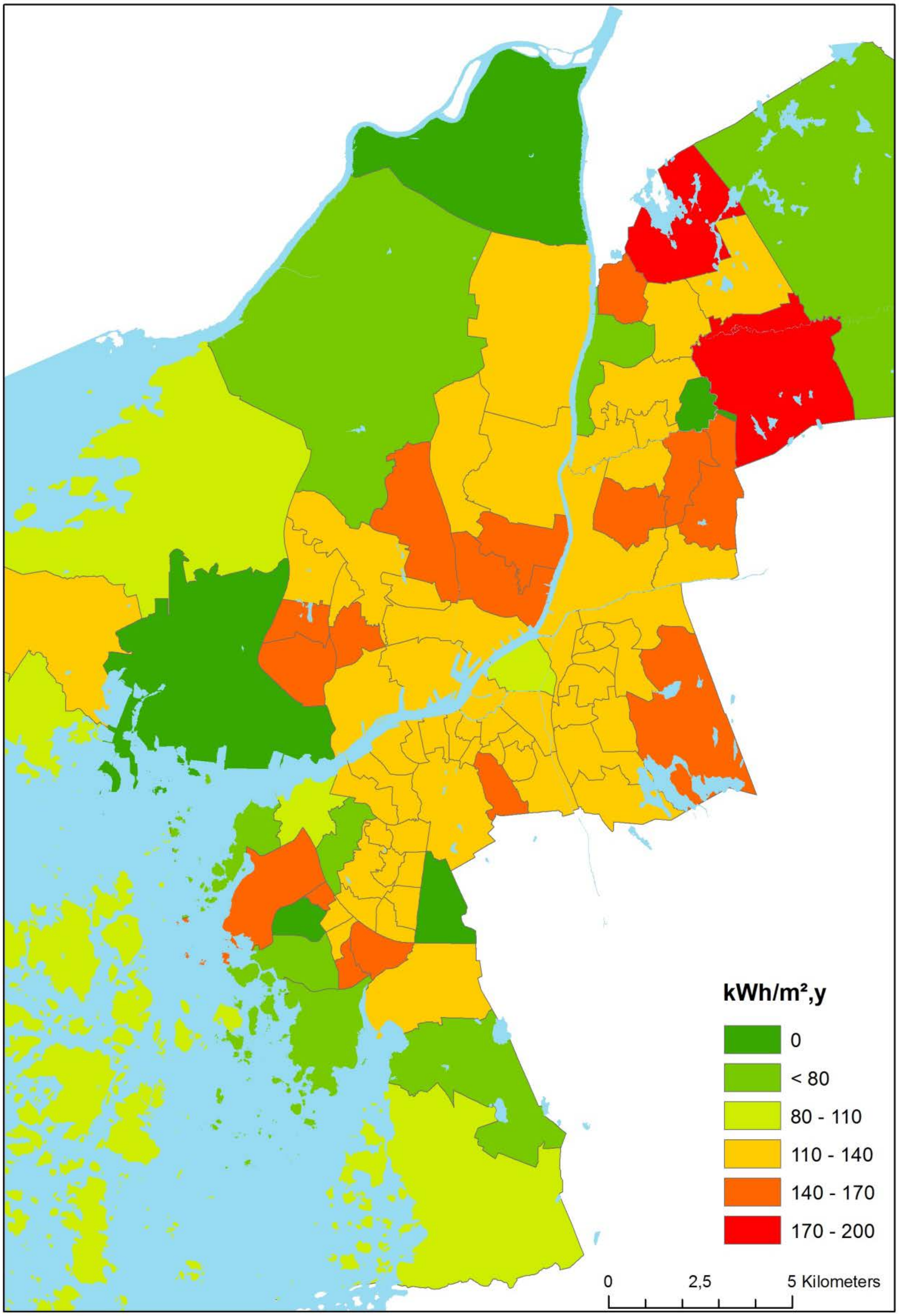

Figure 1 - average energy performance by primary area

Figure 2 shows the measured energy use for SH, DHW and non-domestic electricity use for the MFB stock in Gothenburg. It is divided by into age-groups with their associated share of the total HFA. As can be seen, the energy performance is quite even for the stock up until 1980. The sharp decline in energy use in the building-stock occurring during the 1980s can be explained by more stringent demands on u-values being introduced in 1975 as shown in chapter 4.

