Verbeterde voorspellingen van het energiegebruik voor ruimteverwarming in woningen: onderzoek op basis van velddata en vereenvoudigde modellen

Improving the Predictive Power of Simplified Residential Space Heating Demand Models: a Field Data and Model Driven Study

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Nomenclature

a	Thermal diffusivity	$m^2.s^{-1}$
Av	Average	-
c	Specific heat capacity	J/(kg.K)
ACH	Air change rate	h^{-1}
d	Thickness	m
g	Solar energy transmittance	-
H	Heat transfer coefficient	W/K
Max	Maximum	-
Mdn	Median	-
Min	Minimum	-
n	Air change rate	1/h
N	Number of cases in a sample	-
n.s.	Not significant	-
OR	Odds ratio	-
p	Probability value	-
r	Pearson correlation	-
R	Thermal resistance	$M^2.K/W$
t	time	h
T	temperature	K or °C
U	Thermal conductance	$W/(m^2.K)$
V	Volume	m^3

Greek symbols

α	Angle	°
γ	Gain-loss ratio	-
Δ	Difference	-
η	Utilization factor	-
θ	Temperature	°C
λ	Thermal conductivity	W/(m.K)
ρ	Density	kg/m^3
τ	Kendall’s tau b	-
τ_H	Thermal time constant	h
Φ	Heat flow rate	W

Subscripts and superscripts

50	At 50Pa pressure difference
a	Air
abs	Absolute
adj	Adjustment
av	Average
C	Space cooling calculation
cook	Cooking
cool	Space cooling
d	Door
dhw	Domestic hot water
diff.	Difference
e	External/exterior
equiv	Equivalent
g	Ground
H	Space heating calculation
heat	Space heating
hyg	Hygienic
i	Internal/indoor/interior
ins	Insulation
int	Interior
it	Iteration
m	Month
mhz	Moderately heated zone
min	Minimum
p	Periodic
red	Reduction
s	Surface
set	Set-point
sp	Space
spec	Specific
v	Ventilation
w	Window
t	Time
u	Unconditioned zone
yr	Year

Acronyms

3D	Three dimensional
BIM	Building information modelling
CI	Confidence interval
CO2	Carbon dioxide

cs	Case-study
EPB	Energy performance of buildings
EPBD	Energy performance of buildings directive
EU	European Union
FL	Flanders
GE	Germany
ISO	International Organization for Standardization
LCV	Lower combustion value
LT	Low temperature
MZ	Multi-zone
NL	The Netherlands
PH	Passive house
PV	Photovoltaics
UCV	Upper combustion value
UK	United Kingdom
USA	United States of America
VEA	Flemish Energy Agency

Samenvatting

In verschillende landen zijn grote afwijkingen aan het licht gekomen bij het vergelijken van het werkelijk energiegebruik in woningen met het theoretisch energiegebruik berekend aan de hand van rekenmethodes uit de energieprestatieregelgeving (EPB/EPC). Deze kloof tussen werkelijk en berekend energiegebruik is een grote bekommernis in de residentiële bouwsector, waar informatie uit energieprestatiecertificaten vaak de enige energie-gerelateerde basis is om investeringsbeslissingen op te steunen in nieuwbouw en renovatie. Bovendien worden deze vereenvoudigde energieberekeningsmodellen ook vaak gebruikt voor gebouwpatrimoniumanalyses rond het energiebesparingspotentieel op regionaal of nationaal niveau, ter ondersteuning van beleidsmaking. Omwille van die bekommernis hebben talrijke onderzoeken zich toegespitst op gedragsgebonden en fysische oorzaken van deze voorspellingsfouten, bijv. het zogenaamde rebound-effect en temperatuur 'take-back'. Op veel vlakken is er eensgezindheid in de literatuur (bijv. aangaande het belang van gebruikersgedrag), maar het debat is niet gestild rond hoe groot het gedragsgebonden aandeel van voorspellingsfouten is en hoe groot het aandeel is dat veroorzaakt wordt door fysische modelleerfouten. Dit kan deels verklaard worden door het feit dat de grootte van de voorspellingsfouten varieert afhankelijk van de lokale bouwtraditie, energieprestatieniveaus en prestatiebeoordelingskader.

Dit proefschrift zet het onderzoek verder rond de voorspellingskloof tussen vereenvoudigde rekenmethodes en het werkelijk residentieel energiegebruik, met als focus het energiegebruik voor ruimteverwarming in Belgische eengezinswoningen. Steunend op analyses op velddata komende van bewoonde huizen, werd een nieuwe vereenvoudigde rekenaanpak ontwikkeld en gebruikt voor gevoeligheidsanalyses.

Het eerste deel van dit onderzoek steunt op data verzameld aan de hand van bewonersenquêtes, metingen in bewoonde huizen, energiefacturen en officiële energieprestatieberekeningen. Twee datasets worden geanalyseerd. De eerste dataset, die geanalyseerd wordt in hoofdstuk 2, omvat meer dan 500 willekeurig geselecteerde hoog-performante woningen. De tweede dataset, die geanalyseerd wordt in hoofdstuk 3, werd verzameld in twee uniforme wijken, één oude wijk met niet-geïsoleerde woningen en een tweede, nieuwbouwwijk met goed geïsoleerde woningen. De variatie in stookprofielen op kamerniveau en hun correlatie met gebouw- en gebruikers-gebonden parameters worden verder bestudeerd in hoofdstuk 4. De gebruiksprofielen, zowel stookprofielen als ventilatieprofielen, vertonen grote variaties op kamerniveau zowel binnen eenzelfde dataset als tussen datasets en tussen de twee wijken. Er worden kwistigere stookprofielen vastgesteld in de meer performante woningen, vooral

in de woningen met centrale verwarming op lage temperatuur. Met betrekking tot de ventilatiesystemen, blijkt de spreiding van de technische eigenschappen, met name de geïnstalleerde ventilatiedebieten per kamer, zelfs binnen eenzelfde wijk belangrijker dan de spreiding in instellingen die de gebruikers kiezen. De energieprestatieberekeningen overschatten het ventilatiedebiet in oude woningen zonder ventilatiesysteem en houden geen rekeningen met het feit dat de ramen die het meest opengedaan worden deze van de veelal onverwarmde slaapkamers zijn. Dit verklaart voor een stuk de grote overschatting van het werkelijk energiegebruik die deze modellen maken voor oude woningen. Ondanks deze bevindingen, zijn de gebruiksprofielen en de onzekerheden met betrekking tot technische eigenschappen niet de enige oorzaken van de voorspellingsfouten. Statistische analyse op de eerste dataset brengt ook de afwijkingen aan het licht die veroorzaakt worden door technische, veelal conservatieve waarden bij ontstentenis uit de officiële prestatiebeoordelingsmethode. Dit duidt de invloed aan van de EPB-verslaggever die zelf de keuze maakt tussen het gebruik van deze waarden bij ontstentenis of nauwkeurigere gemeten of berekende waarden. De analyse toont aan dat de verslaggeving veelal grondiger gebeurt bij hoog-performante woningen, met een beperkter gebruik van waarden bij ontstentenis. Dit verklaart deels de grotere overschattingen van het energiegebruik bij minder performante woningen (waardoor ook de mogelijke energiebesparingen zullen overschat worden). De beperkte grootte van de datasets en de belangrijke associaties tussen gebouwkarakteristieken enerzijds en gezinstypologieën anderzijds beperken weliswaar de validiteit van het extrapoleren van deze bevindingen naar het volledige patrimonium. Deze verwevenheid tussen gebouwparameters en gezinsparameters stelt bovendien in vraag of het mogelijk is gebouw-gebonden oorzaken van voorspellingsfouten te onderscheiden van gebruikers-gebonden oorzaken.

De data-analyses bevestigen de grote variaties in gebruiksprofielen en binnentemperaturen die besproken worden in de literatuur. Om deze aspecten in rekening te kunnen brengen, werd een multi-zone model ontwikkeld dat wel nog steunt op de vereenvoudigde en efficiënte quasi-steady-state modelleeraanpak uit de EPB-rekenmethodes. Het model wordt beschreven en geanalyseerd in hoofdstuk 5. Het model wordt er vergeleken met de één-zone modelleeraanpakken uit België, Duitsland en Nederland en de resultaten worden in hoofdstuk 6 afgetoetst aan de hand van simulaties op de oude woonwijk, rekening houdend met de werkelijke stook- en ventilatieprofielen. De Duitse en Nederlandse één-zone benaderingen bevatten correctieformules om rekening te houden met nacht-verlaging van de verwarmingstemperatuur en met het feit dat niet alle ruimtes verwarmd worden. Voor de niet geïsoleerde gebouwen liggen de berekende verbruiken in dezelfde grootteorde als deze van multi-zone simulaties. Het feit dat één-zone modellen geen rekening kunnen houden met de ligging van de wel en niet verwarmde ruimtes noch met het feit dat de meest verwarmde leefruimte de ruimte is met de hoogste interne winsten en waarvan de ramen het minst open gedaan worden verklaart wel een deel van de overschatting van het energiegebruik gemaakt door energieprestatieberekeningen. Bovendien vertonen de één-zone modellen belangrijke afwijkingen wanneer verschillende renovatiescenario's worden vergeleken in gevoeligheidsanalyses. De belangrijkste afwijking doet zich voor bij zoldervloerisolatie, waarbij de één-zone modellen de relatieve besparing overschatten met minstens een factor twee, omdat deze modellen de plaats van de isolatiemaatregel niet in rekening brengen, namelijk boven de koudere, onverwarmde slaapkamers. Dit kan de ontwerper, de beleidsmaker of de huiseigenaar misleiden bij zijn beslissingsproces. Bovendien kan dit ook een deel verklaren van de grotere kloof tussen het werkelijk en het theoretisch energiegebruik die vastgesteld wordt bij minder performante woningen.

Ten opzichte van één-zone modellen kunnen multi-zone modellen meer nauwkeurige resultaten aanleveren, maar ze vergen een grotere werklast en grotere rekentijden. Dit verklaart het gebrek aan populariteit van multi-zone modellen bij kleine residentiële bouwprojecten (bijv. eengezinswoningen) en bij gebouwpatrimoniumanalyses. Als antwoord daarop stelt hoofdstuk 7 een nieuwe aanpak voor om multi-zone modellen te maken steunend op beperkte één-zone input-data. De aanpak steunt op parametrische gebouwtypologieën die gemodelleerd zijn in ‘building information modelling’ (BIM) software. In samenwerking met de onderzoeksgroep SmartLab (UGent) werd een BIM-simulatietool ontwikkeld die zowel één-zone als multi-zone simulatiemodellen kan genereren op basis van BIM-modellen uit bijv. Revit-software. Voor gebouwen zonder 3D BIM-model wordt een vooraf gedefinieerde parametrische gebouwtypologie in een geautomatiseerde procedure gefit naar de beschikbare één-zone data van dat gebouw, resulterend in een driedimensionaal vervangingsmodel waaruit de simulatiemodellen kunnen worden gegenereerd. Simulatieresultaten van deze aanpak worden voor drie werkelijke woningen vergeleken met de simulatieresultaten op basis van originele BIM-modellen van die woningen. De analyse toont dat een heel goede correlatie bekomen kan worden tussen de resultaten van de vervangingsmodellen en deze van de originele modellen, op voorwaarde van een goede selectieprocedure voor de parametrische typologie. Een afzonderlijke analyse spitst zich toe op het gebruik van deze aanpak voor gebouwpatrimoniumanalyses, steunend op data uit de Vlaamse EPB-database over 15000 woningen. De resultaten tonen de grote elasticiteit van de parametrische modellen, die toelaat om vervangingsmodellen te maken voor grote aantallen verschillende woningen. Dit vergroot de representativiteit van de patrimoniumanalyse. De combinatie van deze parametrische typologie-benadering met het efficiënte multi-zone algoritme uit hoofdstuk 5 laat toe om meer realistische energiesimulatiemodellen te bouwen die rekening houden met belangrijke parameters zoals werkelijke stookprofielen, zonder daartoe de werklast of de rekentijd noemenswaardig te vergroten.

Summary

Large discrepancies have been found in different countries when comparing real energy use in houses to the theoretical energy use calculated using energy performance of buildings (EPB) calculation methods. This prediction gap has become a major concern in the residential building sector, where the information provided on energy performance certificates is often the only energy related basis to support investment decisions in construction and renovation. Additionally, the simplified energy performance calculation methods are also often used for building stock analyses to support policy making by analysing potential savings on a regional or national level. Following these concerns, numerous studies have focussed on behavioural and physical causes of these prediction errors, e.g. on rebound effect and physical temperature take-back. While literature agrees on many findings (e.g. the importance of user behaviour), there is still a debate on what part of the error is due to user behaviour and what part to physical modelling errors. This can partly be explained by the fact that the size of the reported prediction gaps varies depending on the local building tradition, building performance levels and performance assessment framework.

This dissertation pursues the investigation on the prediction gap between simplified calculation methods and real energy use in houses, focussing on the space heating demand in single-family houses in Belgium. Building on analyses on field data from inhabited houses, a new simplified calculation approach is developed and used for sensitivity analyses.

The first part of the study is data-driven, analysing data from surveys of inhabitants, field-measurements, energy bills and official energy performance calculations. Two datasets are analysed. The first dataset, analysed in Chapter 2, contains over 500 randomly selected high-performance houses. The second dataset, analysed in Chapter 3, was collected in two uniform neighbourhoods, one with old uninsulated houses, the other with new and well insulated houses. The variation in heating profiles at room level and their correlation with building and user related parameters are further analysed in Chapter 4. Large variations in user profiles were found at room level within each dataset, but also between the different datasets and between both neighbourhoods, regarding e.g. heating and ventilation profiles. More lavish heating profiles were found in the higher performance houses, especially in houses with low-temperature central heating systems. With regard to ventilation, variations of technical characteristics even within one neighbourhood, namely of the installed ventilation flow rates, proved more important than the variations in control settings chosen by the user. The regulatory performance assessment method overestimates the ventilation flow rates in old houses without ventilation system and it does not take into account the fact that the windows that are opened the most are mainly those of the often unheated bedrooms. This explains part of the large overestimation of the energy

use in old houses made by the energy performance calculation models. However, the user profiles and uncertainties regarding technical properties are not the only causes of prediction errors. The statistical study on the first dataset also revealed the biasing effects of technical, commonly conservative default values used in the official assessment framework and, by consequence, the importance of the assessors, choosing to use default values or more detailed measured or calculated values. The assessors' work often proves to be more thorough for high performance houses, using fewer default values. This explains in part the larger prediction error in low performance houses. However, the limited sample sizes and the important associations between the building characteristics and performance levels on the one hand and the types of households on the other limit the validity of extrapolating the findings to building stock level. These associations also question whether it is possible to fully discern all building related causes of prediction errors from all user related causes.

The data-driven analyses confirmed findings from literature regarding the strong differences in user profiles and measured temperatures in different rooms. To take this into account, a multi-zone model was developed, which however still follows the simplified and efficient quasi-steady-state approach of the EPB-calculation methods. The model is described and analysed in Chapter 5. It is compared to single-zone modelling approaches from Belgium, Germany and the Netherlands and validated in Chapter 6 by simulations on the old case-study neighbourhood considering the real user profiles. The German and Dutch single-zone approaches include correction formulas for taking into account night-time set-back and the fact that not all rooms are heated. Their predicted energy uses lay in the same range as the results from the multi-zone model for the uninsulated houses. However, the fact that single-zone models cannot take into account the location of the heated and unheated rooms nor the fact that the most heated living area is the area with the largest internal heat gains and the lowest window opening hours explains part of their overestimation of the energy use. Furthermore, the single-zone models showed important biases when comparing different renovation measures in further scenario analyses. Most importantly, all single-zone approaches overestimated the relative energy savings associated with loft insulation at least by a factor of two because they do not take the position of the added insulation into account, laying above the colder, unheated bedrooms. Not only can this lead to biased policy making, design or investment choices, but it also explains part of the larger prediction gap identified at lower compared to higher performance levels in Belgium.

Compared with single-zone models, building a multi-zone model considerably increases the modelling workload. In spite of the increased prediction accuracy they can offer, their calculation times and this increased workload explain the lack of popularity of multi-zone models in small residential building projects (e.g. a single-family house) and for building stock analyses. In response, Chapter 7 presents a new approach for making multi-zone simulations using mainly limited single-zone inputs. The approach is based on parametric typologies modelled in building information modelling (BIM) software. In collaboration with the research group SmartLab (UGent), a custom BIM-simulation tool was developed, accepting models from e.g. Revit-software to generate single-zone

EPB-models as well as multi-zone calculation models. For buildings without 3D BIM-models, predefined parametric multi-zone typologies are fitted in an automated way to the available single-zone data of the specific building, in order to create 3D replacement models. Results from this data-enrichment approach were compared with results based on original BIM-models of three case-study houses. While very good correlations were found between the original models and the replacement models, the findings stressed the importance of selecting an appropriate parametric typology and identified new challenges for improving the fitting procedure. A separate analysis focussed on the use of this parametric typology approach for building stock modelling. Statistical data from the official EPB-database on 15000 houses served as modelling inputs. This analysis proved the large elasticity of the parametric models, allowing building replacement models for very large numbers of different houses, and thus increasing the representativeness of building stock analyses. Combining the approach with the computationally efficient multi-zone calculation model from Chapter 5 allows for more realistic energy modelling, taking into account important parameters such as the real heating profiles, with hardly any increase in workload or calculation time.

1

Introduction

This introduction chapter positions this PhD-dissertation in the broader context of energy use for space heating, the regulatory performance assessment methods and the gap between real and theoretical energy use. It introduces the main concepts from literature and corresponding references that will be discussed in more detail in the following chapters before presenting the problem statement and outlining the general approach and the structure of the dissertation.

1.1 Context

The oil and energy crises of the 70ties spurred research on the reduction of energy use in all sectors including the residential sector. A lot of effort targetted the energy use for space heating. While the technical properties of the buildings were found to prevail in explaining the real energy use for space heating, a large amount of variation in real energy was attributed to user behaviour [1]. Therefore, research focussed not only on technical solutions (e.g. insulation, system efficiencies [2–4]) but also on ways to influence the users' behaviour by e.g. feedback on their energy use and incentives [5–9] and, in support of policy making, on drivers and barriers on the path to large scale implementations of energy conservation measures [10–12]. While research in these fields never ceased, reducing the energy use gained renewed widespread attention since the 90ties, with the emerging awareness about climate change and the need for reducing greenhouse gas emissions. International treaties arose [13,14] and governments translated CO_2-reduction targets into energy performance legislations [15,16], with countries defining minimal requirements for the energy performance of buildings. Thanks to the development of simplified calculation methods [17,18] that found their way into international standards [19,20] and to the wide spread of personal computers that occurred in the meantime, energy performance calculation tools have made their way to becoming a keystone in the practical implementation of these new legislations [21,22]. While originally intended mainly for design support tools [17,18], these models have been implemented in tools supporting the regulatory framework for making standardized calculations of the energy performance of buildings and generating performance assessment reports necessary for compliance control. In addition, this workflow of systematic energy performance calculations and reporting has also made it possible to gather large amounts of data on the building stock, its physical characteristics and theoretical performance levels. Resulting databases have become essential tools for supporting policy making [21–27]. However, analysing that data has revealed large discrepancies between theoretical energy use and real energy use [28–33]. In addition to the large variation in real energy use found at all performance levels, the theoretical models prove to overestimate the average real energy use, with this gap between real and theoretical values being the largest at poor energy performance levels. By consequence, theoretically expected energy savings are hardly ever achieved. This lack of accuracy of the simplified models is of importance because they are also used in studies supporting the elaboration of long term policy plans: scenario-analyses at building stock level on the energy saving potential of the wide range of energy conservation measures and studies about cost-optimal solutions [34–42].

Causes for this discrepancy between theoretically calculated and practically achieved energy-savings can be manifold: incorrect input data, bad workmanship, bad commissioning and/or too complex interaction of systems, difficultly predictable behavioural response, the outdoor climate varying from year to year and of course inadequate modelling approaches. Notwithstanding that these factors are studied extensively, they are still not well integrated in the simplified calculation models that are used for building stock analyses or by architects. Based on comparisons between real and theoretical energy use, empirical correction factors can be defined to correct for the average error of the calculation models [30,31,33,43–45]. However, this post-hoc approach based on one aggregated correction factor has limitations because it does not differentiate between the causes of the prediction errors and because it only corrects for the average error based on a specific population and considering a specific calculation method. It does not discern if the error is caused e.g. by the overestimated system efficiencies or thermal resistances or by overestimated indoor temperatures or a simplified heat balance equation. Consequently, applying this approach in scenario analyses in which different systems, building envelopes or user profiles are considered than those present in the original dataset from which the correction factors were derived could bias the results. For these same reasons, such method is only suitable for correcting average predictions on large numbers of houses, e.g. in building stock analyses, and it does not provide an adequate solution for obtaining more accurate results for a specific house or a specific household. Taking the most important causes of prediction errors into account directly in the energy calculation model, physically, would make the approach more robust, but it requires a better understanding of the causes of the prediction error than the definition of an average correction factor.

1.2 Shortfall, rebound or take-back?

Technical properties prevail in defining the real energy use in houses [1,46–49]. The most important technical properties of a house influencing the energy use (material properties, building geometry, orientation, type and efficiencies of the systems) are taken into account in the regulatory energy performance calculation methods. On the opposite, the real inhabitants of the house are not taken into account in the calculation. Instead, these assessment methods consider a standard user profile. This standardized calculation approach allows comparing the performance of a building with that of another building or with official requirements, rather than comparing the thrift of the inhabitants. However, it also results in a large simplification of reality, where the large variation in user profiles (heating profiles [50–54], ventilation profiles [55–60] and internal heat gains) has a significant impact on the real energy use [1,49,50,61–65]. The assumption of a standardized user profile in the calculation methods therefore explains in part the large and varying discrepancies found between real and theoretical energy use on the level of the individual house and household. In addition, it is argued based on rebound theory that considering the same standard user profile at all energy performance levels is not representative of the average user behaviour and that it explains in part the difference between real and predicted savings.

Rebound theory, originating from economical science, postulates that a higher energy efficiency making a service cheaper or thus resulting in a lower cost per unit of service (e.g. a better insulation level reducing the cost of heating the house to a certain temperature) will result in the users raising their demands (e.g.

with regard to comfort by increasing the indoor temperature), in them paying less attention to wasting energy as a result of less cautious behaviour (e.g. omitting to switch of the heaters when leaving the house) or in them spending parts of the saved costs to other expenditures that use energy (e.g. travelling) [66,67]. The latter option results in a shift of expenditure from one service to another and is referred to as 'indirect rebound'. When the otherwise saved costs are reinvested for the same service, it is referred to as 'direct rebound'. With regard to space heating, this could result in people heating more rooms, leaving the heating on more hours per day or choosing a higher set-point temperature after an energy refurbishment. This direct rebound is not taken into account in the energy performance calculations because these consider a single, fixed heating profile for all energy performance levels. Therefore, this direct rebound effect can explain part of the shortfall, the difference between the higher predicted savings and the lower real savings. There is little debate on the existence of direct rebound, but there is considerable debate on the size of its effect on the space heating demand [67]. This is caused in part by the different terminology used in different studies, with 'rebound' often being used to define much more than only the economic phenomenon described above.

Higher average temperatures are found in insulated houses compared to non-insulated houses. This is often referred to as 'temperature take-back' and sometimes wrongfully assimilated with direct rebound. As will be further discussed in Chapter 2, this temperature rise can result from direct rebound, but it can also have an independent physical cause. In better insulated houses, temperature drops after switching off the heating at night (night-time set-back) will be smaller and unheated rooms (e.g. bedrooms) will remain at a higher temperature between that of the adjacent heated living area and that of the outdoor environment. Some energy performance calculation models consider the buildings as a single-zone with a fixed set-point temperature and thus do not take this 'physical temperature take-back' into account, thus explaining part of the overestimation of the energy savings [68] (see also Chapters 2,5,6). In addition to economic rebound and physical temperature take-back, a third factor is reported in literature to result in an increase of the building temperature, explaining part of the temperature take-back: the installation of a central heating system [69–72]. More specifically, Hunt and Gidman [72] found higher average bedroom temperatures in centrally heated houses compared to houses with local heating systems, but no difference between houses with local heating systems or no heating system in the bedrooms. While this could in part be explained as 'direct rebound', associated with the higher efficiency of the central heating system, this behavioural adaptation is also clearly triggered by the change in type and control of the heating system, as will be further discussed in Chapters 3 and 4. There are thus, in addition to technical uncertainties, different causes of the gap between real and predicted energy use and energy savings which depend on the analysed houses, on the inhabitants and their behaviour and on the considered calculation method.

1.3 Research objectives

Reducing the discrepancies between real and theoretical values requires further understanding of the parameters causing these discrepancies and also requires practical models that allow taking the most important parameters into account in simplified assessment approaches usable for building stock analysis and for support in early design stages. Therefore, the objectives of this study are:

- Identifying the most important parameters explaining the discrepancies between real energy use for space heating and theoretical values calculated according to the regulatory energy performance assessment methods.
- Taking into account the most important parameters in order to build up a more accurate yet practical modelling approach to make more realistic predictions on energy use and savings. This approach should be implementable in building stock analyses supporting policy making and also in the framework of individual housing projects.

1.4 Approach and structure

In this dissertation, two approaches are used for studying the prediction accuracy and the causes of prediction errors. The first approach is data-driven, analysing field data collected on inhabited houses to study the gap between real and theoretical energy use and the most important parameters causing that gap. The second approach is model-driven, based on sensitivity analyses using building simulations. Between both approaches sits the development of the simulation model used for the sensitivity analyses, driven by the findings on the field data and building further on the simplified calculation methods used for regulatory performance assessments. As for most additions to existing models, additional inputs are required for the extended model. In a last section, an approach is presented to define the required additional inputs with a minimum of additional workload, making the approach usable for building stock analyses, simulating large numbers of houses using multi-zone models.

The three data-driven chapters analyse two different datasets on single-family houses in Belgium containing information on the buildings, the users, the theoretical energy use and the real energy use. First, each dataset is analysed separately in one chapter, comparing real and theoretical energy use and analysing building and user related parameters explaining the gap between those two values. Subsequently, the heating profiles derived from the two datasets are analysed and compared in more detail in a third chapter. For both datasets, data on real energy use was collected by means of utility meter readings and surveys of the inhabitants provided data on the users and their behaviour, but the two datasets differ with regard to their sample size, the performance of the houses and the availability of regulatory performance data and measurement data.

Chapter 2 presents a statistical study on a first set of over 500 high-performance single-family houses with different designs, construction methods and services. Technical data on the buildings and on their theoretical energy use was retrieved from the official Flemish Energy Performance of Buildings (EPB) database, making it possible to analyse parameters regarding the assessment procedure and the work of the EPB-assessors.

Chapter 3 presents a study on two neighbourhoods of single-family houses. As opposed to the first dataset this second dataset contains data from field measurements and, while the same energy calculation method was used as for the houses of the first dataset, these calculations were not made in the framework of the official performance assessment of the buildings but specifically for this study. The first neighbourhood consists of old, non-insulated houses while the second neighbourhood is built to current standards. Each neighbourhood separately forms one subset of quasi identical houses, built by one architect and one contractor, using the same design approaches regarding the envelope and the systems. This dichotomy between both neighbourhoods together with the uniformity within one neighbourhood, the availability of measurement data and the uniform approach for calculating the theoretical energy use allow more detailed analyses and a better distinction between differences related to design choices and energy performance levels (between both neighbourhoods) and differences related to variations in user behaviour or workmanship (within each neighbourhood).

Chapter 4 reports on the last data-driven analysis, comparing the heating profiles found in the old non-insulated houses, the recent standard houses and the high performance houses and using statistical analyses to study the variation in heating profiles and correlations with user and building related parameters.

The model-driven part of this PhD-dissertation starts in Chapter 5 with a comparative analysis of modelling approaches that are based on the simplified monthly quasi-steady calculation method from ISO 13790 [20], which is the basis for the regulatory performance calculation models of many countries. This analysis encompasses the approaches from three national standards for taking different heating profiles into account in such single-zone models and it also considers the coupled multi-zone version of the method, allowing for more detailed modelling of building and user profiles. Corrections to that method are proposed.

While Chapter 5 compares the modelling approaches on the basis of their equations, Chapter 6 compares them by using them for simulations on the old houses from the first dataset (Chapter 3). Theoretical values are compared with measured values and modelling simplifications are analysed before presenting the results of a scenario analysis. This scenario analysis evaluates the fitness of the different models for predicting energy savings and comparing energy retrofitting measures.

Chapter 7 considers the practical implementation of the multi-zone calculation method with the objective of making the model usable in the framework of building stock analyses and for decision support in the framework of small housing projects. It presents an approach for building a multi-zone replacement model for a house based on limited single-zone data of that house and predefined, multi-zone parametrical typologies. The approach is automated using Building Information Models (BIM). As a proof of concept, using this approach for building stock analyses is illustrated by simulations on 15000 houses documented in the official Flemish EPB-database, thus based on single-zone data, and by further tests on three case-study houses, comparing the results from the typological replacement modelling approach with results based on original BIM-models of the houses. This approach was developed in collaboration with Tiemen Strobbe from the research group SmartLab (UGent).

Based on the data and simulation analyses, the studies presented in the different chapters of this dissertation verified causes of discrepancies between real and theoretical energy use for space heating that are reported in literature and they identified additional causes that are related to technical parameters and user behaviour. The presented modelling approach combines a simplified calculation method and a practical implementation of that method. Together, they can be used for making more accurate predictions of real energy use and energy savings than possible using regulatory performance assessment models, both at building stock level and at the level of the individual house and household.

2

Regulatory energy calculations versus real energy use in high-performance houses

This chapter investigates the size and causes of the discrepancy between real and theoretical energy use in high-performance houses. The study is based on a statistical analysis on more than 500 houses, with data from surveys of the inhabitants, meter readings from the energy utilities and data from the Flemish Energy Performance of Buildings (EPB) database. The analysis considers not only parameters related to the buildings or to the inhabitants, but also choices made by the EPB-assessor when modelling the house in the framework of the regulatory energy performance assessment. These parameters are analysed in relation to one another and in relation to the discrepancy between real and theoretical energy use.
This study was initiated in the framework of a project for the Flemish Energy Agency (VEA) [73]. This work was published in Building Research & Information and this chapter corresponds, for most parts verbatim, with the published journal article [25]. We would like to thank all inhabitants who participated in the study as well as the Flemish Energy Agency (VEA) and Ipsos for the data collection.

2.1 Introduction

In Europe, the official energy performance regulations for buildings aim at reducing CO2 emissions in a cost effective way by imposing energy performance levels [16,39]. To assess the performance level of residential buildings, standardized, simplified calculation procedures are used, based on technical characteristics of the building and a standard, average user profile [22]. However, it is often questioned whether theoretically predicted energy savings associated with better performance levels are fully obtained in practice, thus throwing doubt on the real return on investments, both financially and regarding CO2 emissions.

The real operational energy use and its determinants have been the subject of many statistical studies. These studies typically use large data sets containing data on the real energy use, on the buildings and on the occupants' behaviour. Their findings proved that while building characteristics strongly prevail, user behaviour also has a significant influence on the real heating energy use [1,46–49]. While endorsing the importance of technical energy saving measures, these findings conflict with the simplifying assumption of a single, average user profile, as defined in the calculation methods. Additional statistical studies included calculated energy figures within their data sets [29,31,32,74]. Their findings reveal a large spread in prediction error that can partly be attributed to variations in user behaviour. Additionally, the calculations were shown to overestimate the real energy use. To a large extent, this applied to old, poorly insulated houses, but to a smaller extent to houses with improved performance levels. In both the Netherlands and Germany the average prediction error shifted further into an underestimation of the energy use when reaching high performance levels [29,32]. This shift in prediction error results in an overestimation of the real energy savings associated with better energy performance levels. It is often associated with an increase in indoor temperature and referred to as 'temperature take-back'. Part of it can be explained by economic rebound. As user behaviour varies with the consumption price, comfort demands might increase with improved energy performance levels [75]. Another part of the temperature take-back can be explained physically. Indeed, the better insulation levels will cause unheated zones to reach higher temperatures and reduce temperature drops during setback periods (i.e. timed periods of heating control when the temperature is lowered) [68]. While not taken into account in the Flemish calculation method, the official calculation methods in the UK, Germany and the Netherlands take zonal and intermittency effects into account [76–78]. Even though these calculation methods are similar and based on the same monthly quasi-steady state method described in ISO 13790 [20], they use different simplified formulas to account for these effects. This exemplifies the many differences between the local implementations of the European energy performance regulations. As a result, the prediction errors and thus also the findings from statistical studies, anchored within their local context, will vary between countries. The present study was launched not only to verify the validity of findings from literature for the local, Flemish context, but also to look further into the aspects of the assessment procedure and the calculation method that might influence the prediction errors.

In Flanders, the European guidelines from the Energy Performance of Buildings Directive (EPBD) [15,16] were implemented in the Flemish Energy Performance and Indoor Climate Decree (EPB-decree) [79]. Since 2006, it requires every new built house to meet the official energy performance requirements. For each building project an accredited EPB-assessor, hired by the builder, calculates and reports the building's energy performance, using the official calculation tool (EPB-software) provided by the government, based on as-built data of the house. For some parameters, accurate data may not be available and may be replaced by a default value. The total, calculated annual energy use comprises the demands for space heating, domestic hot water and cooling and the auxiliary energy for building services (mainly fans and pumps). The space heating and cooling energy use is calculated using a single zone, quasi steady state, monthly calculation method, based on ISO 13790 [20,80]. The electricity production from local photovoltaic (PV) panels is taken into account in the total primary-energy balance. The functional energy use for cooking, for lighting and for domestic electrical appliances is not included in the regulatory procedure for residential buildings. All calculated energy figures are converted into their primary-energy equivalents, with a conversion factor of 2.5 for electricity, and translated into a dimensionless indicator, the 'E-level'. This level indicates the relative primary-energy use of a building, in comparison with a reference value that depends on the size and shape of the building. A larger heat loss area and a larger volume will result in a larger reference value. The E-level therefore assesses the level of technical measures taken to reduce the energy use rather than the absolute value of the resulting energy use.

A data set of 537 dwellings was analysed, containing data from the official EPB-files (input data as well as calculation results), data from surveys (focusing on the inhabitants, the building and user behaviour) and real consumption data retrieved from the energy utilities. This chapter focusses on the prediction error regarding the energy use for space heating and domestic hot water. Statistical methods are combined with adapted EPB-calculations in order to identify the most important causes of these prediction errors.

2.2 Data set and statistical approach

2.2.1 Data collection

For this study, the Flemish Energy Agency (VEA) selected 1850 projects, based on the four following criteria:

- The study’s focus was on current building practice and high-performance buildings. Therefore, the theoretical primary-energy use had to meet at least the requirements for houses with building permits dating from 2012 or 2013.
- The housing units had to have their own individual heating system for real energy figures to be available on household level.
- They had to be inhabited for at least two years for meter readings to be available over at least one full, inhabited year.
- The dwellings’ EPB-files had to be free of any major error or shortcoming with regard to data (e.g. missing data) or with respect to regulatory compliance.

Three complementary data sources provided the necessary information:

- The governmental EPB-database provided technical data on the buildings and on their official, theoretical energy performance.
- Surveys of the households supplied additional data on the buildings as well as on the inhabitants, their behaviour, occupations and comfort appreciation.
- Meter readings from the energy utilities further completed this data set with real, measured consumption data.

VEA keeps one centralized database with data from the official EPB-files of all new buildings. That EPB-database does not contain the full inputs for the EPB-software (e.g. data on each wall). However, it contains some of the most important variables (e.g. the size of the building, the type of services, the average insulation levels) as well as the intermediate and final results of the energy performance calculation. Additionally, the database also holds administrative information (e.g. addresses, the date of the building permit). The preselection of the 1850 cases was based on data from this database.

The survey questions and strategy were developed by VEA together with a market research company. The printed questionnaires were sent by mail to the inhabitants. They could mail it back for free or use an internet-link to fill in the questionnaire online. One reminder was mailed after two weeks and participants could win a non-financial reward. Each participant had to respond to a large number of questions, either multiple choice or requiring numerical inputs (e.g. the number of inhabitants). These questions were selected from a list of 113 questions, depending on the participant’s house and household[1]. The surveys obtained a response rate of 29%, resulting in a total data set of 537 housing units.

Both for gas and electricity, only one consumption figure of approximately one year could be supplied for each house, due to their recent completion.

2.2.2 Data treatment

Filtering

A comparison of the data sources revealed a considerable amount of contradictions, indicating data errors or changes to the building after the completion and EPB-assessment. For example, while the EPB-database indicated the presence of PV panels in 15% of these houses, more recent installations of PV panels tripled the number to 45%. The surveys also revealed that since completion 9% of the houses already received additional thermal insulation. Furthermore, some houses were marked as ‘detached’ within the EPB-database but as ‘semi-detached’ by the inhabitants. This could be explained by later additions of neighbouring buildings. However, verifying all contradicting data and, if necessary, making a new EPB-calculation was beyond the reach of this project. Therefore, erroneous data and all derived variables that could not be corrected were marked as missing data and excluded from further analysis, however without rejecting non affected data or those cases as a whole.

The reliability of the real consumption data was also an important filtering criterion. For gas and electricity, precise consumption figures were available through the annual meter readings. However, for bulk energy resources (wood, pellets, coals, fuel oil and gas cylinders) no such accurate data were available. Therefore, 36 cases were removed from the final analyses on the heating energy use because they used bulk energy resources for space heating or domestic hot water. Additionally, a small number of cases had much less than one year between two meter readings, resulting for example in a period without winter months. These cases were also excluded from analyses on the real energy use and the prediction error.

Sub sampling

The dataset comprises houses with all possible combinations of types of systems (e.g. heat pumps, condensing boilers) and energy carriers (e.g. gas, electricity), for the different end uses (e.g. space heating, domestic hot water). Three subsamples were defined for specific, complementary analyses. Subsample S1 aims at analysing the total energy use and comprises all houses that use a combination of gas and electricity for all their end uses. Subsample S2, which is analysed in more detail within this chapter, was defined for the analysis of the energy use for space heating and domestic hot water. This subsample consists of houses with space heating and domestic hot water appliances based solely on gas while gas is not used for other end-uses such as cooking. Subsample S3 was defined to analyse the remaining, typically electrical energy use for plug loads and auxiliary services, e.g. fans and pumps. It consists of houses that do not use electricity for space heating or domestic hot water, but only for the remaining end uses.

Due to the shortcomings identified while filtering the data set, these subsamples were reduced from their original size of 350, 135 and 260 to 100, 75 and 150 cases, respectively. However, the analyses that did not require real energy use data could be performed on the full data set of 537 houses, except for occasional missing or erroneous data entries.

Normalization method

The study's focus was on the gap between theoretical and real consumption data. Before analysing the difference between both figures, these have to be normalized to comparable boundary conditions such as similar climatic data. The most common way to do this is to normalize the real energy use to the standard climatic conditions considered in the theoretical calculation method. For each end use a different normalization formula has to be used, considering for example a higher influence of climatic conditions on the space heating consumption compared with the domestic hot water consumption. This is especially important for high-performance houses compared with old houses, as the total energy use becomes more evenly balanced between space heating and the other end uses. However, only aggregated consumption figures were available (e.g. both space heating and domestic hot water systems connected to a single gas meter). Using regression methods to separate and normalize the energy uses was impossible, because data on real energy were provided for only one time period per dwelling. Furthermore, applying one common (e.g. degree-day based) formula on all the houses would neglect both the technical differences between the houses (e.g. insulation levels) as well as the behavioural differences between households (e.g. heating profiles).

To tackle these issues, the normalization procedure was inverted. The standardized EPB-calculation of each individual end use, was '(a)normalised' to coincide with the period and climatic conditions of the available, real energy figures. The local EPB-calculation method is a quasi-steady-state, monthly method, based on the international standard ISO 13790 [20]. The predicted energy use was thus calculated for each month of the real consumption period, using the corresponding monthly average outdoor temperatures and the monthly total and diffuse solar irradiation instead of standard climatic data. Data that were needed for the calculations but were not stored within the EPB-database were retrieved by inverse solving procedures, using the available inputs and the results from the official calculation.[2] Subsequently, the recalculated end uses were added per energy carrier to correspond with the aggregated real consumption data. The variation in climatic conditions and time spans between the separate cases was limited as, for most of them, the time period between both meter readings was approximately one year and included the same heating season. In order to make the energy use figures comparable, all reported analyses refer to values per year, obtained after dividing the energy figures by the number of days within the metering periods, times 365). The small remaining variation between the different cases in the average climatic conditions per consumption period was analysed (e.g. expressed in average or cumulated heating degree days or solar irradiation). The influence of this variation on the analysed energy figures (theoretical values, real values or the prediction error per year) proved to be of negligible size and non-significant.

2.2.3 Statistical analysis methods

Statistical analyses on the data were conducted with SPSS. All reported probability values assume a two-tailed distribution and, when applicable, are calculated using the 'exact statistics' or Monte-Carlo methods. Fisher's Exact Probability values (p) were supplemented with odds ratios (OR) for associations between two binary variables. Cramer's V (V) was used for associations between binary and categorical variables. When the necessary assumptions were fulfilled for continuous variables, parametric tests were used. Normality requirements were tested by analysing histograms and Q-Q plots visually and by verifying skewness and kurtosis values as well as results from Shapiro-Wilk tests. Non-normality was an issue for several technical and calculated performance parameters. Firstly, minimal governmental requirements and incentives at specified performance levels resulted in truncated and multimodal distributions, similar to those found on the full EPB-database [81,82]. Secondly, the selection procedure focused on buildings with high performance and thus at one tail of the performance distribution of new houses, resulting in a truncated distribution. Thirdly, the choice between accurate or default values for certain input parameters within the EPB-calculation caused several variables not only to be bimodal, but also not to be continuous. Therefore, these parameters were first studied based on their underlying dichotomous variable (the use of default or detailed/measured values). When needed and sufficient to meet the normality assumptions, logarithmic or square root transformations were used. Subsequently, occasional outliers were investigated. Only very few of them proved to come from erroneous data and were therefore removed. Levene's tests were used to verify homogeneity of variance between samples in t-tests and analysis of variance (ANOVA) tests. When parametric assumptions were still not met, parametric tests were replaced by their non-parametric, rank based alternatives. Mann-Whitney U-tests (U), Kruskal-Wallis tests (H), and Kendall's 'tau b' (τ_b) replaced independent t-tests (t), ANOVA-tests (F) and Pearson's correlations (r), respectively. Parametric tests are more commonly used and often easier to evaluate, but they can require data transformations to meet the parametric assumptions, making the interpretation of the results more complicated. Therefore, results from bootstrapped parametric tests on data without transformations are reported if they were confirmed by both the non-parametric tests and the parametric tests on transformed variables. More specifically, bias-corrected and accelerated bootstrapping (BCa) provided the 95% confidence intervals (95% CI) for both parametric and non-parametric tests [83–85]. These confidence intervals are important as they can be relatively large due to the limited sample size and the large variations within the sample.

Additionally, parametric, partial correlations and multiple-factor ANOVA and analysis of covariance (ANCOVA) tests were performed. These factorial analyses allow improving or verifying the analysis on one variable, after controlling for the other influencing variables and interactions simultaneously.

For most combinations of parameters, the factorial analyses did not influence the findings. In those cases, for reasons of brevity and readability, only the results from the single-factor analyses are reported. Compared with these simplified, linear models however, the real interactions between parameters can be more complex. Furthermore, the analysis might lose power as the number of independent variables increases while the data set remains of limited size [86–88]. In response, parameters that appeared to be important were corrected or neutralized within a new, corrected EPB-calculation, before pursuing further statistical analysis on subsequent parameters. Additionally, this allowed checking hypotheses on the causes of identified statistical associations lying within the calculation procedure. This will be further illustrated in the results. In the last result-section, the most important variables are combined in regression models. For each model, the (unstandardized) regression coefficients (B) and their confidence intervals are complemented with the standardized coefficients (β) and partial correlations.

2.2.4 Data set description

Detached houses are overrepresented in this data set compared with the full set of houses built in Flanders since 2006, as reported in the EPB-database (Table 2.1). With an average gross floor area of 257m² (median (Mdn) = 248m²), the studied houses are also larger. Detached houses are on average larger, explaining part of the average size difference. However, it is mainly the semi-detached and terraced houses within the data set that are atypically large (Table 2.1) [82].

Table 2.1: Distribution of housing typologies and building sizes showing the overrepresentation of large, detached houses compared with the full EPB-database (newly built houses between 2006 and 2010, N=43 336 total including apartments, N=23 401 only single family houses)

	Detached	**Semi-detached**	**Terraced**	**Apart-ments**
Occurrence				
EPB-database: total	26%	20%	8%	45%
EPB-database: single-fam. h.	48%	37%	15%	-
Data sample	68%	28%	4%	-
Median floor area				
EPB-database: single-fam. h.	250 m²	185 m²	170 m²	-
Data sample	258 m²	225 m²	229 m²	-

A total of 83% of the houses within the sample have a mechanical, balanced ventilation system with heat recovery, 33% have heat pumps and 45% have PV panels. While these numbers are not representative at all of current standard built houses, let alone standard practice two or more years ago, these numbers are representative for Flemish houses with similar primary-energy performance levels [81].

Almost all the households own their respective houses (99%) and were responsible for commissioning the builders to construct them (99%). The number of inhabitants and their age show these are mainly young households (Figure 2.1 and Figure 2.2). They are mainly from the middle class. The heads of the families have a good level of education, with 66% having at least one higher-education degree. This percentage is approximately double that of the whole Flemish region [89]. Furthermore, only two heads of the family were unemployed (0.4%), only 5% are retired and there are more company executives (15%) than workmen (13%). The median net available household income lies in the range € 3500-3999 per month.