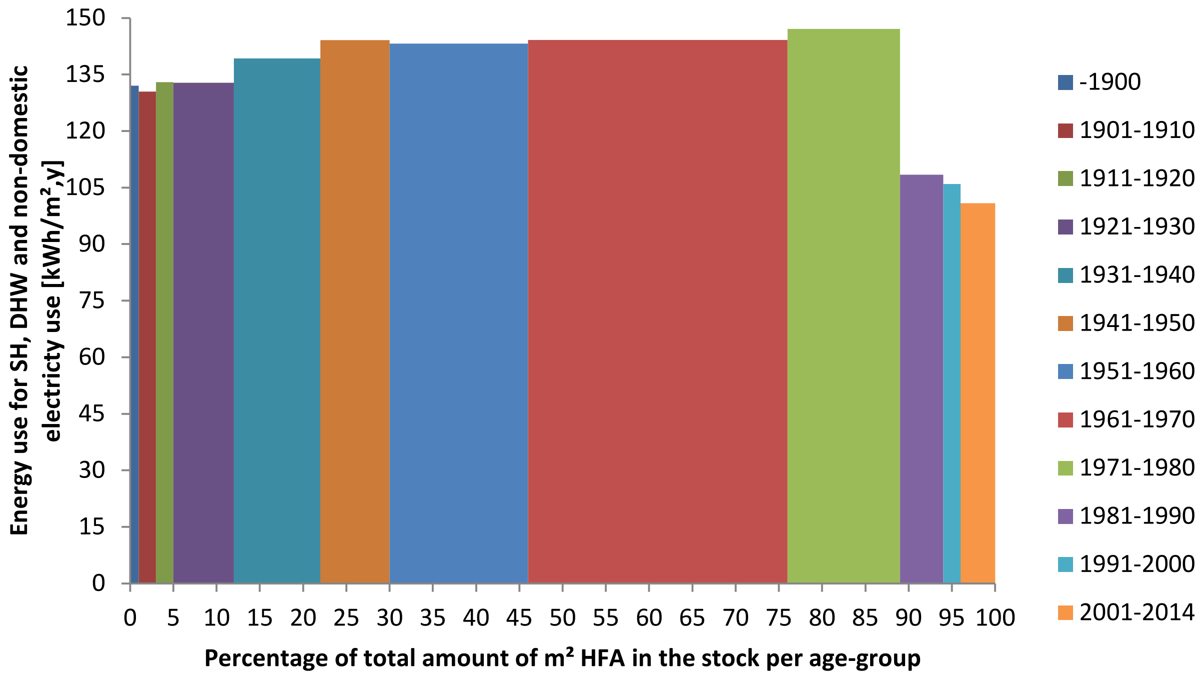

Figure 2 - Measured energy performance for different age-groups of the Gothenburg MFB stock and their respective share of the total stock.

Figure 3 shows the distribution of HFA in the MFB stock divided by property owner, property manager or owner type. The municipality's housing company (Framtiden AB) owns about a third (36 %) of the stock with another third (33 %) being private housing cooperatives. The two largest private housing cooperative managers, HSB and Riksbyggen, are presented separately. The last third of the stock is owned by private owners, individuals, foundations and others where the last category includes estates and non-profit organisations.

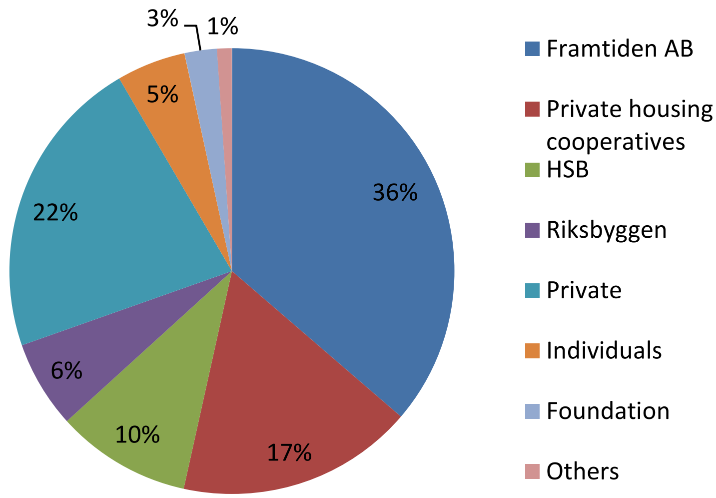

Figure 3 - Percentage of total m² of HFA in the stock divided by property owner, manager and owner type

Figure 4 shows the average year of constuction and value year for the different types of owners. The difference between the average year of construction and value year indicates to what extent the stock of the different owners have been renovated as well as the impending need for renovation if assuming a service-life of 50 years for a building before renovations are needed. A service-life of 50 years is commonly used in swedish renovation studies as described in paper IV (Mangold et al., 2016).

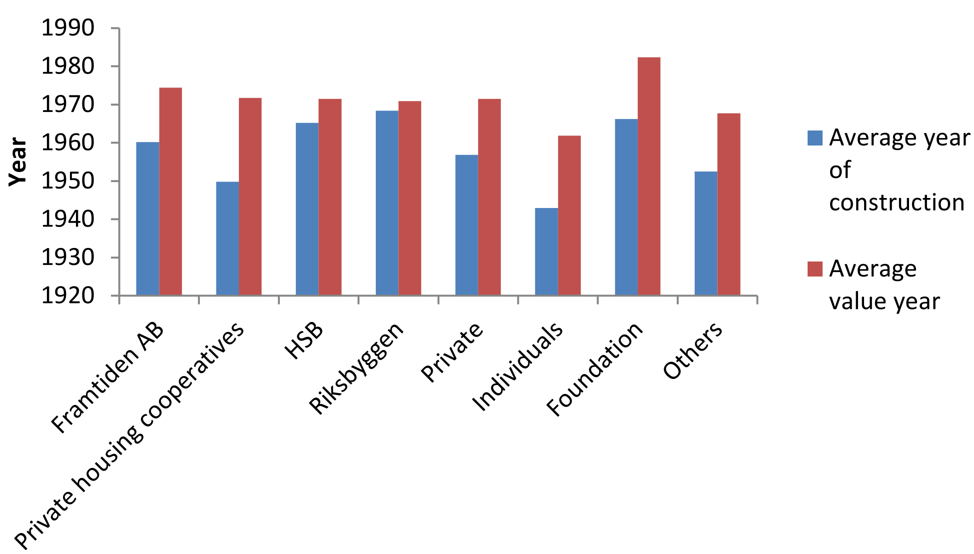

Figure 4 - Average year of construction and value year divided by owner, manager and owner type

While the average year of construction and average year of renovation only gives an idea about the renovation need on a stock level, the difference between the owners are still made clear. The oldest part of the stock can be found in private ownership and private housing cooperatives. It is not surprising then, that the owners of these buildings have renovated them to a larger extent. While much attention is given to the stock built during the period between 1960-1975, the so called million homes programme (MHP), it should also be noted that the older parts of the stock that has gone through major renovation will soon be needing further renovation. Another aspect when considering the need for renovation is not only the potential for measures that are beneficial from an energy saving and carbon mitigation perspective but that also preserve architectural and cultural historical values.

4. Creating a building-stock description

To allow for modelling and analysis of the energy performance of the building-stock, the available building-stock information is condensed to a description of the building-stock where the technical parameters are characterized. Since all information necessary to perform energy calculations are not known directly from the information available, assumptions are made using secondary sources in conjunction with the available information. This is described for the case of a property manager where error investigation is done. Further information on the methodology can be found in Paper I. In Table 3 the reduced set of data that are used to describe the building stock is shown.

Table 4 - Reduced set of data used to describe the MFB stock of Gothenburg

Database	Source	Information
Property managers internal dataset	Property manager	Number of apartments divided by size
EPC	National board of building, housing and planning	HVAC systems, number of stories, attachment to other buildings, measured energy use, number of staircases
2D-map of Gothenburg	City planning office	Footprint and length of external walls
Building register	Swedish mapping, cadastral and land registration authority	Year of construction, year of refurbishment and value year

4.1 Error investigation of EPC data

The property managers dataset is reduced to only contain (MFB), reducing the number of buildings from 557 to 446. Of the remaining 446 buildings, 433 are matched to an EPC and contain spatial coordinates. As the HFA given in the EPC has been subject to questioning, and error analysis is performed for geometrical attributes in the EPC for the 433 buildings in three steps.