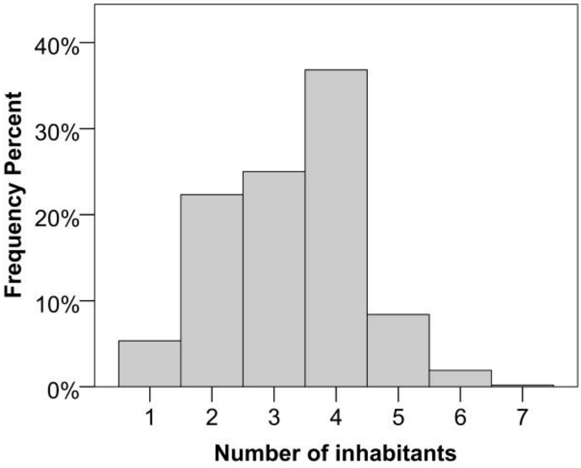

Figure 2.1: Number of inhabitants

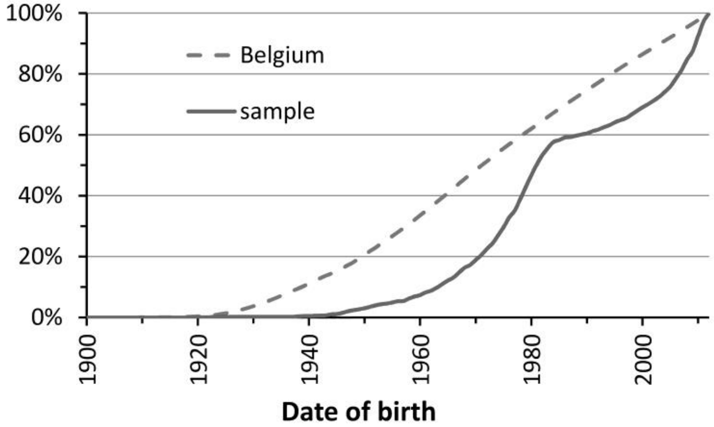

Figure 2.2: Age distribution of all inhabitants (date of birth): clustered differentiation between parents and children

2.3 Results

2.3.1 Energy uses and prediction errors

The official energy performance label, the E-level, proved to be a significant indicator for the total operational energy use according to subsample S1. However, the association was only moderate ($\tau = .24$, 95% CI [.10, .36], $p < .001$) and mainly due to the occurrence of PV panels. When looking only at cases without PV panels, no significant association was found between real energy use and performance label. This corroborates findings in the Netherlands [74] and is partly explained by the definition of the E-level label that is based on the size and shape of the building. Therefore, further comparisons are made between real and theoretical energy figures directly. Figure 2.3 compares the annual, real and theoretical energy uses for the three subsamples, expressed in their primary-energy equivalent. While the cases within the different subsamples are not all the same, the total energy use from subsample S1 in Figure 2.3 can be approximately considered as the sum of the heating energy use from subsample S2 (for space heating and domestic hot water) and the remaining electricity use from subsample S3. On average, the real energy use for heating is higher than the electricity use, notwithstanding the low-energy design of the houses and the primary-energy conversion factor of 2.5 for electricity. However, the average difference is much smaller than suggested by the theoretical values. On the one hand, the EPB-calculation underestimates the electricity use because it does not take the unregulated end uses into account (cooking, lighting and domestic electrical appliances). On the other hand, it overestimates the heating energy use by on average 25%. The real and theoretical values for heating were strongly, positively correlated ($r = .634$ 95% CI [.423, .775], $p < .001$, after logarithmic transformation of both variables). However, the lack of fit is shown not only by the average overestimation of the energy use (Figure 2.3), but also by the large spread in prediction error, reaching from the highest overestimation of 68% to a few underestimations of maximum 47% (Figure 2.4). Subsample S2 is discussed in more detail below, looking further into the causes of the varying prediction errors. These errors are defined as the real energy use minus the theoretical values. Therefore, an overestimation in calculation results in a negative value. The relative prediction errors are expressed as a percentage of the theoretical energy use.

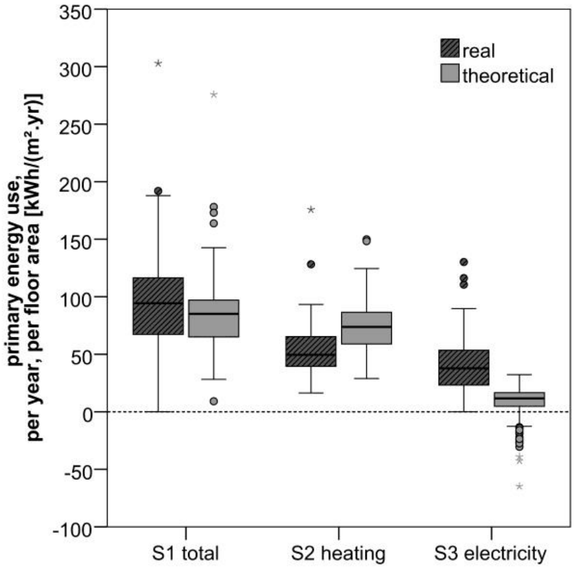

Figure 2.3: Yearly primary-energy use per gross floor area [kWh/(m².year)]: real and theoretical values for each subsample (open dots and stars indicate respectively mild and extreme outliers, lying past the upper or lower quartile by more than respectively 1.5 and 3 times the interquartile range)

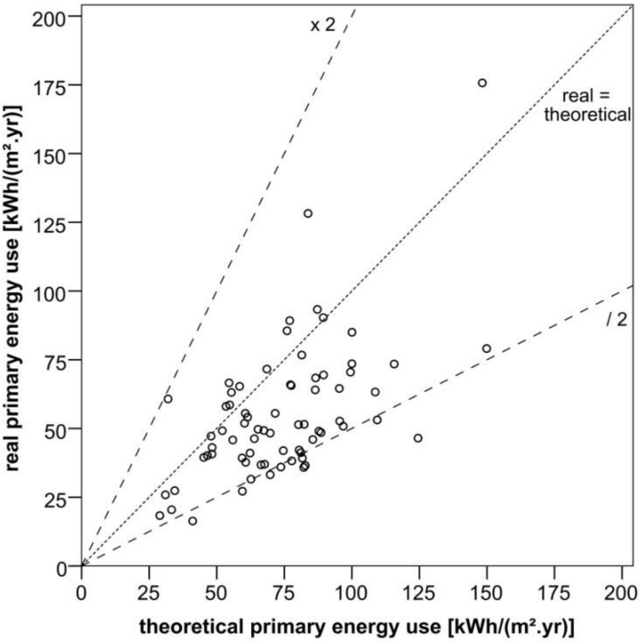

Figure 2.4: Yearly primary-energy use for space heating and domestic hot water (subsample S2), per gross floor area [kWh/(m².year)]: real and theoretical values

2.3.2 Heating and domestic hot water

In order to investigate the error in calculated heating and domestic hot water energy use, various parameters were analysed that were considered as potential explanatory variables. First, geometrical parameters were considered, such as the building volume, floor area, heat loss area and window area. Additionally, reported thermal properties of the building envelope were investigated, ranging from average insulation values to air permeability values and glazing properties. Reported characteristics on the building services completed the included parameters from the EPB-database (the type of ventilation system, the reported system efficiencies). The surveys added parameters regarding the demographics (e.g. age) or behaviours of the inhabitants. The latter comprise figures on daily presence within the house, on the opening of windows and on heating profiles per room type (number of heating hours and heating set points). From the analyses, four parameters were identified as very significantly associated with the prediction error. Three of them are related to building characteristics and their implementation within the EPB-calculation procedure: the reported air tightness of the building envelope, the reported characteristics of the space heating system and the formula for calculating the net domestic hot water consumption. Only one is strictly user related: the heating profile of the bedrooms.

Reported air tightness

Within the Flemish EPB-method, the infiltration heat losses are calculated based on the air permeability of the envelope. This is expressed as a v50-value giving the volume flow rate of air infiltration at 50Pa pressure difference normalized by the heat loss area. While not compulsory, a measured value can be input to the software based on a pressurization test performed after completion of the building. In the absence of a measured value, a default value of 12 $m^3/(h.m^2)$ is used within the calculation of the energy use for space heating. As shown in Figure 2.5, the average overestimation of the energy use proved to be the largest for calculations using the default value, with a mean difference in relative prediction error of 24.0% (95% CI [10.0%, 39.5%], $t(69) = 3.71$, $p < .001$). While a significant part of the cases with measured values have a higher real than theoretical energy use, the EPB-calculation overestimates the energy use in almost all the cases with default values. This indicates that the default value overestimates the real air permeability of the houses without reported, measured values. This corroborates the most recent studies on the air tightness of Belgian houses [90] and appears credible considering the strong dichotomy between the default value and the measured values within this sample (Mdn = 2.6 $m^3/(h.m^2)$) (Figure 2.6).

The relative importance of the reported air permeability is partly explained by the specific sample considered. Firstly, as these are well insulated buildings with most having a balanced ventilation system with heat recovery, the infiltration heat losses take an increased share of the total heat loss. Secondly, as the air permeability is expressed per square metre of heat loss area, any difference from the true permeability is magnified in the calculation of the infiltration rate because of the substantial envelope area of these large, mainly detached houses. Indeed, the heat loss area of the houses was also correlated with the prediction error ($\tau = -.18$, 95% CI [-.33, -.04], $p = .024$). The EPB-calculation was corrected using a lower default value before statistical analyses on additional parameters. Lowering the default value from 12 to 6 m³/(h.m²) made the difference in prediction error between the groups with and without measured air permeability much smaller, though still just below the significance value of 0.05. Neglecting all infiltration heat losses made the difference disappear. However, part of the association could be caused by indirectly associated variables. To reduce the risk of overcorrection, the more realistic default value of 6 m³/(h.m²) was used for further analyses.

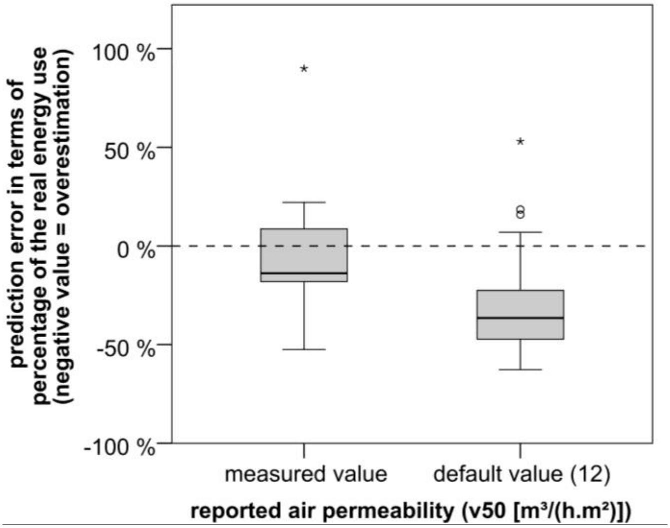

Figure 2.5: Effect of the reported air permeability on the gap between real and predicted heating energy use

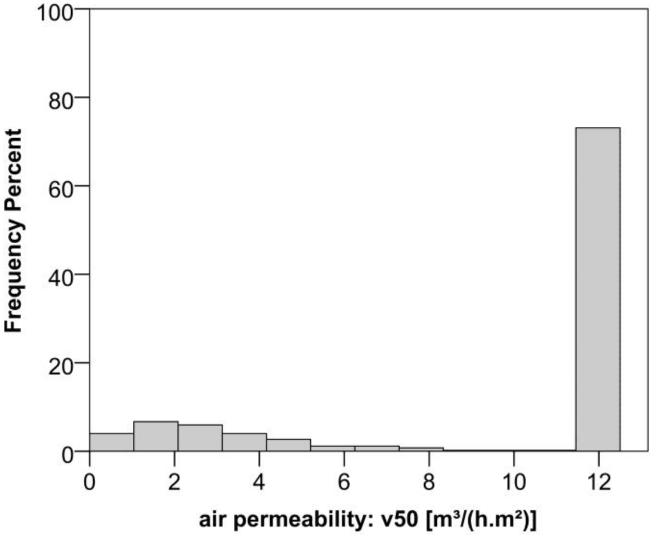

Figure 2.6: Reported air permeability, taken into account in the calculation (v50 in [m³/(h.m²)]): high occurrence of the default value (12m³/(h.m²)) and much lower measured values

Characteristics of the space heating system

The efficiency of gas boilers depends not only on the boiler characteristics, but also on the installation and settings of the whole heating system. The return water temperature of the system has a large effect on the efficiency of condensing boilers. The EPB-method assumes a simplified, linear relationship between boiler efficiency and return temperature. In a similar approach to air permeability, the EPB-assessor can either input the real design return-temperature, corroborated by a calculation of the system's sizing, or use a default value. The default value depends on the type of emission system: 45°C for surface heating systems (floor, ceiling or wall heating) and 70°C for any other system (including radiators and air heating).

A similar observation was made regarding the default value for the air permeability values: the overestimation of the heating energy use was higher for cases using the default return temperature of 70°C (absolute prediction error: $t(69) = 3.60$, $p = .001$, mean difference = 3682 kWh/year, 95% CI [1658, 5740]) (relative prediction error: $t(69) = 3.02$, $p = .007$, mean difference = 19.0%, 95% CI [7.1%, 31.6%]). This was confirmed by comparing the cases with detailed values and the cases with the two different default values for the return temperature, using both one-to-one comparisons (Mann-Whitney U-tests and t-tests) and different *post-hoc* tests on bootstrapped ANOVA-tests (Tamhane, Dunnett T3 and Games-Howell tests). Consequently, the theoretical efficiencies of the gas boilers, calculated using those return temperatures, were also significantly and positively correlated with both the absolute prediction error (τ = .29, 95% CI [.16, .41], p = .001) and the relative prediction error (τ = .26, 95% CI [.11, .39], p = .002): lower efficiencies coincide with larger overestimations. Lower heat production efficiencies will amplify any overestimation of the net heating energy use when translated into final energy use. This by itself can explain the correlation with the absolute prediction error. However, the correlation with the relative overestimation suggests there are additional causes.

The fixed default values could be the culprit, in a similar way as with the reported air permeability. Indeed, using the ‘safe' default value of 70°C does not necessarily mean that the return temperature is that much higher in reality, thus possibly causing a reporting bias. The error can also result from the linear formula used to calculate the efficiency. In fact, the relationship between return temperature and efficiency becomes non-linear below the dew point of the flue gases [91]. On the other hand, the association between the return temperature and the prediction error might have nothing to do with the heat production efficiency, but rather with the distribution or emission efficiency. The different emission systems (e.g. radiators, air heating and floor heating) often require different return temperatures. Therefore, any difference between emission systems that are not (correctly) taken into account in the EPB-calculation might result in an association between calculation errors and return temperatures or derived efficiencies. The thermal inertia of the heating systems for example, is not taken into account in the EPB-calculation. The available data set did not allow further investigation into these hypotheses, but other studies focusing on heating system efficiencies confirm the importance of intermittency, emission systems, sizing and thermal inertia on the total efficiency of heating systems, while these are not taken into account in the EPB-calculation [92–94].

Space heating profiles

Within the EPB-method, space heating is calculated based on a single-zone model. However, different heating profiles occur in different rooms. Information on the space heating profiles was reported in the surveys for each individual room type (living room, kitchen, circulation area, bathroom, toilet, master bedroom, additional bedrooms, garage, attic, basement, office, play room). If that room type were present in the house, the respondents had to state whether it was heated during winter or not. If so, they were asked for the number of heating hours and for an estimate of the set point temperature. No significant correlations were found between the prediction error or the real energy use on the one hand and, on the other hand, the heating set points of any of the rooms. No correlation was found either with the number of heating hours in the living room, the bathroom or the circulation area. Only the heating profiles of the master bedroom proved to be associated with the prediction gap, with an increasing overestimation of the energy use as the number of actual heating hours is reduced (τ = .26, 95% CI [.06, .43], p = .006). As with the previous parameters, the association could be reduced to a simpler dichotomous variable, distinguishing those who do not switch the heater on in their master bedroom at all from those who do (t(68) = -2.68, p = .010, mean difference = -3006 kWh/year, 95% CI [-5365, -714]).

Domestic hot water

The surveys provided the weekly number of baths and showers and the average duration of the showers. No association was found between the consumption data (real values or prediction errors) and any of these inputs, not even when adding up the number of baths and showers and weighing these figures based on the durations of the showers and the average higher consumption of baths. However, the volume of the building proved to influence the prediction error due to the fact that it is being used as a parameter in the calculation of the domestic hot water consumption. In the EPB-method, the volume of the building is considered to be an indicator for the number of inhabitants and therefore the domestic hot water consumption is expressed as a linear function of the building volume. While the direct correlation between the building volume and the prediction error was only significant at a level of $p < .05$, the significance increased after correcting for one or more of the three influential parameters discussed in the previous sections, in a partial correlation ($r_{partial} = -.355$, 95% CI [-.562, -.101], $p = .003$, corrected for the reported air tightness and return temperature and for the bedroom heating). This association could also be attributed to other (indirect) causes. After all, the building volume is also included in the calculation of the ventilation heat losses and, through its geometrical link with the size of the building envelope, it is also associated with the transmission and infiltration heat losses. However, it was only when removing the volume from the calculation of the domestic hot water that its association with the calculation error totally disappeared, while all other associations reported in this chapter remained. These tests were done either by entirely removing the volume terms ($V = 0\ m^3$) or by replacing them by the median of the volumes found in the data set. The error caused by the volume-based calculation is not surprising, as the data set contains a considerable number of large houses, while no correlation was found between the volume of the houses and any available parameter that was expected to influence the domestic hot water consumption (e.g. the number of inhabitants or the number of baths and showers).

Combined regression models

Only 39% of the variation in real energy use was predicted by the variation in theoretical energy use. This was deduced from a first, simple linear regression model with only one predictor, the theoretical energy use (Table 2.2, adjusted $R^2 = .39$). To see how much of the variation in the remaining prediction error could be explained by the four most influential parameters, these were combined into a second regression model, with the prediction error as the dependent variable. The four identified explanatory characteristics were implemented in the model: the reported air permeability, the reported return temperature of the heating system, the heating of the master bedroom and the volume of the building. The three first parameters were implemented by means of their underlying dichotomous variable, formulated in three questions with the answers ‘yes’ and ‘no’ equalling 1 and 0, respectively. Was the air permeability measured? Was the default return temperature of 70°C used? Is the master bedroom heated? Together, their variation explained 38% of the variation in prediction error of the original EPB-calculation, with the use of a measured air permeability being the most influential predictor within the regression (Table 2.3). The prediction error could be reduced by correcting the calculation itself, using a more realistic default air permeability value of 6 instead of 12 $m^3/(h.m^2)$ and considering the same net domestic hot water consumption for everyone, based on the median of the sample's building volumes instead of each individual volume. The prediction error of this corrected calculation was analysed in a third model, with only two remaining predictors: the reported return temperature and the bedroom heating profile. These explained 23% of the remaining prediction error (Table 2.4).

Combining the same four parameters together with the theoretical energy use into a fourth regression model should enable more accurate predictions. However, collinearity issues between the volumes of the buildings and their theoretical energy use made it impossible to obtain a good linear model with all parameters implemented as individual predictors. As an alternative, the original calculation was replaced by the same corrected calculation used in the third model. 58% of the variation in real energy use is explained by this fourth regression model, based on three explanatory variables: the corrected calculated energy use, the reported return temperature and the heating of the bedrooms (Table 2.5). Regression diagnostics, discussed in the endnote[3] of this chapter, asserted the validity of the models, checking for possible autocorrelation and multicollinearity problems and analysing the effect of outliers [95]. Notwithstanding the improvement over the first model, the ability of the last model to predict the real energy use is still limited.

Table 2.2: Regression model 1: prediction accuracy of the original EPB-calculation for space heating and domestic hot water

	B*	**95% CI***	**β**	**p***	**partial corr.**
(Constant)	0.993	[0.003, 2.211]	(-)	.033	(-)
LOG10(EPB-calculation)	0.732	[0.464, 0.957]	.634	<.001	.634

Notes: N = 71, R^2 = .40, adjusted R^2 = .39, * = Bootstrapped values
Dependent variable = LOG10(real energy use)

Table 2.3: Regression model 2: explaining the prediction error of the original EPB-calculation for space heating and domestic hot water

	B*	**95% CI***	**β**	**p***	**partial corr.**
(Constant)	1430.45	[−4228.85, 6889.65]	(-)	.561	(-)
v50: measured?	4514.16	[2521.50, 6507.51]	.408	<.001	.464
building volume	−8.871	[−15.205, −2.552]	−.294	.003	−.355
return temperature: 70°C?	−3068.68	[−5199.20, −920.99]	−.302	.003	−.363
bedroom: heated?	2694.12	[822.35, 4865.73]	.263	.007	.324

Notes: N = 70, $R^2 = .42$, adjusted $R^2 = .38$, * = Bootstrapped values
Dependent variable = prediction error of the original EPB-calculation

Table 2.4: Regression model 3: explaining the prediction error of the adapted EPB-calculation for space heating and domestic hot water

	B*	**95% CI***	**β**	**p***	**partial corr.**
(Constant)	−2312.78	[−3593.31, −920.60]	(-)	<.001	(-)
return temperature: 70°C?	−3254.77	[−5040.07, −1326.21]	−.367	<.001	−.389
bedroom: heated?	2726.72	[923.69, 4554.19]	.305	.006	.331

Notes: N = 70, $R^2 = .25$, adjusted $R^2 = .23$, * = Bootstrapped values
Dependent variable = prediction error of the calculation, with default $v50=6m^3/(h.m^2)$ and domestic hot water calculated with the median building volume

Table 2.5: Regression model 4 : combined prediction accuracy of the adapted EPB-calculation for space heating and domestic hot water, with two additional predictors

	B*	**95% CI***	**β**	**p***	**partial corr.**
(Constant)	−0.651	[−1.540, 0.598]	(-)	.201	(-)
LOG10(adapted calculation: default $v50=6m^3/(h.m^2)$; V=Mdn)	1.133	[0.845, 1.339]	.755	<.001	.756
return temperature: 70°C?	−0.083	[−0.138, 0.029]	−.231	.006	−.331
bedroom: heated?	0.078	[0.024, 0.131]	.217	.008	.320

Notes: N = 70, R^2 = .59, adjusted R^2 = .58, * = Bootstrapped values
Dependent variable = LOG10(real energy use)

2.4 Discussion

2.4.1 Comparison with findings from literature

The lack of association between the real energy use and the dimensionless energy performance label (E-level) observed in this study was also found in the Netherlands with regards to the similar, Dutch performance label [74]. Directly comparing the real and calculated energy figures, the average overestimation of the real energy use in these high-performance houses is 25%. This overestimation is smaller than what was found in previous studies on older houses in Belgium and pursues the shortfall trend identified in those studies [31,96]. Similar shortfall were also found in other countries. However, in the Netherlands and Germany, the overestimation was shown not only to diminish, but also to turn into an underestimation of the real energy use when looking at high-performance houses [29,32].

Previous statistical studies looking at the real energy use indicated that, while user behaviour had a significant impact on the consumption, the building parameters still prevailed in explaining the variation in real energy use [29,31,32,74]. This study extends these findings to the prediction error. Many technical parameters regarding the building envelope and services are already taken into account in the calculation method, while user behaviour is simplified into one standard user profile. However, the technical parameters still prevail in explaining the prediction error, due to simplifications within the calculation method and within the assessment procedures, such as the use of default values. This corroborates with findings from the Netherlands [97], where statistical analyses revealed a similar correlation between system efficiencies and prediction errors and sensitivity analyses emphasized the importance of accurate knowledge on the technical properties of the buildings.

The only important behavioural parameter identified in this study was the heating of the bedrooms. Guerra-Santin & Itard [47] also identified the heating of the bedrooms as one of the most influential behavioural parameters, however complemented with additional behavioural parameters such as the number of heating hours in the different rooms and the opening of trickle ventilators and windows. Furthermore, they also identified the number of showers as significant parameters for the total gas consumption.

2.4.2 Significance, the lack of it and causality

Several parameters were not found to influence significantly the prediction error although they were expected to be important. One important example is the heating profile in the living room, including both heating set points and daily heating hours. The good insulation levels and energy efficient ventilation systems can explain why the heating profile in the living room has little influence on the energy use in these houses. The higher the thermal time constants, the lower the effect of heating setback. However, the lack of significant correlation does not prove these parameters are negligible. Firstly, the lower the space heating consumption, the higher also the relative importance of domestic hot water consumption on the total energy use and thus on the total variation in prediction errors, therefore obfuscating variations related to the space heating. Secondly, existing effects can also be obfuscated by response errors in surveys. These errors can be considerable, especially regarding quantitative values. Uncertainties about individual, reported set point temperatures can for example be large compared with the real variations between cases [51,52,98]. Thirdly, the absence of significant correlations could be explained by the reduced sample size, limiting the power of the statistical analysis for identifying large numbers of significant parameters and reaching reduced confidence intervals. The reduction of the sample size was due to errors and contradictions in the data set, identified thanks to the redundancy between data from the EPB-database and from the surveys.