1. Analytically
2. Visually in the GIS environment
3. Visually through images

Out of the 433 buildings, the EPC for 163 buildings were found to have errors relating to geometrical attributes. In 45 instances, the geometrical attributes were overestimated. Most errors where the HFA stated in the EPC is too large can be explained by how it is derived in the EPC. Since the HFA is rarely measured, the living area is instead used to derive the HFA by multiplying it with 1.15 (for buildings without basement) or 1.25 (for buildings with basement). As such, in buildings where all heated floor area is living area, the HFA of the building is overestimated by 15 % in the EPC. This is typical for 2 storey buildings with external staircases and individual external entrances to all apartments. 38 such buildings have been identified. Other errors include two coordinate errors observed in the GIS environment and five instances with wrong number of stories observed visually through images of the buildings.

There are 118 buildings where the geometrical attributes is underestimated in the EPC. Similar to what is stated above, the most commonly applied methodology in the EPC by deriving HFA from living area causes errors here as well. This is typical for 2 and 3 storey buildings with a heated basement. As the heated floor area is derived by multiplying the living area by 1.25, less than half of the basement would be accounted for in a 2 story building assuming the area of the basement equals that of the floors above ground. There are 38 instances of this occurring. Six instances have been observed where the recommended factors of 1.15 and 1.25 have not been used as prescribed. The two coordinate errors always occur in pairs and is a result of the building IDs being mixed in the EPC. Perhaps most surprisingly, the most common attribute error is number of stories with 72 instances. In many cases this seems to be the result of counting the basement twice but there are also instances where an 8 storey building is registered as a 3 storey building which would suggest manual error.

The correct number of stories has been added and the four instances with jumbled coordinates have been fixed manually. For future development this should be handled automatically by determining the number of stories from a 3D-modell combined with a digital terrain model and average story height. This would also improve the accuracy for buildings where a 2.5D model is not sufficient to determine the façade area.

4.2 Age-type classification

As the U-value is not given in the available databases, and age-type classification is done to estimate a likely U-value. The age-type classification is created using historic building regulations, architectural history books and surveys. The classification follows the most common method of dividing buildings into different age-type categories. Using an architectural history book (Björk et al., 2013) containing 32 different MFB types spanning a period of 120 years (1880-2000) together with historic building regulations, average U-values for an age-type classification has been specified and applied in Paper I. As not all of the 32 building types listed in the book are unique considering the type but rather construction methods or other architectural features, they are grouped to form overarching categories. In total they are divided into seven different categories and 27 time periods. As all building types do not exist for all time periods the total number is reduced. Furthermore, for several building types the U-value does not change significantly, or at all, over several time periods. The number of unique average U-values used in the age-type classification is 33. Ideally, balcony access blocks would be put into a separate category but as there is no feasible way of identifying them they have instead been added to the category large slab block. This is reasonable as they have similar U-values.

U-values for the age-type classification are derived from structural drawings provided in the architectural history book. These are aggregated to an average u-value based on typical shape factors and adjacency. For time periods where there is no knowledge on the structural composition, the u-value is instead taken from the building regulations. National building regulations for Sweden have existed since 1946 and have since contained demands connected to the U-value of the building. Due to different climate conditions, regulations have been differentiated by climate zones. All values given here in this section refers to Gothenburg applicable. From 1946 to 1988 demands on U-values were set at a component level and differentiated between light and heavy constructions, see Table 6. From 1989 to 2006 the demand was instead given as an average U-value for the entire building and from 2007 and onward the regulations have been set as an average U-value as well as measured energy use, see table 5. The measured energy use included in the energy performance of a building in regards to the building code is SH, DHW and non-domestic electricity use. As the way demands are set has changed, it is difficult to make a comparison between buildings built before 1989 and those built later as the shape factor, adjacency to other buildings and window to wall area ratio would impact the results.

Table 5 - Demands on average U-value and measured energy use for space heating, domestic hot water and non-domestic electricity use.

Building code	Valid	Average U-value [W/m²,k]	Measured energy use (for buildings with electric heating) [kWh/m²,y]
NR*	1989-1994	$0.18 + 0.95 * Aw/Aenv$	
BBR* 1-8	1995-2002	$0.18 + 0.95 * Aw/Aenv$	
BBR 9-11	2003-2006	$0.18 + 0.95 * Aw/Aenv$	
BBR 12-15	2007-2008	0.5	110 (75)
BBR 16-18	2009-2011	0.5	110 (55)
BBR 19-21	2012-2014	0.4	90 (55)

* NR stands for Nybyggnadsregler and BBR stands for Boverkets byggregler, English translation: New construction rules and the national board of building, housing and planning's construction rules. Aw denotes window area and Aenv denotes envelope area.

Table 6 - Demands on U-value for building components in the Swedish building code from 1946-1988

Building code (unit)	Valid	Heavy brick construction	Light brick construction	Other stone material	Wood	Heavy roof construction	Wooden roof construction	Floor	Window
BABS* 46 (kcal/m², ch)	1946-1950	1.0	0.9	0.8	0.6	0.6	0.5	0.4	2-pane
BABS 50 (kcal/m², ch)	1951-1960	1.05	0.95	0.85	0.65	0.55	0.45	0.45	2-pane
BABS 60 (kcal/m², ch)	1961-1967	1.0	1.0	0.8	0.5	0.5	0.4	0.4	2-pane
SBN* 67 (kcal/m², ch)	1968-1975	1.1	1.1	0.8	0.5	0.5	0.4	0.4	3.1
SBN 75 (W/m²,k)	1976-1981	0.3	0.3	0.3	0.3	0.2	0.2	0.3	2
SBN 80 (W/m²,k)	1982-1988	0.3	0.3	0.3	0.3	0.2	0.2	0.2	2

* BABS stands for Byggnadsstadgan and SBN stands for Svensk byggnorm, English translation: Building code and Swedish building code

4.3 Energy demand calculation

To create a model of the energy performance of the current state of the building-stock, the technical characteristics together with the spatial information is used as input to a previously developed energy, carbon and cost assessment model for building-stocks (ECCABS) (Mata and Sasic Kalagasidis, 2010). The method of describing the stock, which is presented in paper 1 (Österbring et al., 2016), uses building specific information where available rather than using representative buildings to describe the stock. In the GIS environment, the footprints of the 433 buildings and all buildings adjacent to them are put in a new layer. The areas of all footprints are calculated. All non-pertinent adjacent buildings, in general complementary buildings, are removed. All remaining footprints are split into polylines. As the lines contain information on directionality, all lines not facing towards the outdoors can be removed. The length of the remaining lines are calculated and linked back to the footprint they belong to. As such, the length of the facade and the area of the footprint are known for each building. These values are then multiplied by the number of stories with an estimated story height depending on the year of construction which gives the façade surface area. The estimated storey height is given in table 4.

Table 7 - Assumed storey height based on year of construction

Year of construction	Storey height, m
-1940	3.20
1941-1975	2.70
1961-1975	2.70
1976-	2.60

The calculated envelope area is used in the ECCABS model together with the average U-values from the age-type classification, building-specific information from the EPC on HVAC systems and assumptions on user behaviour to calculate the energy demand for SH and HW for the portfolio.

5. Analysis of the Building-stock

This chapter starts by presenting results based on the building-stock information that has previously been presented at different levels of aggregation before ending with a section on the results from using the developed description of the portfolio of a property manager in the ECCABS model.

The extent of the renovation need until 2025 considering a service-life of 50 years calculating from the value year is evaluated both spatially and graphically for the different property owners, managers and owner types. Figure 5 shows the spatial distribution for primary areas of the sum of m² HFA in need of renovation. On the left, all buildings in the MFB stock are included and on the right, buildings from the MHP (1960-1975), are highlighted. These buildings are of particular importance as they consititute the largest part of the stock (42 % of all HFA) and have the highest average energy use (146 kWh/m²,y). Unlike buildings from earlier time-periods, these buildings have to a large extent never been renovated. The buildings from the MHP are nearing the end of their service-life and require renovation in the coming decade. If substantial reductions in energy demand is to be achieved, EEM needs to be implemented in this part of the stock. As presented in Paper IV, many of these buildings are situated in areas with economically disadvantaged groups and rent increase due to substantial renovation measures may result in increased societal inequity.