As opposed to the absence of expected correlation, there is also a risk of finding a correlation that is due to an external, confounding factor or amplified by a secondary correlation. This risk is even extended to the use of the calculation tool by the EPB-assessor, depending on his thoroughness. For example, measured air tightness levels were much more likely to be reported in timber frame buildings (Table 2.6). Assessors who used measured air tightness levels were also much more likely to apply measured values instead of default values in other parts of the calculation, for example for the lengths of the hot water tubes and the window shading angles (Table 2.6). Therefore, the difference in prediction error associated with the use of default air tightness values might be amplified by these other parameters and might not only be due to the real air permeability being lower than the default value. Indeed, better reported performance levels are not only the consequence of better buildings but also of more thorough EPB-assessors. This is illustrated by the fact that assessments of (nearly) passive[4] and very well insulated houses[4] are more likely to use detailed window shading angles in the calculation (Table 2.6).

Table 2.6: Significance and causality: underpinning statistics

		N	**p**	**OR**	**95% CI**
measured air tightness: Y/N	light weight construction: Y/N	506	< .001	4.15	[2.01, 8.95]
" measured air tightness: Y/N	detailed tubing lengths	491	.001	11.95	[5.28, 12.72]
" measured air tightness: Y/N	detailed window shading	491	.018	2.20	[1.09, 4.35]
(nearly) passive: Y/N	*" detailed window shading*	489	.005	4.32	[0.86, 12.94]
very well insulated: Y/N	*" detailed window shading*	490	.007	3.10	[1.26, 6.28]

Notes: OR = odds ratios, df = 1, significance value p = Fisher's exact probability, confidence intervals provided by BCa bootstrapping.

2.4.3 Standardization within energy labelling and prediction tools

A large part of the prediction error and of its variation was due to the freedom of choice between default and measured values as input for the calculation, especially for the air tightness of the building envelope. The default air permeability was originally based on test data on houses obtained before the launch of the EPB-regulations in Flanders [99]. A conservative value was selected in order to encourage better construction quality, supported by measurements on air tightness. However, most of the recent new-built houses, especially low-energy houses, have become much more air tight [90]. Additionally, as insulation levels and ventilation systems have improved, air infiltration takes a larger share within the overall heat loss of buildings. As a result, accurate knowledge of the air permeability of buildings becomes more important. Choosing more realistic default values can help bridging the prediction gap. However, this would oppose itself to the role of conservative default values, namely to admonish building teams to perform better and to verify their results, by rewarding these efforts through better energy labels based on measured values. Furthermore, more positive default values could even result in some kind of impunity for those buildings that really do perform badly.

The realistic estimation of user behaviour is an even more complex challenge within energy performance regulations. The problem is not only to define which user profile to consider as a standard one. The contradiction there lies between, on the one hand, defining one default user behaviour to enable comparison of energy labels and, on the other hand, delivering accurate, personalized predictions on energy use to the inhabitants and investors. Furthermore, implementing personalized, zonal differentiation (e.g. different profiles in bedrooms, bathrooms and living rooms) is in contradiction with the single zone calculation of the official method and the resulting, simplified geometrical input.

A single calculation procedure cannot be optimal both for performance assessment within a regulatory and policy framework and for accurate prediction of the energy use of a specific household. Indeed, these can become conflicting aims when defining user profiles and default values. However, conscious modelling choices and increased knowledge about the building characteristics can already considerably reduce the gap between theoretical figures from the assessment procedure and real energy figures. Furthermore, the workload for performing both types of calculations could be lowered drastically by embedding them both in the same calculation tool, sharing required inputs and algorithms, however with different default values and allowing additional inputs such as personalized user profiles.

2.4.4 Representativeness, selection and response biases

Before extrapolating the study's findings to other cases or for policy making, one has to consider possible selection and non-response biases. The study aimed at exploring the prediction error for high-performance houses in general. However, as put forward in the case description, this set of mainly large, detached houses and young families, having the means to build these well-equipped, high-performance houses, is not representative for the whole Flemish population. Furthermore, the extensive survey obtained not only a low total response rate of 29%, but also the response rates were significantly larger for builders of high-performance houses (lower E-levels), as shown in Table 2.7 (χ^2 (3, N =1850) = 25.07, p <.001, V = .12). The concern of looking at a sample of deliberate low-energy builders, being more conscious about energy use and acting accordingly, seemed strengthened by the surveys. Not only did better (lower) E-levels correspond with higher response rates, but also with more respondents reporting themselves as 'very frugal, doing anything they can to lower their energy use' (Mdn = 51, 95% CI [49, 55], N = 75), compared with others (Mdn = 59, 95% CI [57, 60], N = 413) (U = 11932.50, z = -4.49, p <.001). The inhabitants of (nearly) passive houses[4] were the most eager to evaluate themselves as very frugal, even more so than inhabitants of very well insulated houses[4] in general (Table 2.8). Whether or not they really are more frugal than others is hard to assess, but they were less likely to own energy-guzzling equipment such as a tumble dryer and more likely to own hot fill dishwashers or washing machines instead of purely electrical ones (Table 2.8). The reported willingness to participate in further studies (62%) was double the original response rate and only tells something about those who already participated, voluntarily, to this study. Interestingly however, the willingness was the highest for people in a light weight (timber frame) building (Table 2.8). Timber frame constructions are becoming more popular in Belgium, despite a tradition of masonry in the Belgian house building sector. Ecological reasons and the possibility of putting (part of) larger insulation thicknesses within the construction thickness have increased the popularity of timber frame construction in the more engaged market. Indeed, lightweight, timber-frame constructions are heavily overrepresented within the (nearly) passive house[4] and very well insulated[4] subsamples (Table 2.8).

The above findings do not prove any selection or non-response bias of the study's findings. However, they indicate there is a risk of such bias [100] and that the complex link between the building and the user related variables will make it even harder to investigate causalities. This also obliges us to be cautious about possible extrapolations, while stressing the need for further investigations and additional studies.

Table 2.7: Response rate to the survey, suggesting a sample of motivated low-energy builders

	≤ E40	**E40-E50**	**E50-E60**	**E60-E70**	**TOTAL**
Contacted	167	241	611	833	1850
Participated	70	86	183	199	537
Response-rate	42%	36%	30%	24%	29%

Table 2.8: Representativeness, selection and response bias: underpinning statistics

		N	p	OR	95% CI
(nearly) passive: Y/N	auto-evaluation: very frugal/less	519	< .001	4.54	[1.94, 10.52]
very well insulated: Y/N	*" auto-evaluation: very frugal/less*	518	.004	2.76	[1.34, 5.20]
(nearly) passive: Y/N	tumble dryer: Y/N	522	< .001	4.57	[1.52, 24.19]
very well insulated: Y/N	*" tumble dryer: Y/N*	518	.007	2.29	[1.30, 4.20]
(nearly) passive: Y/N	hot fill cleaning equipment: Y/N	512	.010	4.08	[0.56, 14.85]
very well insulated: Y/N	*" hot fill cleaning equipment: Y/N*	511	.006	3.40	[1.38, 6.86]
light weight construction: Y/N	agrees to further studies: Y/N	506	.016	2.59	[1.32, 6.44]
(nearly) passive: Y/N	light weight construction: Y/N	504	< .001	21.73	[8.85, 58.85]
very well insulated: Y/N	*" light weight construction: Y/N*	505	< .001	8.84	[4.05, 18.86]

Notes: OR = odds ratios, df = 1, significance value p = Fisher's exact probability, confidence intervals provided by BCa bootstrapping.

2.5 Conclusions

This study investigated the relation between real and predicted energy use in low-energy houses in Flanders, Belgium. This focus on new, low-energy houses, together with the survey approach, led to a sample of mainly young families living in large, detached, high-performance houses. Their total, real energy use was slightly underestimated by the regulatory EPB-calculations due to the electricity use for lighting and domestic appliances which are not considered in the EPB-regulation. On the contrary, the gas consumption for space heating and domestic hot water was strongly correlated with the theoretical values, but it was overestimated by the calculation by on average 25%. Additionally, the prediction error for space and water heating varied greatly from one case to the other.

Significant correlations were found between building parameters, household parameters and prediction errors for space and water heating, notwithstanding the limited sample size. This was achieved by iterations between statistical analyses and model corrections, based on subsequent findings. Whether the master bedroom was heated or not was the only behavioural parameter that was significantly correlated with the prediction error. The additional influential parameters were related to the EPB-formulas or the assessment procedure. The prediction error was correlated with the building volume due to the EPB-formulas that assume a linear relationship between the building volume and the net domestic hot water consumption. Furthermore, the use of default values both for the air permeability of the envelope and for the return water temperature of the heating system proved to be strongly associated with the absolute and relative prediction errors. Adding to this, EPB-calculations performed with measured instead of default values for one parameter were also more likely to use more detailed and project-specific input data for other parameters as well, resulting in a better theoretical performance. Not only does this explain the high, partly indirect correlation that can be found between the prediction error and one parameter for which a default value can be chosen. It also stresses the influence the EPB-assessor has on the reported energy performance. These findings demonstrate the opposing purposes of technical and behavioural default values within the official calculation method. For calculations of energy labels, within a policy framework, a balance must be found between realistic default values resulting in better predictions of the real energy use on the one hand and, on the other hand, conservative default values, inciting building teams towards better design, workmanship and measured quality control. For calculations aiming at accurate predictions of energy use in low energy houses, it is crucial to have accurate knowledge of the input data, if not through measurements of the specific building or information on the user profiles, than at least through realistic (default) values from literature.

This study’s findings stress the need for additional investigations into the accuracy of official energy performance calculations, encompassing the full complexity of both the real energy use and of the regulatory framework. In order to reduce the prediction error, additional knowledge is needed about its causes, ranging from technical parameters to behavioural parameters and from calculation formulas to default values and the workflow of the EPB-assessors. To achieve this, analyses will have to supplement the EPB-database with enough complementary data such as measurements on-site and thorough surveys.

2.6 Endnotes

[1] Depending on the specific building and household, the respondent was guided through the survey and communicated to which following question he could directly go (e.g. avoiding questions about secondary heating systems if he reported only one system). In the online questionnaire this personalized filtering happened automatically. Nevertheless, 59% of the participants chose the paper approach. The questions were subdivided in thematic sections. After a first section on housing typology and household composition, the second section aimed at linking the different energy sources (e.g. electricity, gas) to the different end uses (e.g. space heating, domestic hot water). Subsequently, each of the end-uses was treated in one separate section, with an emphasis on the end uses included in the EPB-calculation. These sections contained both technical and behavioural questions. The last, smaller sections gathered mainly data on changes to the building and privacy-sensitive information (e.g. financial information).

[2] The EPB-database contains all theoretical, monthly, primary energy uses, but does not include important underlying parameters. For each house, the heat loss coefficients and thus the monthly heat losses were recalculated exactly according to the official formulas based on the parameters available in the database: total heat loss areas, average U-values, technical properties of the ventilation systems and building volumes. Similarly, the thermal time constants were recalculated based on the size of the building and the construction type. Retrieving the case-specific, monthly ratio between solar irradiance and solar heat gains required an inverse solving procedure based on the recalculated, monthly heat losses, internal heat gains, time constants and the net heating demand. While the monthly values of the net heating demand were not available, these could be back-calculated starting from the available primary energy figures, system and generation efficiencies and primary energy conversion factors. Similar approaches were used for all end uses included in the EPB-method, combining intermediate, bottom-up and top-down recalculations of fixed and monthly values, based on the official formulas. This allowed replacing the standard, monthly climatic data of the EPB-method with the real, monthly climatic data of the metering period without making important, disputable assumptions or simplifications.

[3] The presence of autocorrelation was unlikely for any of the four reported regression models, with Durbin-Watson numbers between 1.837 and 2.033. Multicollinearity problems did not seem to occur, considering the good variance inflation numbers (VIF) (the highest VIF being 1.065), and looking at the condition indices and variance proportions. A limited number of outliers were identified. All Cook's distances within each model were well below 1 and all cases within model 2 or 3 were below twice the leverage value. However, four cases within model 1 and one case within model 4 exceeded three times the leverage value. Additionally, the standardized residuals showed a common outlier for models 2 and 3. Looking further at the standardized DFFIT and DFBETA values, respectively 3, 3, 2 and 1 cases had a higher influence on

models 1, 2, 3 and 4. To assess this influence, the regression analyses were calculated again without these cases, but the results did not change meaningfully. All parameters remained significant and the new regression coefficients still lay around the middle of their original bootstrap confidence intervals. Indeed, some outliers compensated for each other's influence, as indicated by both positive and negative DFBETA's found for the same coefficient. As a result, some confidence intervals became slightly smaller, especially for the intercepts, but without important shifts. Because there was no reason to assume these outliers contained erroneous data, the reported models include these outliers. The presence of outliers and the large variance the models cannot explain suggest there are still important additional parameters that were not identified.

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[4] Passive house certification in Flanders can be dispensed by the local passive house institute. They use a similar quasi-steady state calculation method as the regulatory EPB-method, but with different climatic data, a different set point temperature and different geometrical definitions for the heat loss area and volume of the building, resulting in different results than the EPB-calculations. Therefore, a 'nearly passive house' cluster was defined with the following criteria: having a net energy use for space heating lower than or equal to 20 kWh/m^{2}year or a balanced ventilation system with heat recovery, $n50 \leq 1/h$, an average U-value ≤ 0.4 W/m^{2}K and an average U-value of the opaque areas ≤ 0.2 W/m^{2}K. The 'highly insulated' cluster was defined as follows: having a net energy use for space heating lower than or equal to 30 kWh/m^{2}year or a balanced ventilation system with heat recovery, $n50 \leq 1.5/h$, an average U-value ≤ 0.45 W/m^{2}K and an average U-value of the opaque areas ≤ 0.25 W/m^{2}K.

3

User and building related parameters influencing space heating demand: case-study analysis on complementary neighbourhoods

This chapter pursues the data-driven investigation on the gap between calculated and real energy use initiated in Chapter 2, but focusses on lower performance houses and through a different approach. It presents an analysis and comparison of two uniform neighbourhoods, one with old, non-insulated houses and one with houses built to recent building standards. It elaborates on findings previously discussed in conference papers [96,101,102] and complements them with additional analyses. These analyses are based on data not only from surveys, energy utilities and EPB-assessments, but also from in-situ measurements on the building envelope, the ventilation systems and the indoor temperatures. The main focus of this chapter is on the heating profiles, the ventilation profiles and the presence of people in the different rooms and how these relate to the measured temperatures and to the gap between real and theoretical energy use.

3.1 Introduction

Previous Chapter 2 broached the subject of the gap between theoretical and real energy use in houses, but the analysis was limited to high performance houses. Therefore, the findings will mainly apply to new residential buildings, while they might not apply to houses built to lower standards only a decade ago or to the larger market of residential renovation projects on old houses. The trend of higher overestimation of the real energy use at higher theoretical energy demand levels that was found within the restrained performance range analysed in Chapter 2 is reported in literature to further increase to a more drastic extent when looking at older buildings having lower energy performance levels [29,31,32,97]. While the analysis in previous chapter found causes of prediction errors that were related primarily to inaccurate input data in the calculation models (e.g. caused by the use of default values), studies on the overestimation of energy savings associated with improvements compared to old buildings often relate those errors to different forms of temperature take-back. Those can be related to economic rebound or to higher average indoor temperatures as a direct result of the improved insulation levels, as discussed in 2.1 (see also [31,66,68,69,75,103]).

Many studies based on field-data show that *average* indoor temperatures are higher in better insulated buildings and that this can explain in part why actual savings are lower than theoretical savings [70–72,104–106], but there is little indication of behavioural changes with regard to heating profiles, e.g. changes in *set-point* temperatures [52,107]. The latter would be a better indicator for higher demands set by the inhabitants and the importance of user behaviour, because the former, the reported increase in average temperatures, can also result from physical temperature take-back only. On the other hand, if more demanding heating profiles were to be found in better insulated buildings, this could support the importance of behavioural rebound in explaining the lower actual savings. Because heating profiles are usually different in different types of rooms (e.g. bedrooms versus living rooms), the investigations on heating profiles should not be focussed only on living rooms. Most field studies on indoor temperatures that go further than analysing average living room temperatures mainly look at measurement-derived set-point temperatures and heating times defining the heating profiles in the *living rooms* and/or at *average* temperatures in the other rooms (often only the bedroom, sometimes with a differentiation between day-time and night-time temperature) [54,105,108,109]. Those studies mostly agree that, compared with the living rooms, the bedrooms show lower average temperatures and that their temperature increase after renovation is higher, explaining an important part of the temperature take-back at building level. In addition, statistical studies have found significant correlations between e.g. the heating of bedrooms and the *real* energy use, as discussed in previous chapter (see 2.3.2 and 2.4.1, [25,47]). However, little is reported about possible associations between the heating profiles in those bedrooms (or in bathrooms, circulation areas etc.) and the *theoretical* building performance levels, that could support the hypothesis that behavioural rebound explains part of the temperature take-back found in the former studies. The heating profiles in those rooms are sometimes documented in the latter studies (e.g. [47,48]) and can supply valuable information for defining standard heating profiles, averaged over all building performance levels. However, there is a lack of detailed analyses on possible differences in those heating profiles *at different* performance levels. This is worth further investigation because there are e.g. several studies that suggest changes to the heating systems in those rooms could cause a change in their heating profiles and further explain temperature rise in the building, e.g. following the installation of a central heating system [70–72]. Therefore, one of the aims of the study presented in this chapter is to increase the knowledge on heating profiles not only in the living room, but also in other types of rooms and with a comparison between old, non-insulated houses with local heating systems and new, insulated houses with a central heating system.

In order to investigate the link between those user profiles and related building properties, the latter have to be investigated as well. Firstly, this also allows putting user related variations and uncertainties in perspective, compared e.g. to technical uncertainties. Secondly, the better the understanding of the technical parameters and the smaller their uncertainties, the better the analysis will be able to discern and understand the relation between the investigated user profiles and the building characteristics and performance. In fact, Chapter 2 showed that uncertainties and default values related to technical parameters can be at least as important in explaining the prediction errors as behavioural parameters, stressing the need for more detailed knowledge on discrepancies between assumptions in EPB-models and real technical properties of the building envelope and systems. For these reasons, this study requires analysis on more detailed data than the data analysed in Chapter 2, which only comprised behavioural data that was self-reported by the inhabitants, technical data that resulted from the regulated EPB-assessment process, affected e.g. by the use of default values, and data on energy use during only one metering period. The study presented in this chapter is based also on field-measurements and a larger number of energy meter readings. The data was collected on two uniform neighbourhoods of single-family houses, one consisting of old, not insulated houses and one consisting of houses that are representative for standard houses built between 2005 and 2010. This enables comparisons between user profiles in technically different buildings with different performance levels, as suggested in previous paragraph. At the same time, this enables efficient data collection and comparisons between user profiles found across similar houses of a single neighbourhood.

3.2 Case-study approach on two neighbourhoods

3.2.1 Case-studies

General approach and selection

Three considerations defined the choice of the case-studies. Firstly, for the cases to complement one another in analyses focussing on the gap between theoretical and real energy use and energy savings, the cases had to be illustrative of the heterogeneity and evolution in thermal performance within the Belgian housing stock. Secondly, to distinguish variations due to differences between inhabitants from variations caused by technical differences between buildings, it was decided to select different clusters of quasi identical buildings. While working with clusters of quasi-identical buildings does not necessarily reduce the number of uncertainties regarding the buildings, a larger number of these technical uncertainties would be systematic over all cases within one cluster. Thirdly, limiting the study to one housing typology would prevent large geometrical variations to obfuscate variations in insulation and appliances between the subsets.

Therefore, uniform neighbourhoods of single-family houses were selected. Uniformity was defined as follows: each neighbourhood had to be built by one single construction company and one architect, in one period in time, according to the standards of that time, with similar materials and services across all houses and with as few differences as possible regarding their design. As such, each neighbourhood is a separate cluster of nearly identical houses with different households. This way, for a common housing typology, general trends and variations in user behaviour can both be analysed separately for each neighbourhood and its specific set of building characteristics, as well as depending on the building characteristics, by comparing findings on both neighbourhoods.

Selected neighbourhoods

The analysis is based on data about 62 single-family houses with 182 inhabitants that are part of two different neighbourhoods. Both neighbourhoods share some basic characteristics that are typical for many Belgian houses. They both consist of two-storey, three-bedroom single family houses, with brick cavity walls and a tiled roof sheltering an uninhabited attic space. The living area (including a living room, a kitchen and a toilet) is located on the ground floor. The sleeping area on the first floor consists of three bedrooms and one bathroom. The houses within both neighbourhoods are clustered in groups on both sides of parallel streets (Figure 3.1 and Figure 3.2). Both neighbourhoods thus contain terraced and semi-detached houses with mirrored orientations, resulting in a limited spread in building characteristics within each neighbourhood. Contrasting these typological similarities between the two neighbourhoods and the homogeneity within each neighbourhood, they strongly differ with regards to the technical properties of the buildings and their systems which are typical for their respective age.

The first case-study ('cs1': 36 houses) is an old social housing neighbourhood from the 1960s. The houses are not thermally insulated, have no mechanical ventilation system and are mainly heated by a single gas furnace in the living room. Over their 50 year lifespan, only few houses have been refurbished and only to a very limited extent. The heating systems remained mostly unchanged, with only one house (W27) being equipped with a central heating system with radiators. Small electric heaters were installed in the bathrooms and some inhabitants added an electric heater in their bedroom. Some windows were replaced on individual basis, causing an unstructured mix of single and double glazing as well as of wood and PVC window frames. The amount of double glazing is very limited, with only three houses having double glazing in both living room windows.

The second case-study ('cs2': 26 houses) is a five-year-old neighbourhood of privately owned houses. The houses near the present Belgian building standards, complying with the energy performance regulations from 2006. All the houses have standard insulation levels resulting in an average U-value between 0.53 W/(m².K) and 0.60 W/(m².K) depending on the typology. They all have a central exhaust ventilation system and a central hydronic heating system with a gas boiler and radiators. The ventilation systems are not demand-controlled, but can be set by the user to one of three pre-set flow-rates using a centralized, manual switch positioned in the living area. The heating systems are controlled by a central thermostat which is also located in the living area. While 16 of these 26 houses are based on one single design, the remaining ten houses have slightly different lay-outs, causing some additional, though still limited typological variations within this sample.

Figure 3.1: cs1: old neighbourhood (source: Microsoft Bing Maps ® [110])

Figure 3.2: cs2: recent neighbourhood (source: Microsoft Bing Maps ® [110])

3.2.2 Data collection and analysis

General approach and selection

The collected data covers both building and user related parameters as well as real energy use. In-situ measurements complemented surveys of the inhabitants and consumption data from utility bills and additional meter readings. The scopes of the measurements and surveys both supplemented each other and overlapped, with e.g. questions on heating set point temperatures while interior (resulting) temperatures were also measured. This way, measurements and surveys could be compared and cross checked.

Because this study focussed on the energy use for space heating, all data collection took place during the winter season, with up to three visits to each house. The clustering in neighbourhoods allowed planning those visits efficiently in order to reach a good rate of data versus the time spent on site. This was also important for the data collection not to be too demanding for the inhabitants, whose participation to the study was voluntary.

While this study mainly aims at analysing the impact of user behaviour, uncertainties related to the building characteristics are not neglected for two reasons. Firstly, comparing the variations and uncertainties regarding user behaviour impacts with building related ones is important to put the findings into perspective. Secondly, the building related uncertainties might cause errors in the energy calculation models that could affect the analysis on the different prediction errors between houses within one neighbourhood and across neighbourhoods. Therefore, the theoretical energy use was calculated using the results from the measurements on the building characteristics. Default values defined for regulatory performance assessment of houses in Flanders [80,111] were used for technical characteristics that were not measured, being mainly the characteristics of the heating and ventilation systems.