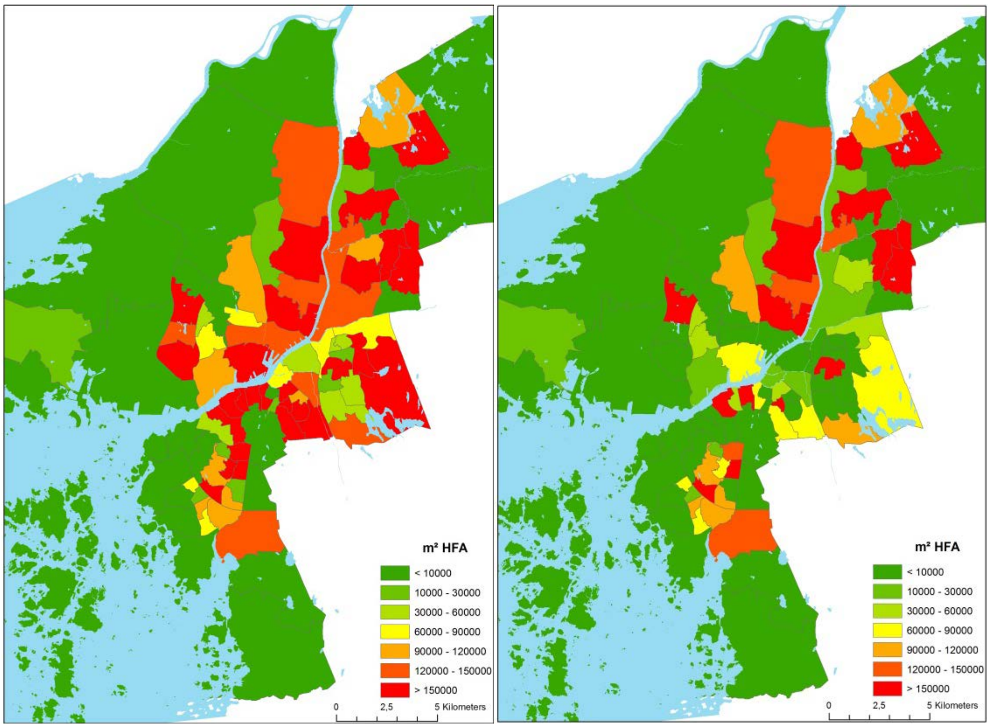

Figure 5 - m² of HFA that exceeds a service-life of 50 years until 2025 for the entire stock on the left and for buildings built between 1960-1975 on the right

Figure 6 shows the share of the stock of the different property owners, managers and owner types that will reach a service-life of 50 years until 2025. It is clear that the renovation need will be substantial as most building owners will need to renovate more than 50 % of their total stock. In total, almost 10 000 000 m² of HFA requires renovation using the assumption of a service-life of 50 years. While this may be representative for certain components of the buildings in question, it is likely that other components will have a longer life-span. This is also likely to be impacted by the maintenance of the buildings which may vary significantly between different building owners and managers.

There are some individual differences regarding the renovation need however. The highest renovation need can be found in the group of individuals who owns MFB. While the housing company of the municipality, Framtiden AB, is the largest building owner they have a slightly lower renovation need than other private owners on average. Considering the private housing cooperatives, those that are managed by HSB and Riksbyggen have a substantially larger renovation need than the average housing cooperative. It should be noted that while the value year changes if the cost of renovation is more than 20 % of the cost of new construction, smaller renovations and regular maintenance which may prolong the service-life of a building significantly does not. As HSB and Riksbyggen are property managers, their core business is to provide mainly maintenance services to the housing cooperative members and as such the renovation need may be overestimated.

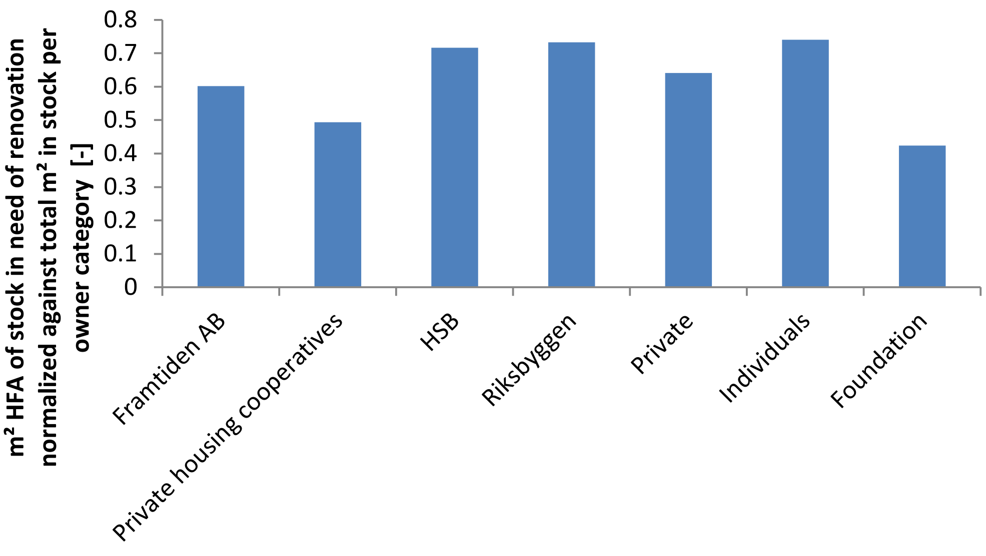

Figure 6 – Share of HFA in need of renovation for property owners, managers and owner types

Figure 7 shows the energy performance for the MFB stock of Framtiden AB at different spatial resolutions with areas shown at a more detailed level indicated by the rectangle. The average energy performance is shown for primary areas on the left, for base areas in the middle and for individual buildings on the right. This highligts the importance of spatial scale when evaluating the energy performance of the stock. While results on a higher spatial scale can be used to identify areas where EEM should be prioritized, the lower the spatial scale the more differentiated and detailed this prioritization can be done. The ability to pinpoint where renovation aiming at considerable reduction in energy should be prioritized is of vital importance considering the substantial renovation need in the stock.

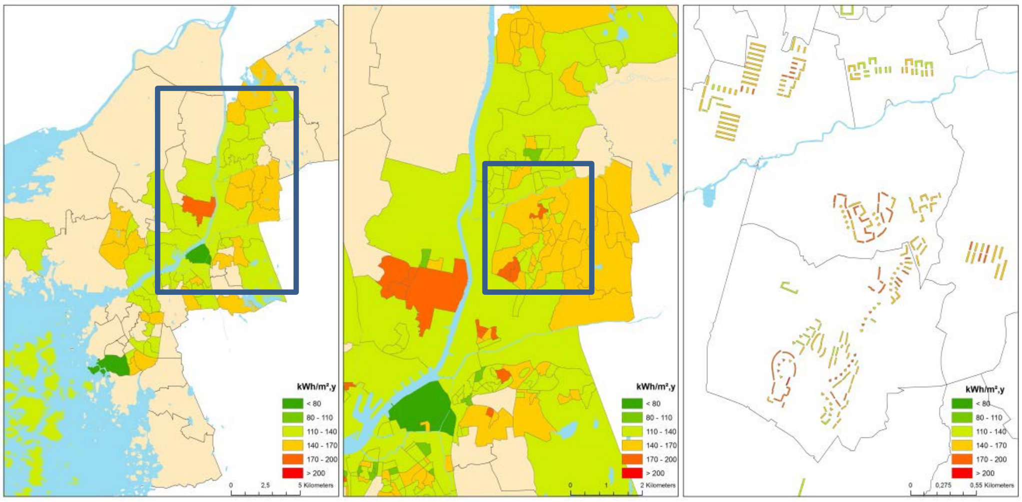

Figure 7 - Energy use aggregated at different spatial scales for the MFB stock of Framtiden AB. On the left, aggregated to primary areas, in the middle to base areas and on the right on a building level. The marked rectangle indicates the which area is focused on in the following figure

The method for creating a building-stock description detailed in Chapter 4 and Paper I have been used as input to calculate the energy demand for the local portfolio of a property manager using a previously developed BSM tool. While calculated energy use for SH and DHW based on the building-stock description of the portfolio differ less than 3 % from measured values, for 150 of the 433 buildings the calculated energy demand deviate more then 30 % from measured values, see figure 8. These are generally the smaller buildings in the portfolio as they only consitute 25 % of the HFA. One possible explanation for this is that these buildings to a larger extent use heat-pumps. These have proven to be problematic for two reasons. First, the efficiency of heat-pumps have a large impact on the calculated energy demand and as these values are not given in the EPC, the assumptions regarding the efficiency becomes a large uncertainty. Second, as the energy use in the EPC is often not measured separately for the heat-pump but rather distributed from total electricity use based on the judgement of the energy expert it may very well be that the calculated energy demand is closer to reality then what is stated in the EPC.