Measurements

The measurements focused both on the building characteristics (through IR-thermography, heat-flux measurements, air-tightness measurements and measurements on the ventilation flow rates) and on the indoor climate (indoor temperature, humidity, CO2-level). The aim was not only to gather data for cross-comparisons between houses, within and between both neighbourhoods, but also to make comparisons between real values, design values and default values used in the EPB-models (e.g. regarding air tightness, ventilation rates, indoor temperatures).

The air tightness measurements were performed following ‘Method A’ (test of a building in use) from ISO 13829 [112], as prescribed and further detailed in [113] for use within EPB-calculations in Flanders. This method aims at measuring the uncontrolled air leakages through the building envelope in its real, daily use state.

The air flow rates induced by the mechanical ventilation systems in the new neighbourhood were measured at the exhaust vents in the bathroom, the kitchen and the toilet separately. These measurements were done for the three flow rates that the users can select using the centralized control switch.

Conducting heat flux measurements on the old walls from cs1 was considered important because no original technical product specifications were available. The measurements took place on the lateral facades of four different semi-detached houses, with measurements at two different locations on each wall. The heat flux measurements were analysed with the simple average method, the average method with storage correction and the dynamic method from ISO 9869:1994(E) [114]. Thereby, the results allow estimating the uncertainty on the assessed thermal transmittance caused by varying wall properties, measurement conditions, sensor placement and methods of analysis. No accurate heat flux measurements could be conducted on the walls of the new houses, mainly due to the limited areas between windows and wall-floor junctions.

Indoor and outdoor temperature and humidity were measured during at least one full week over time intervals of 5 to 10 minutes, using small, autonomous loggers. The monitoring took place in the most important rooms: living rooms, kitchens, circulation areas, bathrooms and at least two bedrooms, including the master bedroom. Temperature and humidity were also measured in the basements of cs1 and the attics of cs2. Additionally, CO2-levels were measured in the living room and in the master bedroom. Within this chapter, these measurements are only looked at from the perspective of space heating profiles and energy use. More detailed analyses regarding the indoor air quality were reported separately in papers focussing on CO2 levels in living rooms and bedrooms [115,116] and on humidity in bathrooms [116,117].

Surveys

The surveys of the inhabitants focused on the socio-economical background of the users, their habits and their interaction with the building as well as on their motivations, their understanding of the building and their appreciation of the resulting performance (energy use and comfort). The surveys were submitted to the inhabitants during the heating season, directly following the measurement period for the survey data to correspond as closely as possible with the measurement data without influencing the inhabitants' behaviour during that measurement period. The participants were thus not asked to keep detailed diaries of all activities and behavioural aspects of interest at high frequency over the whole week. Instead, they were asked to draw daily profiles for an average weekday, for each person or for each room. This was asked with regard to the presence of people, the heating of rooms, the opening of windows and, for cs2, the settings of the ventilation system. The inhabitants of cs2 were also asked to report their presence and heating profiles for an average weekend-day. The survey further included specific questions to complement these profiles (e.g. Do you close the windows when it rains? Do you close the windows when the heating system is on?). When applicable, these questions allowed input per individual inhabitant as well as per different room or appliance. To avoid misinterpretations and to lower the workload for the participants, the surveys were adapted to each specific neighbourhood (e.g. omitting questions on the operation of mechanical ventilation systems for the old housing neighbourhoods where these systems were not available). Three of the households of cs1 who participated to the measurement campaign did not respond to the survey, thus resulting, for that neighbourhood, in 33 households with survey data out of the 36 with measurement data.

Real energy use

DATA

Technical, practical and financial constraints limited the monitoring options, making it impossible to install smart metering devices or to collect meter readings very frequently over a long period of time. Additionally, the surveys and listed measurements required already a considerable voluntary participation from the inhabitants. Therefore, data on real energy use was collected in a less intrusive and less extensive way. Historical, approximatively yearly meter readings were supplied by the utilities. The surveys contained questions on the most important changes to the buildings or to the household (e.g. refurbishments, births, deaths, people moving in or out…), allowing to consider only the meter readings that relate to the current, measured and surveyed status of the house and of the household. To complement this yearly data, the meters were read at each visit to the houses. This resulted in a number of yearly readings (with medians of respectively 8 and 4 for cs1 and cs2) and 2 or 3 additional readings during the heating season, with varying time intervals and climatic conditions between subsequent readings. Periods of less than two months were merged together so as to limit disturbances due to occasional variations (e.g. holidays). For the houses of cs2, the first billing period was also removed because it showed considerably higher gas consumption for several cases that could not be explained by differences in climatic conditions. This could be linked to the drying out of the newly built masonry construction [118–120] or to different uses of the buildings being included in that first billing period (e.g. the finalization of some construction works). Including the data from the first billing period could therefore result in erroneous estimations of the long term energy demand.

ANALYSIS

The analysis focusses on the energy use for space heating. However, the available consumption data consisted of gas meter readings while, apart from the heating systems in both neighbourhoods, the cooking appliances in most houses in cs1 were also gas based, as were the domestic hot water appliances in cs2. Because of the limited number of mainly yearly meter readings, regression analysis based on heating degree days did not succeed in disaggregating the energy use for space heating from the total gas-based energy use. Instead, the actual energy use for space heating was estimated for each gas metering period by subtracting an estimation of the energy use for domestic hot water and/or for cooking, for each case separately depending on its gas based appliances. Subsequently, the remaining estimate of the energy use for space heating of each metering period was normalized based on the respective heating degree days to correspond to the climatic year considered in the EPB-method.

The final energy use for domestic hot water was estimated to account for 2324 kWh/year for an average household of 3 people (754 + 523 *N, with N = the number of inhabitants based on the survey data). This pre-calculation results from using the empirically based method defined for the British Standard Assessment Procedure for Energy Rating of Dwellings (SAP) [121,76] in combination with the system efficiency values defined for the energy certification of houses in Flanders [122]. The SAP-method was preferred to the Flemish calculation method for defining the domestic hot water demand because the latter calculates the net demand based only on the volume of the building (see 2.3.2), without explicit reference to the number of inhabitants while the formulas from the former allow calculating the demand based on the number of inhabitants reported in the surveys. Furthermore, the SAP-method also accounts for seasonal effects reported in literature, related both to fluctuations of the demand for domestic hot water by the user and to fluctuations of the cold water inlet temperature reported in literature [123–126]. Those corrections were also included in the calculation because the periods between two gas meter readings did not correspond to exactly one year. The domestic hot water consumption calculated this way based on the SAP-method lies within the same range as the average values from field studies from the UK [124], The Netherlands [127] and Greece [125].

The energy use for cooking using gas ovens and gas hobs was estimated to account for 525 kWh/year for an average household of 3 people, with further correction of 50 kWh/year per inhabitant in case of smaller or larger households. In the absence of relevant detailed field studies from Belgium, these estimates are based on average numbers from several field studies conducted in other West European countries [128–135] that also underline the variability of the real energy values depending on the actual household and reveal variations between countries. Similar to the calculation of the domestic hot water demand, seasonal variation was also included for the cooking demand by considering 25% higher and lower cooking consumption compared with the annual average during mid-winter and mid-summer, respectively, based on [129,135].

The climatic year considered in the EPB-method is defined by 12 monthly average outdoor temperatures and corresponding monthly total solar irradiance [136] and not by heating degree days or daily values allowing to calculate the corresponding heating degree days. Those were defined in this study based on 11 years of daily temperatures measured in Belgium (Ukkel, 2001-2011). First, those daily temperatures were scaled for each monthly average temperature to correspond with the monthly average temperature defined in the EPB-method. Subsequently, the heating degree days of those 11 fitted years were calculated (with a base temperature of 16.5°C) and averaged to obtain an average EPB-equivalent number of heating degree days per year, obtaining a value of 2417.

All the referenced studies indicate the large variability of the cooking and domestic hot water energy use depending on the actual household. Similarly, the real indoor temperature also varies between houses as a result of varying user profiles and thermal properties of the building. By consequence, errors on the normalized energy use for space heating can result from the selected approach being based on average, predefined values for the base temperature. In order to consider the sensitivity of the results to these assumptions, calculations were also performed with a higher and a lower base temperature (+/-1,5°C) and by varying the pre-calculated energy use for cooking and domestic hot water by +/-50%.

Statistical analysis

In comparison to Chapter 2, statistical analysis accounts for a more limited share of the present case-study chapter. The statistical analysis focusses on possible correlations between the real energy use or the prediction error on the one hand and, on the other hand, parameters that are not taken into account in the regulatory performance assessment method: the socio-demographics of the households, their user profiles (presence, heating and window opening) and the fact that some houses within the old neighbourhood were not inhabited.

The statistical methods used in this chapter were discussed in 2.2.3. All associations reported in this chapter also assume 2-tailed distributions and are reported with their 95% confidence intervals (95% CI) resulting from bias-corrected and accelerated bootstrapping (BCa). Because of the small sample sizes of the two neighbourhoods, in order to reduce the risk of type I errors (a "false positive"), associations were considered to be significant only if confirmed by the parametric tests and by their non-parametric alternatives, including their 95% CI's. Because of those small samples and the higher influence of outliers on results from parametric tests, as well as for brevity, only the results from non-parametric, non-factorial tests are reported.

3.3 Results

3.3.1 Technical inputs for the performance assessment

As a result of the evolving building standards, the houses in the new neighbourhood are supposed to achieve a considerably better thermal performance than the old, barely renovated houses. This was at least partly confirmed by in-situ measurements (air-tightness and heat-flux measurements, IR-thermography). By way of example, Figure 3.3 compares the measured air leakage rates for both samples with reference data for Belgian single family houses. The reference data includes a random sample of houses built in the late 1980s and early 1990s from the Senvivv-project [99], a random sample of standard dwellings from the past 5 years (UGent) and recent measurement data from private party consultants (BD), of which the explicit low-energy houses (LEH) are separated, as a representation of todays ‘engaged’ market segment [90]. The air tightness in both neighbourhoods proved to be in line with the expectations for their respective building periods and standards. The spread in air permeability values within each neighbourhood can partly be attributed to workmanship and to the presence of a few semi-detached houses in both neighbourhoods. The much higher spread within the old neighbourhood, up to a factor of three, is explained by the leakier envelope, accentuating the difference between terraced and semi-detached houses, as well as by occasional, small retrofits (e.g. window replacements and replacements of mailbox-holes in the walls by new mailboxes hung on the walls).

Figure 3.4 shows the variations to the thermal transmittance measured on the old walls: variations between the four walls, between both measurement points of each wall, and between results from different analysis methods on the data of each measurement point. Despite the different results, most values lie within each other’s error margins. Those are constituted mainly of the error-estimation due to placement according to ISO 9869 [114]. The part of the error bars between the horizontal cross-lines indicates the estimated error due to the analysis method itself. Nevertheless, one measurement on the wall of house W34 clearly shows a higher level of heat losses. This could partly be due to measurement inaccuracies, but local disruptions such as mortar bridges in the cavity and wall ties should not be dismissed. In both cases, the value of taking more than one measurement point is to be stressed. Excluding this one measurement, the values are on the lower end compared with values from a reference sample of non-insulated cavity walls from a Belgian research project on cavity wall retrofitting [137].

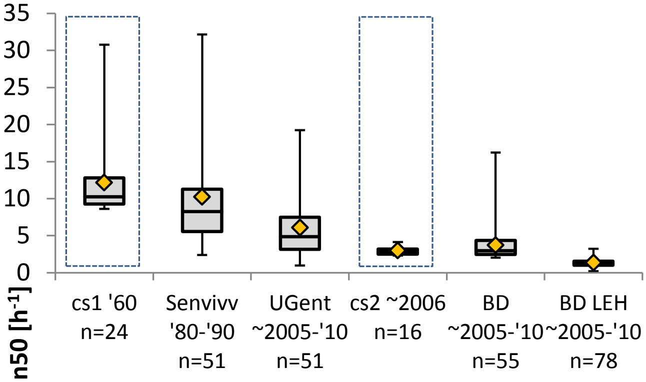

Figure 3.3: measured air leakage (air change rate per hour at 50Pa pressure difference)

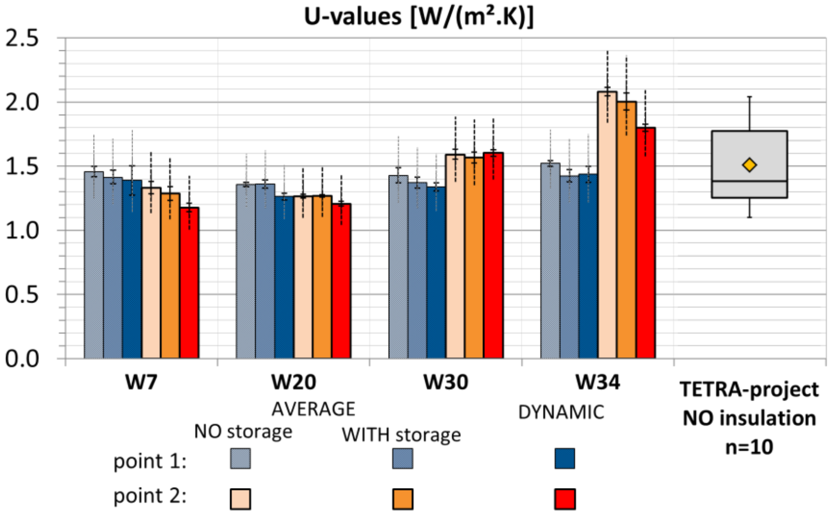

Figure 3.4: thermal transmittance of the four test-walls of cs1 (W7, W20, W30, W34), based on heat-flux measurements (analysis based on ISO9869 [114]: average method with and without storage correction factor and dynamic method)

3.3.2 Energy use for space heating

Theoretical energy use

Table 3.1 summarizes the most important building characteristics of the two neighbourhoods as well as the theoretical energy use for space heating calculated based on the Flemish EPB-method and using the measured air permeability values and, for cs1, the measured thermal resistance of the walls. The limited typological variations, the differences in air permeability between the different building envelopes and the different orientations cause variations in theoretical energy use within each neighbourhood. Still, the difference between both neighbourhoods remains much higher, with a theoretical energy use for space heating that is on average three times higher in the old houses of cs1 compared with the new houses of cs2.

Table 3.1: building characteristics and theoretical energy use for space heating

		S_{floor}	S_{loss}	V	U_{av}	n50	Q_{heat}	
							net	final
		[m^2]	[m^2]	[m^3]	[W/ (m^2.K)]	[-]	[kWh/ (m^2.yr)]	
cs1	av	82	165	226	1.46	12.12	208	322
	mdn	82	157	227	1.47	10.25	199	308
	min	80	157	221	1.33	8.62	177	289
	max	82	193	227	1.51	30.78	251	386
cs2	av	134	238	387	0.55	2.86	76	97
	mdn	123	203	353	0.54	2.93	73	92
	min	123	202	353	0.53	2.33	68	85
	max	173	316	488	0.60	3.88	90	119

Real energy use

ANALYSIS OF THE NORMALIZATION METHOD

Figure 3.5 shows the characteristic values of the actual yearly energy use for space heating defined based on the gas meter readings. The figure also shows the intermediate steps made for defining those values. The light grey markers show the yearly energy use after subtraction of the pre-calculated domestic hot water and cooking energy use, but before being normalized to correspond to the climatic year considered in the EPB-method. The real energy use is shown to vary much more from one year to the other in the old houses of cs1 than in the new houses of cs2. This larger spread in yearly values for the old houses is partly explained by the higher number of years for which consumption data were available, thus increasing the variation in climatic conditions included in the dataset of cs1. Normalizing the energy use based on the heating degree days drastically reduces this spread, as is shown by the dark grey markers in Figure 3.5. Nevertheless, for some houses the values of different yearly metering periods still show large differences even after normalization. Further analysis showed that, for those cases of cs1, the normalized yearly consumption data was still correlated with the heating degree days. This suggests that the base temperature used for calculating the heating degree days or the subtracted consumption for domestic hot water or cooking were not accurate enough for those cases. Therefore, for each house of cs1, the final characteristic, normalized value of the actual energy use, being the value to be used for further analysis (indicated by a black dot in Figure 3.5), was defined by a regression on those normalized year values as a function of the corresponding heating degree days. Some cases of cs2 also show different normalized consumption figures for each metering period. However, the correlation with the corresponding heating degree days was not as significant as in cs1, impeding the use of a regression for defining the characteristic value. Instead, for cs2, the normalized value of the last yearly metering period was selected as the final characteristic value (indicated by a blue marker in Figure 3.5). This choice was made because those last metering periods were very similar, including for all cases of cs2 the same heating season (spanning in total from August or September 2010 to August or September 2011).

The error bars on the characteristic consumption figures in Figure 3.5 indicate the range of results of the method discussed in the previous paragraph obtained when varying the base-temperature of the heating degree day calculation by +/-1.5°C and the pre-calculated domestic hot water and cooking energy use by +/-50°C. The largest errors bars are found for the new houses of cs2 and the few old houses of cs1 having also a gas-based water boiler. This indicates the large errors on the characteristic actual energy use for space heating that could result from not having real consumption data for space heating and domestic hot water separately. On the other hand, the old houses with electric domestic hot water boilers have only very small error bars, indicating the limited uncertainty caused by the unknown real cooking energy use and the choice of the base-temperature, i.e. when following the approach discussed above, ending with a regression over several normalized year-values. The higher uncertainty caused by not knowing the real energy use for domestic hot water compared to not knowing the real cooking energy use is proportional to the different average energy use linked to both end-uses. It is important to note that part of those possible errors can be systematic within one neighbourhood, as a result of the large homogeneity between the cases with regards to both technical parameters (e.g. the domestic hot water system) and socio-demographic parameters influencing the energy uses, and that such systemic errors would not affect comparative analysis between cases of the same neighbourhood.

RESULTS OF THE CHARACTERIZATION METHOD

Figure 3.5 clearly shows the large spread in energy use that is found between houses, also between houses of the same neighbourhood. The highest consumption value is three times higher than the lowest value within cs1 and that ratio between highest and lowest consumers is four when looking at cs2 (Table 3.2). Notwithstanding these large spreads in energy use within each neighbourhood and the large uncertainty on the actual energy use for space heating in cs2, the average energy use is distinctly lower in the new houses than in the old houses, by on average a factor two (Table 3.2). Still, the two highest consuming households in the new neighbourhood consume more energy than the least consuming household(s) in the old neighbourhood.

Table 3.2: normalized real energy use for space heating [kWh/(m^2.year)]

	min	average	median	max	max/min
cs1	85	151	134	270	3.2
cs2	31	68	68	118	3.8

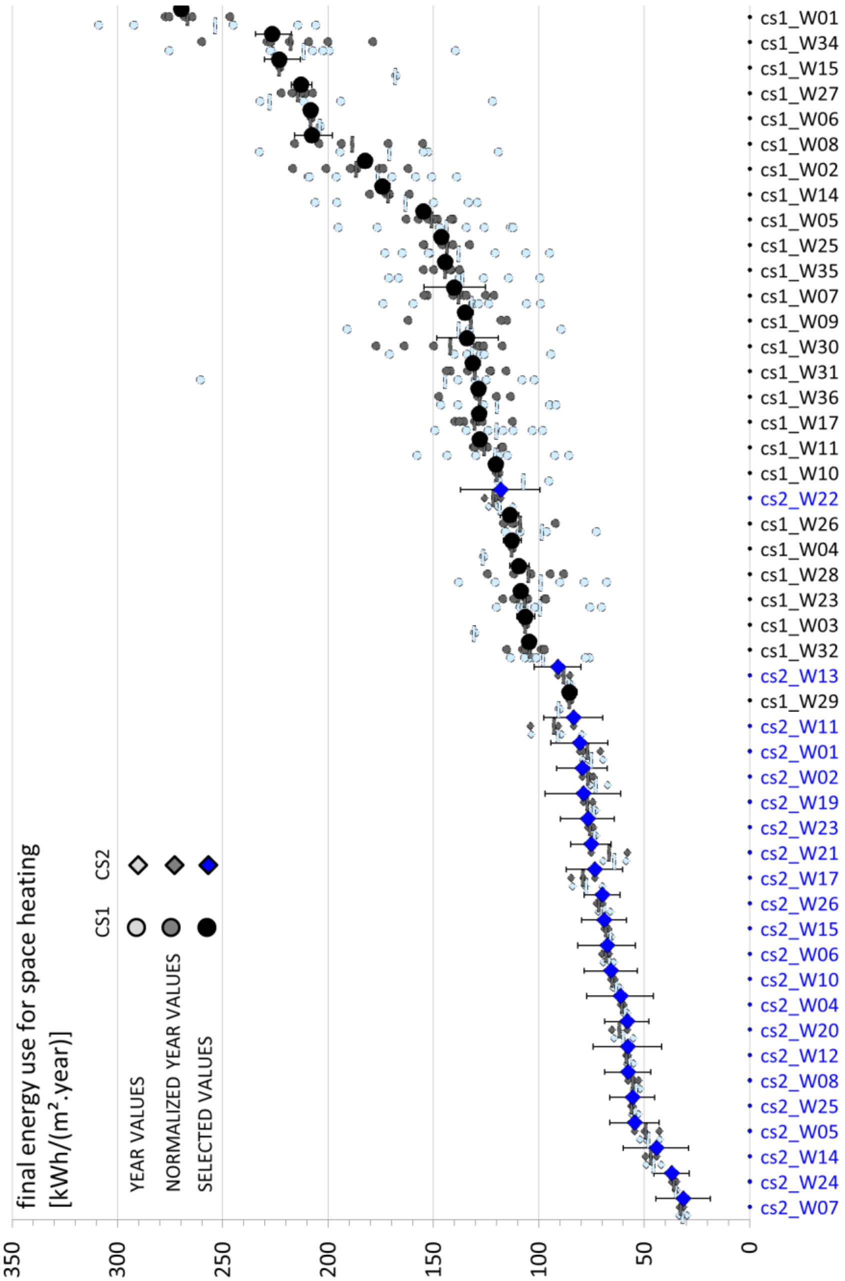

Figure 3.5: actual yearly energy use for space heating:cs1 and cs2, before and after normalization, selected value (linear regression value for cs2 and last year for cs1, error bars: +/-50% estimated energy use for cooking and domestic hot water estimation and +/- 1.5°C base temperature)

Real versus theoretical energy use

Figure 3.6 and Table 3.3 compare the final energy use for space heating derived from the meter readings with the theoretical values from the EPB-calculation. The clear distinction between the tightly and distinctly clustered, theoretical values of both neighbourhoods (abscissae), strongly contrasts with the large spreads in real values found in each neighbourhood and the small overlap of their real values (ordinates). The EPB-calculation proved to strongly overestimate the actual energy demand, with the real energy use being on average 53% and 30% lower in cs1 and cs2, respectively. Because of the lower energy performance of the old houses, this results in the absolute prediction error being on average 5.8 times higher in cs1 (-169 kWh/(m².year)) than in cs2 (-29 kWh/(m².year)). By consequence, the reduction in energy demand associated with better building performance levels in cs2 compared to cs1 proved to be 62% less than assumed: on average 84 kWh/(m².year) instead of 224 kWh/(m².year).

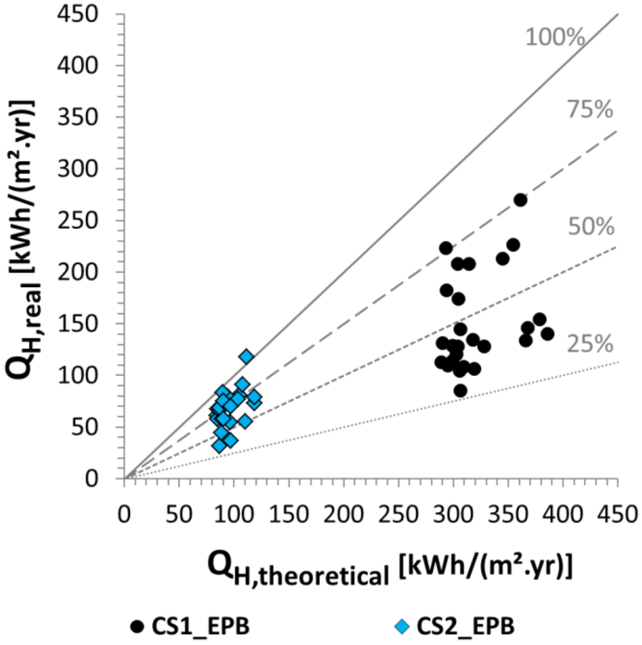

Figure 3.6: yearly space heating energy demand: deduced from energy bills vs. theoretically calculated according to the official EPBD method (normalized per unit of floor area).

Table 3.3: real vs. theoretical energy use in cs1 and cs2 (only cases with both values)

	N		Qheat,final		real – EPB	
			EPB	real	abs.	relat.
	[-]		[kWh/ (m²·yr)]	[kWh/ (m²·yr)]	[kWh/ (m²·yr)]	[%]
cs1	26	av	321	151	-169	-53%
		mdn	306	134	-179	-58%
		min	289	85	-246	-72%
		max	386	270	-70	-24%
cs2	22	av	97	68	-29	-30%
		mdn	92	68	-27	-28%
		min	85	31	-60	-64%
		max	119	118	6	6%

3.3.3 User profiles

The following paragraphs analyse user-related parameters that are potential causes of the differences found between real and theoretical energy use. Before analysing the user profiles, the related socio-demographics of the inhabitants are summarized. The link between the socio-demographic characteristics and the user profiles will be further discussed in section 3.4.

Inhabitants

The first neighbourhood consisted of rented social houses. The houses in the second neighbourhood were privately owned, in many cases by their respective inhabitants. This new neighbourhood mainly housed young families, while the first set of households was more heterogeneous, with, as shown in Figure 3.7 and Figure 3.8, more elderly people and lower education levels. Cs1 also housed more retired and unemployed people than cs2 (Table 3.4). All 26 households in the new neighbourhood (cs2) had at least one of the parents working outside of home and three out of four had both parents working outside of home. In the old neighbourhood (cs1), less than half the number of households had one person working out of home and less than one out of five had both parents working out of home. Making no distinction between working outside of home or from home barely increases these employment figures (Table 3.4).

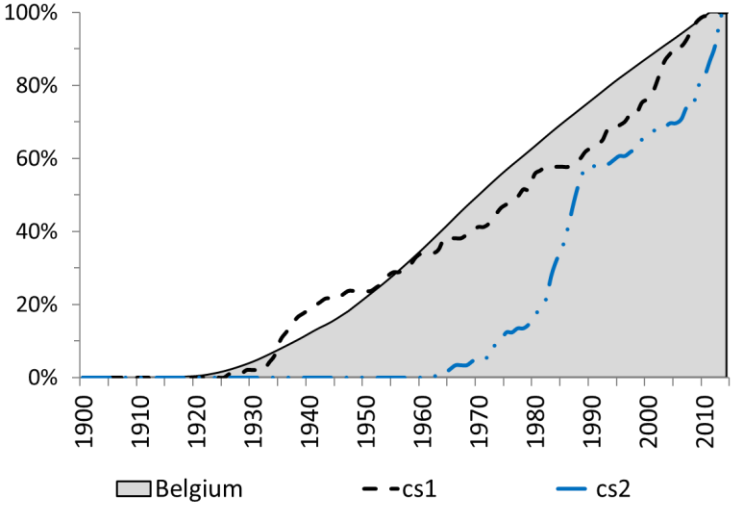

Figure 3.7: Date of birth: cs1 & cs2, compared to the Belgian population (cumulative distribution)

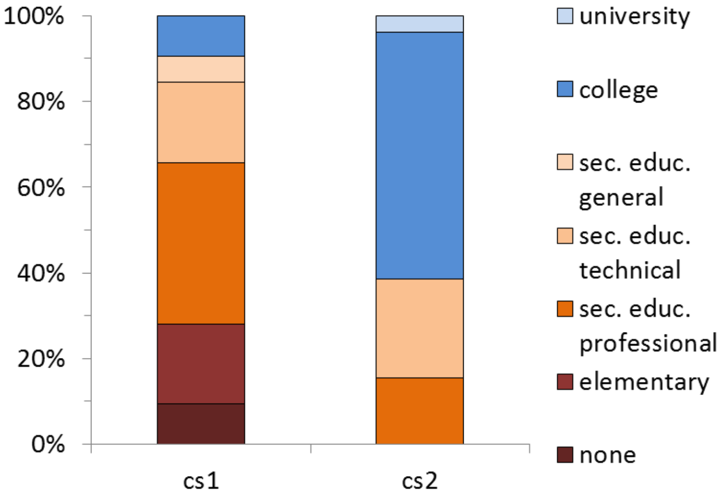

Figure 3.8: degree of education: highest diploma within each household

Table 3.4: employment status

	total	Working out of home		Working (out of home or at home)	
		At least 1 parent	Both parents	At least one parent	Both parents
cs1	33	13	6	15	7
cs2	26	26	20	26	20

Presence in the house

People's occupations define where they are during the course of the day. As a reference with regard to the presence of people within houses, presence profiles derived from statistical data for Belgium are depicted in Figure 3.9 [138], next to the results from both the old neighbourhood (Figure 3.10) and the new neighbourhood (Figure 3.11 and Figure 3.12). The stacked coloured areas represent the probability for an individual to be present in a certain room of the house during the course of the day. A stacked probability of one means that everyone stated to be present in their house at that time of day, while zero means that no one stated to be at home at that time. The additional lines show the probability of *at least one* person being present and are thus also dependent on the size of the household. In cs1 (Figure 3.10), the probability of presence in the houses and more specifically in the living room during weekdays was much higher than the Belgian reference level. The opposite was true for cs2 (Figure 3.11). As opposed to the Belgian reference data, the neighbourhood profiles showed no significant increase of presence in the kitchen at lunch-time during week-days. Instead, the probability of presence in the living rooms of cs1 remained high during day-time without a significant drop during lunch-time, suggesting a preferred use of the heated living room for dining instead of the small kitchen. During the weekend, the occupancy profiles in cs2 changed dramatically, as shown in Figure 3.12. Time-shifts in the morning and in the evening, increased presence in the living room and a wider spread of use of the kitchen over lunch- and diner-time are the most noticeable differences.

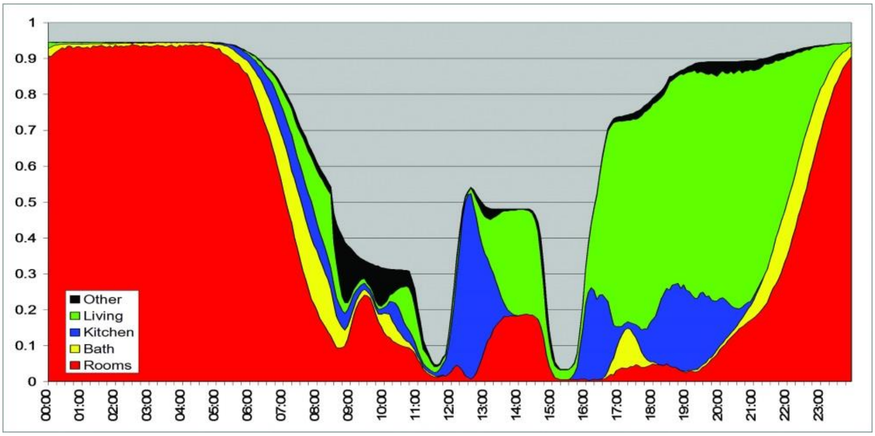

Figure 3.9:Probability of presence: (a) Belgian reference data [138].

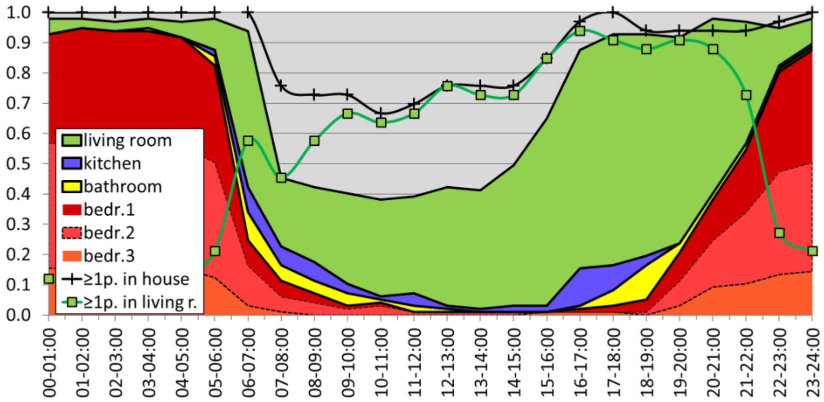

Figure 3.10:Probability of presence in cs1 during week-days.

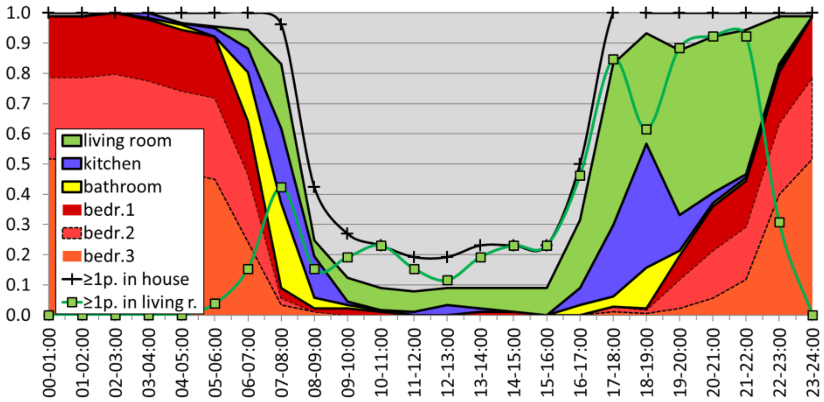

Figure 3.11: Probability of presence in cs2 during week-days.

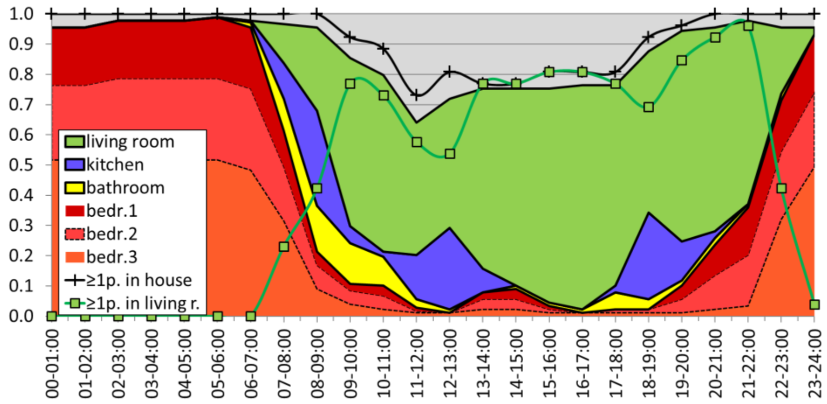

Figure 3.12: Probability of presence in cs2 during weekends.

Space heating

TIME PROFILES

Daily probability profiles for the heating of each room were derived from the questionnaires in a similar way as the presence probability profiles. Both presence and heating profiles proved to be strongly correlated in the living rooms for both neighbourhoods and in the bathroom of the old neighbourhood. The electric heaters in those bathrooms were reported to be turned on only when the bathroom was in use. For the living rooms, this correlation between presence and heating is more clearly visible when comparing the heating probability profiles of the living rooms, as shown in Figure 3.13 for cs1 and Figure 3.14 and Figure 3.15 for cs2, with the probability of having at least one person present in the living room (the green lines in Figure 3.10, Figure 3.11 and Figure 3.12). A deviation from this correlation between the reported presence and heating in the living room occurs at night in cs1. The probability of leaving the gas heater on all night is higher than the presence probability in that old neighbourhood and also higher than the heating probability in the new houses (only one household in cs2 did not apply night-time heating reduction). However, analysing the temperatures measured in the living rooms of the old neighbourhood revealed that the night-time values of Figure 3.13, which are based on the surveys, are overestimated. 6 of the 12 households of cs1 that reported to leave the gas furnace on all night long actually proved to switch it off at night, as was clearly visible from the strong temperature drops occurring each day during the reported sleeping periods.

For the other rooms, the heating probability shows no association with the presence probability. In most bathrooms and kitchens of cs2, the heating remained on regardless of presence in that specific room, but when at least one person was present anywhere in that house during daytime, synchronously to the heating in the living area and following the settings of the central thermostat. This results in much higher heating probabilities for the bathrooms and kitchens in cs2 compared with cs1. A similar but smaller difference was noted between the bedroom heating profiles of both neighbourhoods. Only 6 out of 33 households in cs1 heated at least one bedroom. Except for one of these 6 households that left the heating in one bedroom on for nearly the whole day, they did this only temporarily in the evening until going to sleep. In cs2 the number of households heating their bedrooms remains low (8 out of 26 households). However, as opposed to cs1, only 2 of those 8 households did this only in the evening while the other 6 households left the radiator valve of at least one bedroom open all day, thus heating those bedrooms whenever the central thermostat located in the living room switched on, including e.g. in the morning. Figure 3.14 and Figure 3.15 show a lower probability of heating the bedrooms when the living room is heated (approximately 20%), but these figures relate to each separate bedroom and only two of those 7 households left the radiator valves open in all three bedrooms. Summarizing the bedroom heating profiles of both neighbourhoods, no bedroom was heated at night while people lay there asleep, but some bedrooms in cs2 were heated during day-time, also when not being used.

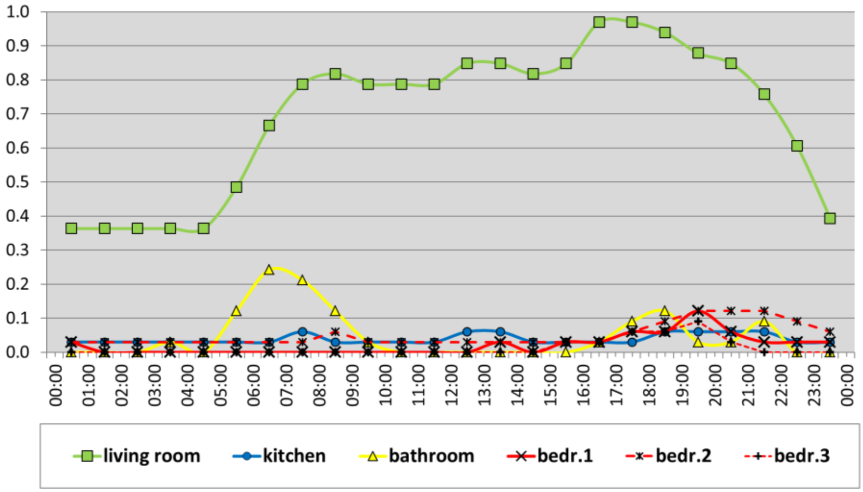

Figure 3.13: Probability of heating in cs1 during week-days

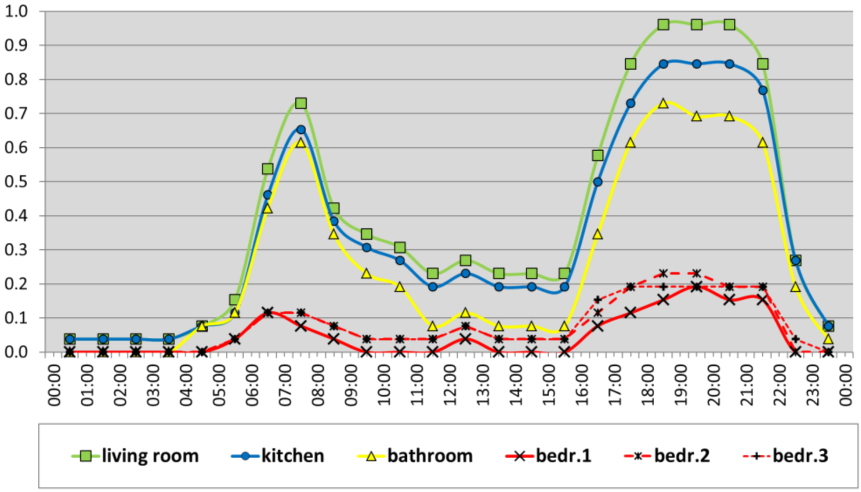

Figure 3.14: Probability of heating in cs2 during week-days.

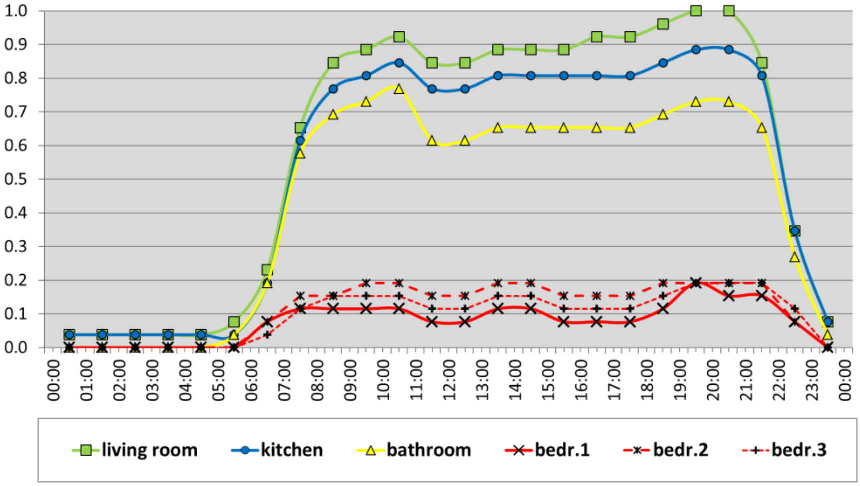

Figure 3.15: Probability of heating in cs2 during weekends.

SET-POINT TEMPERATURES

The heating set-point temperatures complement the heating durations in defining the space heating profiles. The set-point temperatures used for further analysis are those of the living rooms, deduced by cross-analysis of data on the heating period collected from the surveys and the continuous indoor temperature measurements during one week in the heating season. Figure 3.16 compares these values, for cs2, with the set-point temperatures reported by the inhabitants in the surveys. Depending on the case, the self-reported values overestimate or underestimate the measurement-derived values with differences up to 4°C and no correlation was found between both sets of values. 15 of the 24 self-reported values proved to be underestimations, resulting however in the self-reported values (average: 20.9°C) being on average only 0.6°C lower than the values deduced from the measurements (average: 21.5°C).

Figure 3.17 illustrates the large spread in heating profiles between individual houses by showing for each living room both the average number of heating hours per day and the heating set-point temperatures (derived from the measurements). The heating durations ranged from 4 hours to 24 hours per day and were corrected compared with the values shown in Figure 3.13, taking into account the night-time reductions that were not reported by the households. The overall gap in heating hours between cs1 and cs2 is shown to be largely bridged during the weekend (error bars). The variation in heating behaviour is even more striking when taking into account the heating set-point temperatures, ranging from 17°C to 28°C. The highest values were found in the old neighbourhood.

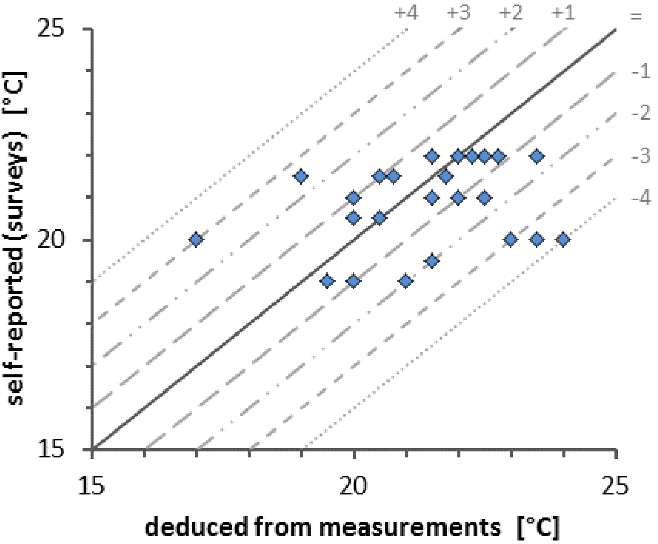

Figure 3.16: divergence in setpoint temperature of the living rooms of cs2: measurements vs. surveys.

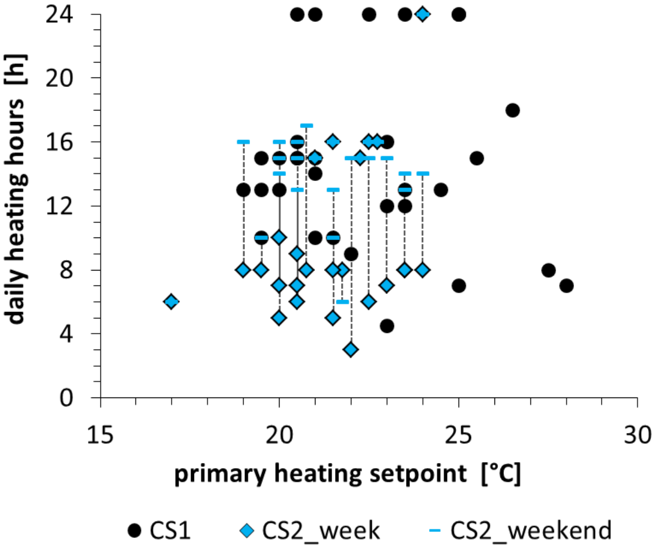

Figure 3.17: Daily heating hours and primary set points for the living rooms (cs1 & cs2).

Ventilation

In the EPB-calculation, the assumption of a standard user profile and the lack of differentiation between rooms disregard variations between houses and between the rooms of each house not only with regard to heating profiles, but also with regard to ventilation profiles, resulting from the use of ventilation systems and windows. For both the old and the recent dwellings, the surveys showed a recurrent asynchrony in space and time between the opening of windows on the one hand and both the presence in and the heating of the rooms on the other hand. As shown in Figure 3.18 and Figure 3.19 for cs1 and cs2 respectively and further summarized in Table 3.5, the windows in the most heated rooms, the living rooms, were reported to be opened only very rarely and for brief periods (usually less than one hour). On the opposite, most households reported to open the windows in the rarely heated bedrooms, but mainly during the day, especially in the morning when leaving the bedroom. This asynchrony between using and heating the rooms on the one hand and opening the windows on the other hand was further stressed by the high number of households reporting to close their windows when switching the heating on: 25 of the 33 households of cs1 (76%) and 16 of the 26 households of cs2 (62%). The use of the bedroom windows thus varied between households, but showed no significant difference between the neighbourhoods. On the contrary, the bathroom and kitchen windows were clearly opened less often in the new houses than in the old houses. The probability of the bathroom windows being open during day-time is approximately two times lower in the new houses and only one household in cs2 reported to open the kitchen window, moreover only for a short amount of time at the end of the afternoon.