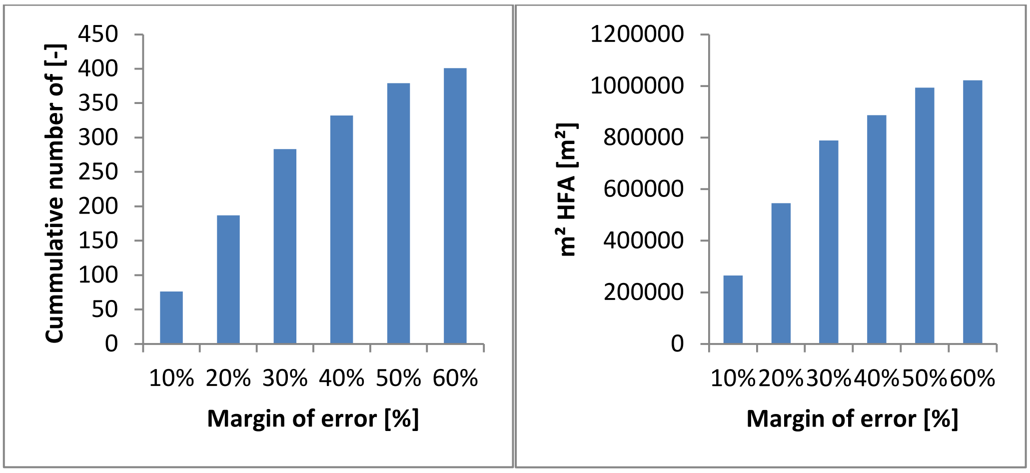

Figure 8 - cumulative number of buildings on the left and m² HFA on the right by which calculated energy performance deviates from measured energy performance

6. Conclusions

This thesis with appended papers has shown that available data sources can be used to describe the characteristics of the stock on a building level while considering the location and context. Building attributes such as year of construction, value year and owner from the Swedish Property register, spatial data provided by the City planning office of Gothenburg as well as EPC from the national board of housing, building and planning can provide detailed and valuable information to policy makers, urban planners and property owners. Being able to target property owners is especially promising as this is something that has been largely missing previously in the research field.

In this work, the extent of refurbishment needs of the MFB stock of the city of Gothenburg have been assessed by owner as well as spatially. The extensive need for renovation need during the next ten years that has been shown also provides an opportunity for achieving considerable reductions in energy demand and associated emissions of green-house gases. This work gives an overview of the existing situation and is a starting point for the development of renovation strategies and trajectories for the transformation of urban building-stocks. Future work on renovation needs should expand the parameters used to describe the composition and state of the stock. The analysis should include environmental impact of the construction process and materials in relation to the environmental impact of a reduced energy demand as well as life-cycle cost analysis. Another topic for further research is to evaluate policy and subsidies in relation to rent increase in economically disadvantaged areas.

The work in this thesis has also showed that it is possible from the available building-stock information to model the energy performance of the stock on a building level. This is crucial if the environmental, social and economic impacts of EEM are to be evaluated on a building level. Further work is needed to reduce the margin of error. This can to some extent be handled by improvement of the methodology used by using a 3D GIS-model for calculating envelope areas and specifying U-values at a component level. In addition, calibration methods could be incorporated to quantify uncertainties. Furthermore, the methodology used for describing the building stock is based on grouping buildings according to energy performance. In this case, the façade material is only considered as a thermal resistance. This assumption may need to be revised if environmental and economic impacts are to be evaluated.

The spatial visualization of renovation activities related to individual buildings can be used to support communication with urban planners, policy makers and property owners regarding coming renovation needs in an urban context. It is also clear from this work that while the renovation need will be large in the near future, information at aggregate levels need to be used with care when suggesting areas to where measures are to be prioritized to avoid unnecessary costs for the owner as well as the tenant. Further work is needed to assess what information different stakeholders involved in the transformation of the urban building stock needs and how it should be presented and visualized. Based on the literature review it can be concluded that while validation studies that have been done shows large discrepancies on a building level for models based on representative buildings, many still choose to visualize results on a building level.

While there is sufficient quantity of building-specific information available to describe the composition of the MFB stock, the renovation need as well as use the information available for modelling the energy demand, quality aspects need to be considered. Data available in the Swedish EPC have quality issues regarding the geometric properties of buildings that need to be considered. This work has suggested how the inaccuracies regarding the HFA can be identified and handled on a stock level and partly on a building level. Furthermore, future studies regarding renovation on a component level need to evaluate the possibility of using the value year as a basis since it mainly relates to the building and the remaining service-life of individual components may differ significantly.

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