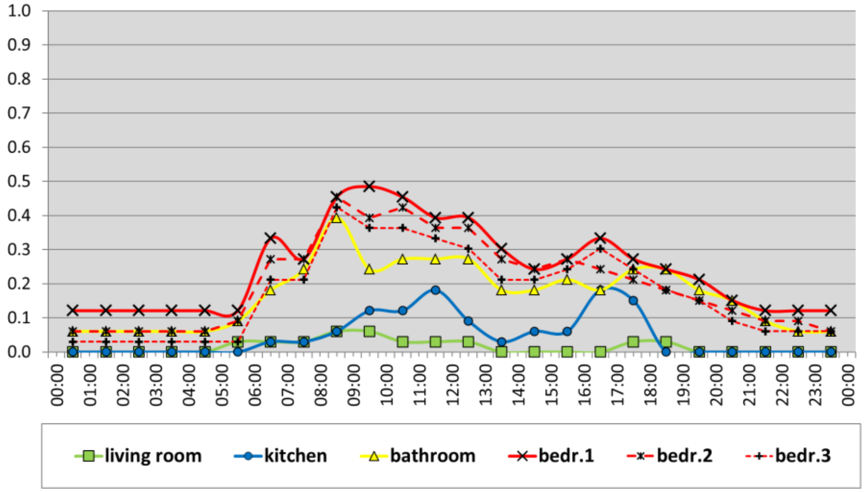

Figure 3.18: Probability of airing the windows in cs1.

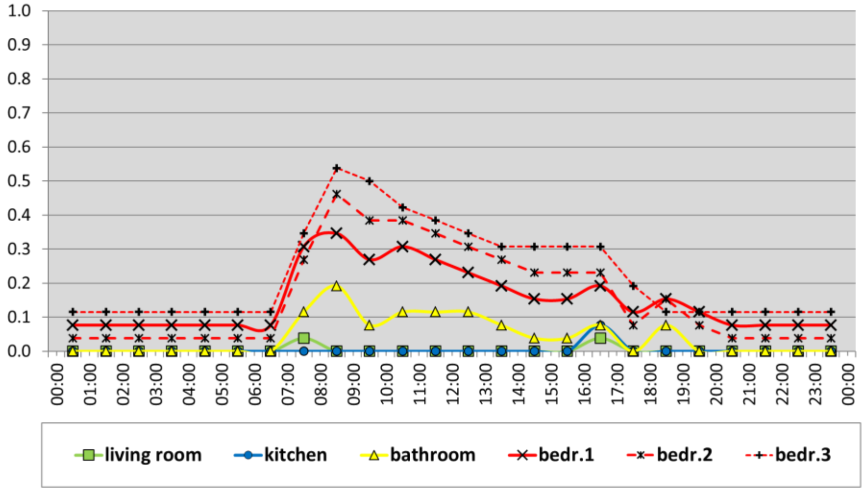

Figure 3.19: Probability of airing the windows in cs2.

Table 3.5: number of households reporting to open the windows during an average week day

		cs1	cs2
TOTAL (N)		33	26
OPENING OF WINDOWS*			
living room	daily	6	2
	more than 2 time-slots of max. 1 hour	1	0
bedroom**	daily	32	20
	also at night	5	4
bathroom	daily	22	9
	left open for several hours when not in use	12	3
kitchen	daily	16	2

notes:
*deduced from the average 24 hours week-day profiles, filled in by the inhabitants per time slot of 1 hour
**at least one bedroom of the house

Compared to airing by opening the windows and relying on natural pressure differences, the mechanical exhaust ventilation in cs2 could be thought of as a more effective ventilation solution, technically more robust while still freely controllable by the users. On the contrary, the measurements demonstrated large divergences in installed flow rates between the different houses, while the surveys showed a very uniform use of the ventilation systems across all households. According to the local ventilation standard for these houses, the highest exhaust flow must be at least 75 m^3/h for the kitchen, 50 m^3/h for the bathroom and 25 m^3/h for the toilet, but the discrepancy between installed and prescribed flow rates were striking. The prescribed 75 m^3/h could not be reached in any of the kitchens (Figure 3.20), while in most toilets the 25m^3/h-target was reached at the second or even the lowest flow rate (Figure 3.22). Moreover, the differences in installed flow rates between the houses was very high, with factors of approximately 2.5, 2 and 6 between the lowest and the highest flow rates for the kitchens (Figure 3.20), the bathrooms (Figure 3.21) and toilets (Figure 3.22), respectively. On the opposite, the use of the ventilation system by the user showed less variation across households. Almost every household (23 out of 26) stated that they left the ventilation system at its lowest flow rate quasi all the time, with only two and one households having their ventilation system set by default on the second and on the highest (third) position respectively. Only one household reported to interact with their ventilation system every day, increasing the flow rate in their daily profile around cooking and dinner time. Nine out of 26 households from cs2 reported to increase the flow rate only occasionally, less than every day, to remove odours (six households), to lower the humidity level in the bathroom or after using the tumble drier (three households) or when they have visitors (two households).

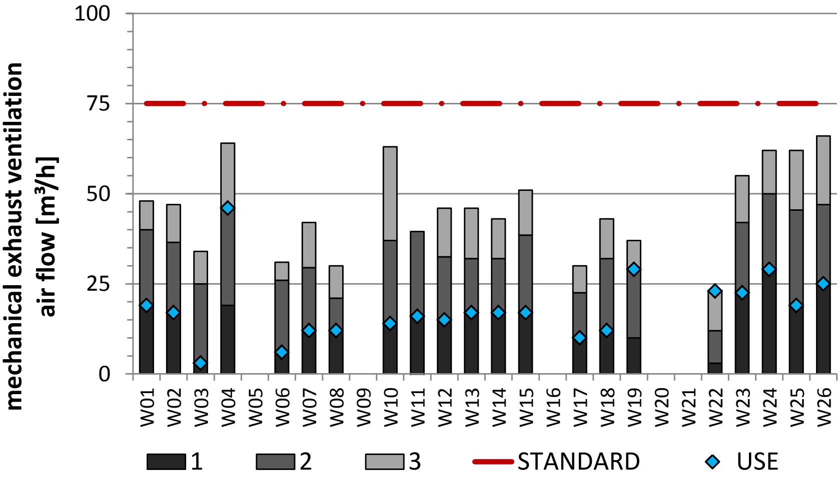

Figure 3.20: Exhaust ventilation air flows in cs2: kitchen.

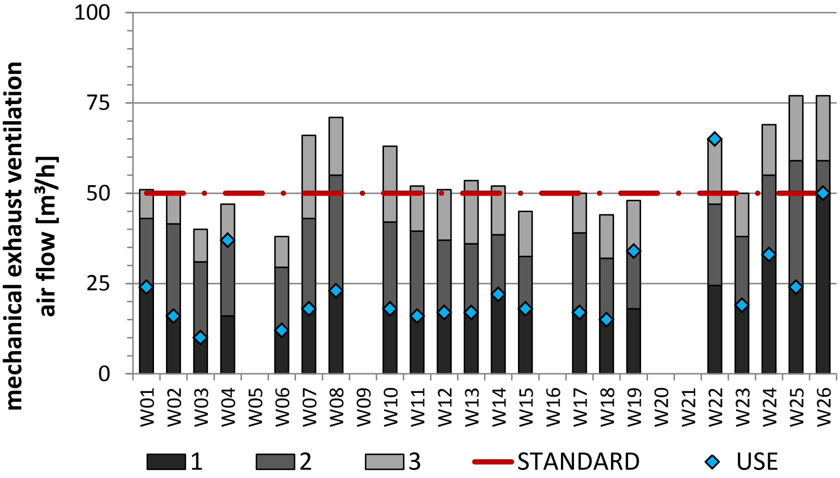

Figure 3.21: Exhaust ventilation air flows in cs2: bathroom.

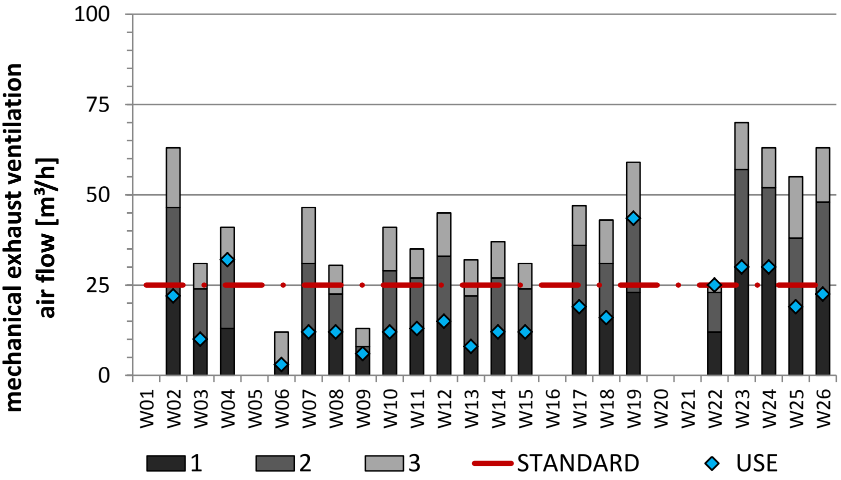

Figure 3.22: Exhaust ventilation air flows in cs2: toilet.

3.3.4 Effects on indoor temperatures and energy use

Differences in building characteristics and user behaviour influence both the resulting indoor comfort and the energy demand. This paragraph looks at both performance criteria of the houses by means of measured indoor temperatures and of the normalized energy use figures respectively.

Indoor temperatures

Figure 3.23, Figure 3.24, Figure 3.25 and Figure 3.26 show the temperatures measured in each house during one winter week, in aggregated form per neighbourhood and per room type. Figure 3.23 and Figure 3.24 relate the indoor temperatures of cs1 and cs2, respectively, to the day cycle, thus comparably both to the daily fluctuations of the external climate and to the reported daily presence, heating and ventilation profiles discussed in the previous sections. The values shown in these figures are calculated in two steps. First, the measured temperatures are averaged for each room of each house separately per daily interval of 15 minutes (from 0:00 to 24:00), resulting in an average daily profile for each room. Subsequently, the median and the 10% and 90% interval of those profiles are calculated per 15 minutes over all houses, per room type. Figure 3.25 and Figure 3.26 illustrate the dependency of the daily average indoor temperatures of all rooms except the living rooms on the daily average outdoor temperatures, for cs1 and for cs2 respectively. These charts demonstrate the higher thermal homogeneity between the rooms of the new houses (cs2) and the smaller dependency of their indoor temperatures on the outdoor temperature, when compared to cs1. This is mainly a result of the better insulated envelope and the higher uniformity with regards to the heating profiles found in cs2 (e.g.

more heating hours for the bathrooms and bedrooms). Because the living rooms are heated more consistently, their temperatures are not significantly correlated with the outdoor temperature. The temperature drops caused by night-time heating set-back are larger in the old houses (Figure 3.23), due to their lower thermal time constant and accentuated by some higher set-point temperatures. Within both neighbourhoods, the temperature hierarchy remained the same between the most heated living rooms, the intermediate circulation area and the mainly indirectly heated bedrooms, however with much higher temperatures in cs2 for all but the living rooms. However, the longer heating durations in the kitchens and bathrooms (see 3.3.3) of the new houses (cs2) together with the improved insulation level raises the position of their temperatures in relation to that of the other rooms. The difference between the kitchen temperatures and living room temperatures were already small in cs1 because most doors between kitchen and living room were either removed or always left open. In cs2, where there also were some open kitchens, there is no significant difference anymore between the kitchen temperature and the living room temperature. The difference between cs1 and cs2 is stronger with regard to the bathroom temperatures. In cs1, the average bathroom temperatures lay very close to the bedroom temperatures, however with higher extreme values (Figure 3.23 and Figure 3.25). In cs2, the median profile of the bathroom temperatures lay very close to the median profile of the living room temperatures, while the 90% percentile for the bathroom values lay higher all day long (Figure 3.24). This results not only from temporary peaks when the bathroom is in use, as Figure 3.26 shows that for some cases the daily average temperatures were higher in the bathroom compared with the living room.

Variations in indoor temperature profiles are higher in cs1, not only between room types, but also between rooms of the same type. This is demonstrated by the wider 10%-90%-bands in Figure 3.23 (cs1) and the larger spread in daily average indoor temperatures for any outdoor temperature in Figure 3.25 (cs1), compared with Figure 3.24 and Figure 3.26 (cs2), respectively. Cs1's higher variation in heating profiles, as discussed in 3.3.3, is only one reason for these wider variations in temperature profiles. The lower thermal insulation levels and the lower resulting thermal time constant of the old houses increase their dependency on the varying outdoor temperature, as illustrated by Figure 3.25. As measurement periods increase, over days with varying outdoor temperature, so will the width of the bands in Figure 3.23 and Figure 3.24. While this is the case for both neighbourhoods, this effect is larger for the old, non-insulated houses because of the larger dependency of their indoor temperatures on the outdoor temperature (Figure 3.25 and Figure 3.26).

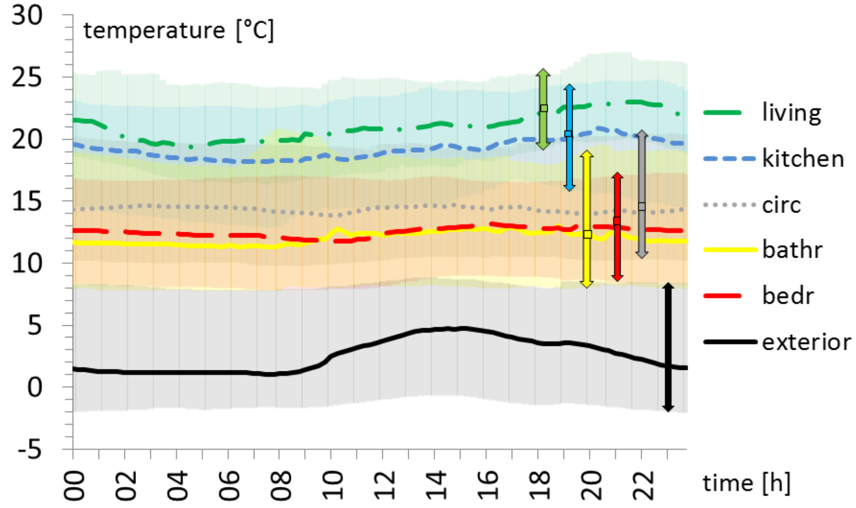

Figure 3.23: Daily temperature profiles (median and 10%-90%-bands) in cs1.

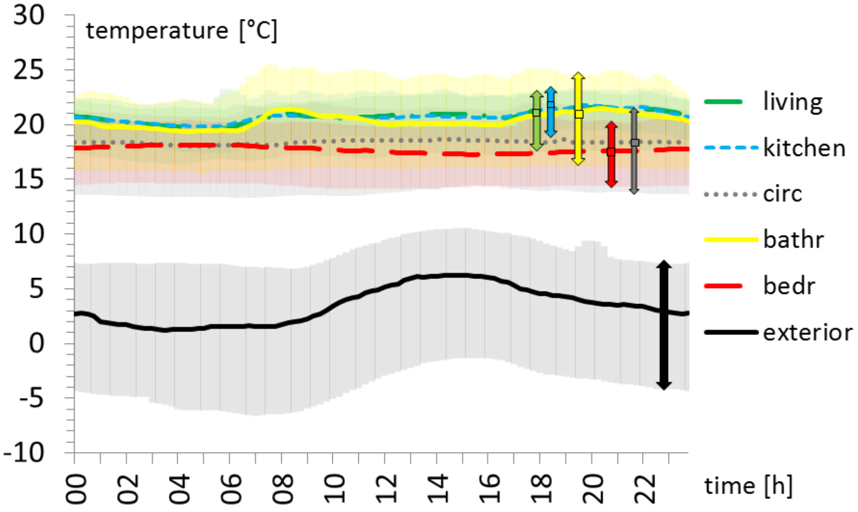

Figure 3.24: Daily temperature profiles (median and 10%-90%-bands) in cs2.

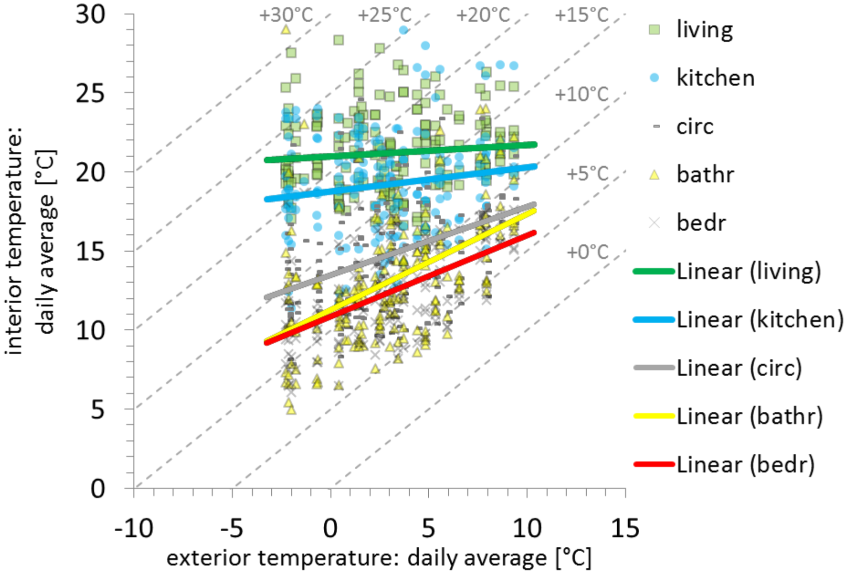

Figure 3.25: Dependency of indoor temperature on outdoor temperature variations: cs1

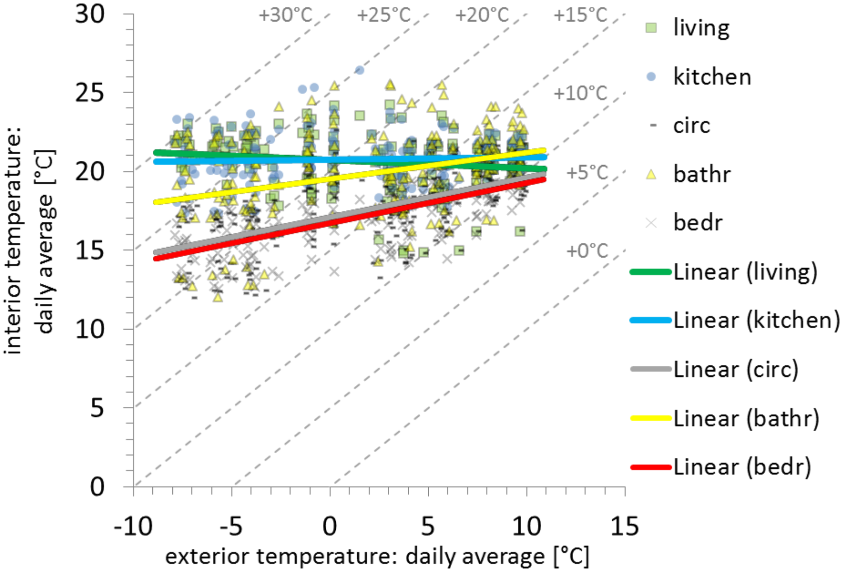

Figure 3.26: Dependency of indoor temperature on outdoor temperature variations: cs2

Energy use: statistical analysis of the determinants (Table 3.6)

BUILDING PARAMETERS (TABLE 3.6)

The building homogeneity within each neighbourhood is disturbed mainly by the alternation between terraced and semi-detached houses. As a direct consequence of the heat loss area being taken into account in the EPB-calculation, this typological differentiation was found to affect the theoretical energy use in both cs1 and cs2. However, the number of adjacent houses (1 for semi-detached houses and 2 for terraced houses) did not prove to be associated with the real energy use in cs1. Additional statistical tests showed that this was caused by the presence of uninhabited houses in that neighbourhood. If only the number of *inhabited* adjacent houses were considered, than a significant negative association was found with the real energy use. Inversely, the higher the number of *uninhabited* adjacent houses (0, 1 or 2), thus differing from the assumptions in the EPB-model, the lower the overestimation of the energy use made by the EPB-model in cs1.

On the opposite, for cs2, where all the houses were inhabited, the number of adjacent houses proved to be associated with the real energy use and not with the prediction error. However, part of this association could be coincidently indirect, because the number of adjacent houses was also associated with the daily heating hours of the living room and the related presence of at least one person in the house or in the living room specifically. Those presence and heating parameters were also associated with the real energy use, but not significantly with the prediction error. This suggests that the difference in typologies is the main cause of these associations with the consumption data, but this could not be checked based on factorial analysis. The limited sample size and the important correlation between the number of adjacent houses and the daily heating hours made those factorial tests inconclusive.

USER PROFILES (TABLE 3.6)

No correlations were found between the real energy use or the prediction gap on the one hand and the household characteristics (age, number of inhabitants…) on the other hand, for any of the neighbourhoods.

No associations were found between the daily heating hours and the consumption figures for cs1, while, as discussed in previous paragraph, the associations between those parameters that were found in cs2 could be accidental. Still, the heating profiles were found to influence the energy use: the heating set-point temperature of the living room that was deduced from the measurements proved to be significantly associated with both the real energy use and the prediction error in both neighbourhoods. Contrastingly, no such correlation was found if, for cs2, the self-reported set-point temperatures were used.

No associations were found between the real energy use or the prediction error on the one hand and the heating profile data about the other rooms. With regard to those other rooms, only a higher number of opening hours of bathroom window in cs2 was found to be associated with a higher energy demand and with a smaller gap with the theoretical energy use. Separately, the numbers of hours that the windows were open in the bedrooms, living room and kitchen were not proven to affect the energy use significantly. Still, summing the opening hours of all windows of the house did result in a more significant association with the real energy use and the prediction error than if only the bathroom window was considered. Compared to the other rooms, the higher significance of the bathroom could be explained by the combination of (1) a high heating probability supporting higher indoor temperatures, (2) the presence of an exhaust vent of the mechanical ventilation system in that room and (3) a higher variation in window opening hours, the latter making the consequences of opening the windows more apparent in the data set.

Table 3.6: statistical associations related to the energy use for space heating: cs1 and cs2

		NB	**N**	**Kendall τ_b**		
				p	**τ_b**	**95% CI**
TYPOLOGY						
adjacent houses: number	energy use: theoretical (EPB)	cs1	26	< .001	-.608	[-.716, -.450]
adjacent houses: number of inhabited	energy use: real	cs1	26	.005	-.449	[-.690, -.137]
adjacent houses: number of uninhabited	energy use: prediction error	cs1	26	.022	.367	[.098, .588]
adjacent houses: number	energy use: theoretical (EPB)	cs2	22	< .001	-.677	[-.745, -.569]
adjacent houses: number	energy use: real	cs2	22	.018	-.430	[-.677, -.097]
adjacent houses: number	heating: hours, week-day, living r.	cs2	22	.008	-.511	[-.741, -.170]
DURATIONS: HEATING & PRESENCE						
heating: hours, week-day, living r.	energy use: real	cs2	22	< .001	.608	[.381, .785]
SET-POINT TEMPERATURE						
heating: set-point θ, living r. (measured)	energy use: real	cs1	26	.027	.318	[.017, .596]
heating: set-point θ, living r. (measured)	energy use: prediction error	cs1	26	.003	.433	[.126, .700]
heating: set-point θ, living r. (measured)	energy use: real	cs2	22	.017	.371	[.094, .642]
heating: set-point θ, living r. (measured)	energy use: prediction error	cs2	22	.006	.433	[.114, .696]
WINDOW OPENING						
windows: opening hours, bathroom	energy use: real	cs2	22	.035	.361	[-.034, .634]
windows: opening hours, bathroom	energy use: prediction error	cs2	22	.006	.474	[.142, .710]
windows: opening hours, building	energy use: real	cs2	22	.016	.381	[.021, .679]
windows: opening hours, building	energy use: prediction error	cs2	22	.016	.381	[.057, .659]

3.4 Discussion

3.4.1 Explaining the prediction gap

The correlations discussed in section 3.3.4 explain part of the *variability* in energy use and in the prediction error as a result of variability in user profiles and as a result of some houses not being inhabited. However, this does not explain why the EPB-models *overestimate* the energy use in all houses and the difference in energy use between the two neighbourhoods.

Difference between both neighbourhoods: behavioural rebound?

HEATING PROFILES OF THE LIVING ROOMS

Both the lower set-point temperatures and the shorter heating durations found in the living rooms of the new houses (Figure 3.13 and Figure 3.17) compared with those of the old houses (Figure 3.14 and Figure 3.17) are in contradiction with the higher overestimation of the energy use by the EPB-model found in the old houses and with the theory on behavioural rebound that is often put forward as one of the causes for the resulting smaller difference that is found in real life between the energy use in old and new houses. That theory postulates that a higher energy efficiency resulting in a lower cost per unit of service (e.g. cost of heating the house to a certain temperature) will result in the users raising their demands (e.g. with regard to comfort by increasing the indoor temperature) or in them paying less attention to wastes in energy resulting from less cautious behaviour (e.g. forgetting to switch of the heaters when leaving the house) [66].

SET-POINT TEMPERATURES

As opposed to the comparison between these two neighbourhoods, a statistical analysis by Shipworth et al. [52] revealed significantly higher set-point temperatures in houses with double-glazing and draught-proofed windows (on average +1.7°C, $p = 0.007$) compared to houses with single glazing and without draught-proofing. The hypotheses they put forward is that those increased temperatures could be evidence of behavioural rebound or simply of the fact that more energy efficient homes enable reaching warmer temperatures. The latter hypothesis might apply in the houses with single-glazing and without draught-proofing in their dataset considering their low average set-point temperature (19.6°C). In fact, plotting the temperatures measured in cs1 also revealed a lack of heating power: the targeted temperatures were often only reached a fair amount of time after the furnace was switched on and while the people were already present in the rooms, sometimes for several hours in case of high demand temperatures. However, this lack of heating power did not result in lower temperatures being ultimately reached and therefore in lower set-point temperatures being deduced from the measurements in cs1: low set-point temperatures were found only in two houses (18.5 and 19°C) while most houses reached much higher values (Figure 3.17) resulting for some cases in daily average living room temperatures exceeding 25°C (Figure 3.25). The former argument put forward by Shipworth et al. that rebound can apply to set-point temperatures in better insulated houses is more difficult to verify or to support based on literature. In fact, a later study by the same author [107] showed no increase in reported set-point temperatures after different upgrades of the building envelopes (roof insulation, double glazing and draught proofing). Still, this leaves the question why, on the opposite, the set-point temperatures are higher in several of the non-insulated houses of cs1. Two hypotheses are put forward based on literature. The first hypothesis relates to the inhabitants: the higher set-point temperatures can in part be explained by the higher number of elderly inhabitants, demanding higher indoor temperatures [47,50,105,139–142]. However, no correlation was found between the age of the inhabitants and the set-point temperature in cs1. The second hypothesis relates to the buildings: the higher set-point temperatures can be selected not for reaching higher comfort levels, but for reaching *similar* comfort levels in the old houses as in the insulated houses. Higher set-point temperatures do not necessarily guarantee higher comfort levels. The poor thermal performance of the building envelope of the old houses was pointed out by the air-tightness and heat-flux measurements, and the presence of large single glazed areas. Combined with the centrally located gas furnace, the air infiltration and the cold window and floor surface temperatures increase the risk for local discomfort, such as draught, radiation asymmetry and cold floor temperatures. Increasing the set-point temperature can partially compensate these forms of local discomfort. Furthermore, these weaknesses of the building envelope and the lack of a central heating system create cold areas in these non-insulated houses, as illustrated by large temperature difference between the rooms (Figure 3.23 and Figure 3.25). Weihl and Gladhart [142] found that in such cases inhabitants rely on overheating the main heated area to keep those cold spots bearable and not because they want the house to reach such high temperatures. This also requires more frequent adjustments to the settings of the heating system than needed for keeping the indoor temperatures within acceptable ranges in weatherized houses [142]. Comparisons between the temperature profiles of both neighbourhoods corroborated this, showing more frequent and higher oscillations of the living room temperatures during the heating periods in the old houses of cs1 compared to the new houses of cs2.

HEATING DURATION

Similar to the higher heating set-point temperatures, the longer heating times in the living rooms of the old houses compared with the values found in the new houses can also be associated with both their different inhabitants and their different building properties. The probability of heating the living room proved to be associated with the probability of at least one person being present and, together, their higher day-time values in the old neighbourhood can be explained by the lower number of people working outside of home in cs1 as a result of unemployment or retirement [125,143,144]. This hypothesis is strengthened by the smaller difference across neighbourhoods when looking at the weekend values in cs2: this higher uniformity during weekends with regard to presence and heating profiles in the living rooms corresponds with the higher uniformity reported in literature with regard to time-use across employment statuses during non-working days compared with working days [144]. Still, these socio-demographic differences between neighbourhoods only explain their different heating probability values during day-time, as a result of different time-use and presence. They do not explain the higher probability of heating the living rooms in cs1 during night-time, when (nearly) all inhabitants reported to be in their bedrooms. Similarly as to the higher set-point temperatures, the longer heating times in the living room can also be explained as a solution for keeping the bedroom at a bearable temperature at night. Indeed, while not asked for in the survey, observations during the visits to the houses and talking to the inhabitants revealed that the doors were often left open to indirectly heat the rest of the house. This corroborates findings from a field study by Conan [55], where 57% of the households stated to always leave the bedroom doors open with heating the bedrooms being the most common reason for doing so. The need for this indirect heating solution in cs1 is confirmed by the low measured bedroom temperatures in those old houses (on average 13°C), notwithstanding the higher probability of leaving the heating system on 24 hours per day.

Concluding, the higher heating set-point temperatures and longer heating hours in the living rooms of cs1 are likely a result of socio-demographic parameters (age and employment status) and a solution for reaching bearable comfort levels in the living room and across the house instead of a result of higher comfort expectations or more lavish behaviour in the old houses, which would oppose the rebound theory.

HEATING PROFILES IN THE OTHER ROOMS

On the contrary, more lavish bedroom heating profiles were found in 7 cases of the new neighbourhood (cs2) letting the bedrooms being heated whenever the central thermostat switches on. The setting of the centralized thermostat in cs2 in the living room is more determinative for the heating times in the bedrooms, bathrooms and kitchens than the use of those rooms. As opposed to the living rooms, those rooms are heated for longer durations in the new houses compared to the old houses. These longer heating times are not justified by an increased use or by a higher heating demand to reach comfort levels: the presence in the bathroom, kitchen and bedrooms during week-days is not significantly higher in the new house and the better insulation level of those houses will result in higher temperatures in those rooms even without additional heating. The increased bathroom heating times thus does not seem to result from increased needs. Three other explanations are put forward. Firstly, the presence of a centralized heating system with central (clock-)thermostat in cs2 makes the synchronous heating of all spaces the easiest and thus the most obvious control choice. Secondly, this could be a case of behavioural rebound: the expectation of a lowered heating demand due to the higher insulation levels in cs2, further emphasized by differences in income between the two groups of households, could explain the more demanding heating profiles found in the bathrooms and the bedrooms of cs2 [69,31,66]. Thirdly, with regard to the kitchens, the frequent occurrence of open kitchens in cs2 could further explain why their heating probability profile fits the heating profile of the living rooms even more closely than is the case for the bathrooms.

EPB assumptions versus field data

INDOOR TEMPERATURE

The relation between daily indoor and daily outdoor temperatures found in the old houses of cs1 (Figure 3.25) closely matches with measurements from 1978 in 1000 homes in the UK [72]. Notwithstanding the lower set-point temperatures and shorter daily heating times found in the living rooms of cs2, the fact that their bathrooms, kitchens and bedrooms are heated more and the building envelope is insulated results in higher temperatures in those recent houses (Figure 3.26), matching more closely with measurements from 2003-2005 in 39 insulated Belgian houses built after 1980 [145–147]. This difference in average indoor temperature in houses with versus without insulation and the lower indoor temperatures found at lower outdoor temperatures are not taken into account in the Flemish energy performance calculation. The Flemish EPB-method considers one time and space averaged heating set-point temperature: 18°C for 24h per day in a single-zone model, independently of the energy performance of the building and without additional factors accounting for the fact that not all rooms are being heated ([80], see Chapter 5). The corresponding average interior temperatures in the models will thus be at least 18°C and are thus, for most of the heating season, overestimated for the old houses without insulation, but not for the insulated houses of cs2. This is further illustrated by Figure 3.27, showing for both neighbourhoods the *building* temperatures calculated as a room-volume weighed average of the room temperatures. It explains in part the overestimation of the heating demand in the old houses and the more so the smaller difference in real energy use between the two neighbourhoods compared with the theoretical prediction.

This is corroborated by a study by Deurinck et al. [68] analysing the physical part of the temperature take-back by comparing results from the same Flemish EPB-method with results from dynamic multi-zone simulations using a stochastically generated distribution of heating profiles. They found a building average temperature increase of 0.94°C at 5°C outdoor temperature when improving the average U-value from 2.00 $W/(m^2.K)$ to 0.58 $W/(m^2.K)$ and a corresponding overestimation of the savings by the EPB-model by 6%. While those values are shown to vary strongly depending on the simulated user profile, they are much lower than the average difference of 2.3°C seen at 5°C in Figure 3.27 and the 62% reported in section 3.3.2. This can be explained partly by the different buildings considered and by the different heating profiles considered in that study and the different heating profiles found in cs1 and cs2: as opposed to the figures from Deurinck et al., the figures presented here result not only of the physical temperature take-back.

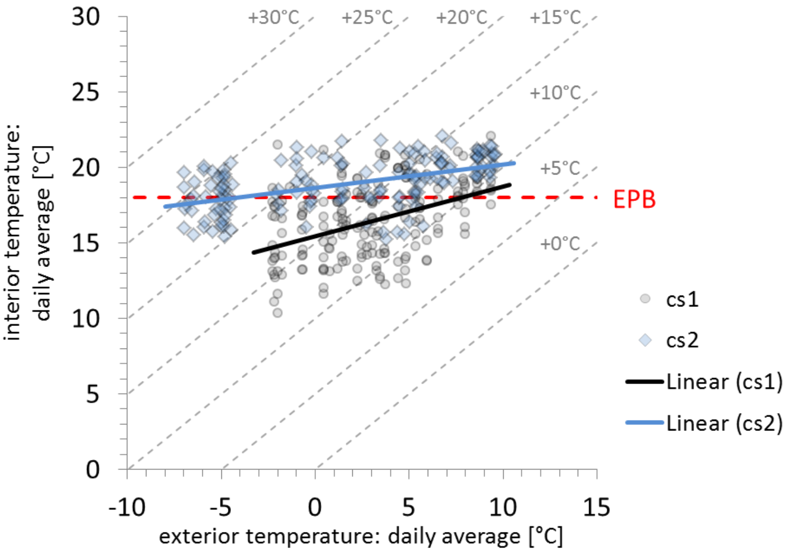

Figure 3.27: Dependency of building average indoor temperature on outdoor temperature variations: cs1 and cs2

Other field-based studies found even higher temperature increases associated with better building insulation levels and with centralized heating. Hunt and Gidman [72] found that centrally heated houses were on average 3°C warmer than other houses and that the difference was greater ‘upstairs’ (mainly in the bedrooms) compared with ‘downstairs’ (mainly in the living rooms) (at a mean outdoor temperature of approximately 6.6°C). However, the authors noted that the presence of a central heating system was also associated with other building characteristics and socio-demographic parameters that could accentuate these differences, similarly to what we found comparing cs1 and cs2. Later studies by Oreszczyn et al. [105] and Hong et al. [70,71] found similar temperature increases on building level (approximately +2.8°C) when both the heating system and the building envelope were upgraded, with also a higher temperature increase in the bedrooms than in the living rooms. The increase was smaller but still significant if only one of both was upgraded, with the increase associated with upgraded heating systems alone (+1.89°C) being higher than the increase associated with only insulation measures (+1.19°C) [71]. The latter is in good agreement with the simulation results from Deurinck et al. Looking further at the effect of different heating systems, Hunt and Gidman [72] noted that on average the temperatures in rooms with a non-central heating system were not significantly different from those rooms with no heating element at all, suggesting a more intermittent use of non-central system than of central heating system. This also further corroborates the comparison made in this chapter between the bathroom heating profiles in cs1 and cs2 (3.3.3) and the corresponding discussion in the previous section.

Hong et al. [70,71] pursued their analysis by looking also at data on energy use and found that, as a result of the temperature take-back, introducing a gas central heating system was not found to reduce the energy use despite the better theoretical efficiency. The situation does not appear to be as extreme for the case-studies analysed in this chapter because a lower energy use was found in cs2 compared to cs1, even though it was smaller than the theoretical difference. However, the difference in performance level between the two neighbourhoods was not the result of limited renovation measures as in the study Hong et al. [70,71], but of the larger difference in building standards between current and approximately 50 year old houses. Still, the same phenomena apply and the increased building average temperature not being taken into account in the EPB-method can in part explain why the real difference in energy use between both neighbourhoods was much smaller than predicted by the EPB-models.

VENTILATION

Similarly to the fixed, single-zone averaged heating profile, the Flemish energy performance calculation methods consider, in addition to the infiltration air flow due to envelope leakage, the same hygienic ventilation flow rate in old houses without dedicated ventilation system as in equally sized new houses with mechanical ventilation systems [80,122,148] (except if the latter have a demand controlled ventilation system [80]) without differentiation between rooms because of the single-zone calculation approach. While the old houses had no mechanical ventilation system, the results showed that this was not compensated by the users opening the windows more often than in the new neighbourhood with ventilation system (except for the bathrooms). This is in agreement with a Danish study by Frontczak et al. [149] who found no significant difference in window opening behaviour depending on the presence of a mechanical ventilation system. The fact that the thus lower hygienic ventilation in the old houses compared with the new houses is not taken into account in the EPB-calculation can further explain why the difference in actual energy use between the two neighbourhoods is lower than the difference in theoretical energy use.

In addition to this lower hygienic ventilation rate on building level, the rare opening of windows (occurring mainly in the bedrooms during day-time) was shown to occur asynchronously to the heating of the rooms both in space and in time (see 3.3.3). Other studies corroborate these findings with respect to zonal differentiation [55–58,60] and time differentiation [58,150]. Based on extensive field surveys, Brundrett [59], Conan [55,56] and Wouters and De Baets [57] also found that the windows in the living areas where opened less often and for shorter periods compared with the windows in the bedrooms, especially during winter season. Measuring the use of windows in single-family houses, Weihl [150] also found that window opening and room heating seldom occur simultaneously: windows were opened only for 2.6% of the hours exhibiting furnace use and the furnace was used only 6% of the time that windows were opened. Furthermore, both Conan [55,56] and Weihl [150] reveal the lower probability of opening windows (especially those in the living area) at lower outdoor temperatures, when it would have the largest impact on the space heating demand.

The fact that opening the windows mainly occurs in the unheated bedrooms and also asynchronously with the heating of the rooms can explain part of the overestimated energy use for space heating, but this will also depend of the accuracy of the total ventilation rates considered in the EPB-method. Interestingly, the study by Wouters and De Baets [57] was conducted in 1985, long before the modern EPB-regulations, and focussed on social houses in Belgium, making them comparable to the houses of cs1. Combining the survey-based data on window openings with formulas for calculating the resulting air flows, they estimated the opening of windows during winter time to result, on average for the single family houses, in an air change rate (ACH) of 0.31 with a median value of 0.14. These estimated values on building level are in the same range as values found by Kvisgaard et al. in 14 natural ventilated dwellings in Denmark, based on the difference between measured values while in use and while not in use, during winter [151]: an average ACH of 0.32 with a median value of 0.24 as a consequence of window openings. This is much lower than the air change rate for hygienic ventilation considered in the Flemish EPB-method (0.77 for the houses of cs1, i.e. in addition to 0.25 due to infiltration), while these average values from literature would be even lower if it were not for a small proportion of high values, as indicated by the even lower median values and the skewed distributions in [151]. Comparisons with other studies (e.g. reported in the literature study by Fabi et al. [58]) are often more difficult because of the different climatic conditions (e.g. during summer), the presence of ventilation systems or the lack of differentiation between air change rates due to infiltration as opposed to the opening of windows. However, the even lower, average total ACH of 0.2 measured in mainly naturally ventilated single family houses built in Sweden between 1961 and 1975 [152] further support the argument that the total air change rate in the old houses without mechanical ventilation system of cs1 is overestimated by the EPB-method. For a terraced house of cs1, the hygienic ACH of 0.77 accounts for 17.5% of the total calculated heat losses. Reducing that estimated ACH by a factor of three to a more realistic value of 0.26 would reduce the total estimated heat losses by 11.6% and the relative reduction of the theoretical heating demand would be even higher, considering that part of the heat losses are compensated by solar and internal heat gains. Considering also the asynchrony in time and space between the heating profiles and the window opening profiles causing those air flows would further reduce the prediction gap.

Energy performance vs. energy use: thermal comfort and indoor air quality (IAQ)

Those fixed, standardized heating and ventilation profiles are considered in the energy performance calculations in order to enable comparisons not of the real energy use, but of the energy performance of the houses (compared to one another and to legal requirements). All houses, with more or less insulation and with better or less efficient systems, are therefore compared considering they will be used so as to guarantee a similar and good indoor climate. This indoor climate is considered to consist of a good thermal comfort and good indoor air quality (IAQ) associated in the model with those fixed heating and ventilation profiles, respectively. It is therefore logical that the calculated energy use will overestimate the real energy use in houses where lower consumption is reached at the expense of the indoor climate, e.g. by lowering the set-point temperatures below comfort levels or omitting to ventilate the rooms.

The measured room temperatures in the old houses, except for the living rooms, are below comfort levels. The higher difference between real and calculated energy use in the old houses of cs1 thus comes at the expense of thermal comfort. Therefore, from the perspective of comparing the energy performance of houses and not their real energy use, one can state that the calculated heat balance should not consider the real average indoor temperatures measured in these houses and that the discrepancy between calculated and real energy use that is associated with decreased indoor temperatures below thermal comfort level should not be corrected in the performance assessment method.

On the opposite, separate analyses of the CO2 and humidity measurements in both neighbourhoods did not univocally indicate that the absence of a ventilation system without being compensated by more frequent opening of the windows resulted in lower indoor air quality in the old houses compared with the new houses [115,117]. In spite of the increased duration of the window openings in the bathrooms of cs1, the absence of a ventilation system combined with the lower bathroom temperatures resulted in increased relative humidity levels in those bathrooms and condensation spots on the non-insulated walls of those bathrooms. However, the CO2-levels in the living rooms were similar in both neighbourhoods and, on the contrary, the CO2-levels were higher in the bedrooms of the new houses than in the bedrooms of the old houses. This mainly results from the higher air leakages via the envelope of the old buildings on the one hand and, on the other hand, from the unreliable driving forces and buoyancy effects affecting the performance of the exhaust system, as discussed by Laverge et al. [115]. Therefore, when modelling these old houses with very leaky building envelopes and without ventilation system, it is questionable to consider the same hygienic ventilation flow rate as a result of window openings in addition to the higher infiltration flow rate, not only when aiming at estimations of their real energy use, but also when making energy performance assessments for comparisons with other buildings with and without mechanical ventilation system.

3.4.2 Data accuracy and completeness influencing statistical analyses on the prediction gap

The results revealed important variations in real user profiles and differences between these profiles and modelling assumptions, e.g. with regard to the heating set-point temperatures. These explain part of the variations in real energy use and part of the gap between theoretical and real energy use. However, some of these variations are not always found to be statistically significant in studies analysing larger data sets (see Chapter 2). The lack of statistical significance in those studies can also be explained in part by findings on these two case-study neighbourhoods.

Explanatory variables

Comparing the measured temperatures with the reported heating profiles showed good agreements with regard to the duration of the heating periods, except for 6 out of 59 households, all from cs1, omitting to report switching off the heating system at night. This could result from the heating periods being interpreted by the respondents as including the times when only the pilot flame of the gas furnace remains on. As reported by Weihl and Gladhart [142] and observed in this study, it is still easier for inhabitants to report their recurrent daily schedules than to make accurate estimates of the temperatures. In fact, we found large discrepancies and no correlation between the self-reported heating set-point temperatures and the measured values. This confirms findings from previous studies comparing measured with self-reported temperatures [51,52,98,140,142], showing even higher discrepancies for individual cases, exceeding 5°C. This can explain the lack of correlation found between self-reported temperatures and energy use found in statistical studies on real data ([47], see also Chapter 2 [25]), as opposed to the strong influence of set-point temperatures revealed by simulation based sensitivity analyses [97,153,154]. One exception is the statistical study by Steemers et al. [49] where a correlation was found between real energy use and set-point temperatures on a dataset of approximately 4800 houses, however the correlation was small and the data set did include actual thermostat settings, not only self-reported estimates. In other studies where significant correlations were found between energy use and self-reported indoor temperatures, the latter often referred to self-reported *time-weighted* set-point temperatures or to self-reported *average* indoor temperatures [47,155–157]. Instead of being only related to the heating set-point temperature during occupancy, the former parameter includes also an estimate of the night-time set-back temperature and duration while, in addition, the latter parameter also results from the technical properties of the building (e.g. the insulation level influencing the temperature drop during heating set-back periods). This could explain why significant correlations with energy use are more easily found for self-reported heating parameters that result not only from temperature-estimation but also from time-estimation.

Not only user related parameters reported by the inhabitants, but also technical parameters reported by professional energy performance assessors can be inaccurate and therefore limit the power of statistical analysis on those parameters or on derived values, e.g. the theoretical energy use. The study reported in Chapter 2 [25] revealed important prediction biases associated with the use of default values instead of measured air permeability values or more accurately calculated system efficiencies. The measured air flow rates in cs2 proved that real technical properties can strongly diverge from their regulated design values. In fact, notwithstanding the ventilation system were exactly of the same type and installed by the same company, the real ventilation flow rates varied more as a result of different tuning than as a result of different user behaviour. Similar findings about the installation of ventilation systems, revealing the need for better quality control, and about the use of ventilation systems were made in other field studies in Belgium [158,159], in Finland [160] and in the Netherlands [47,161].

Reported behavioural and technical data from surveys and EPB-assessments can thus contain considerable errors, affecting not only the accuracy of energy calculation models, but also the power of statistical analyses investigating to what extent those inaccurately reported parameters influence the real energy use.

Dependent variables

The lack of accurate values on those explanatory parameters is not the only lack of accuracy reducing the power of the statistical analysis on real energy use and prediction errors. The figures representing the real energy use, used as the dependent variable, can also lack accuracy or representativeness for the actual energy performance of a building on the long term. This was illustrated by the uncertainty on the normalized real energy use for space heating in both neighbourhoods, caused by simplified and standard assumptions in the degree day based method and possible variations over time in physical properties of the buildings (e.g. resulting from the drying of initial moisture content [119,120]) or in the use of the building. These elements can thus cause a mismatch between explanatory variables and the dependent variables, affecting the correlations between both variables. The fact that the statistical analysis reported in 3.3.4 did identify a few significant correlations in spite of the uncertainty on the consumption data reported in 3.3.2 results in part from approach of the study.

Case-studies, methodology and indirect correlations

A structured research approach based on data from uniform neighbourhoods was presented. It showed the value of combining different types of measurements and surveys (e.g. for defining heating profiles) and the need for more detailed methods for distinguishing different end-uses from aggregated consumption data and for normalizing the energy use (e.g. the energy use for space heating based on gas meter readings). The uniformity of the neighbourhoods allowed identifying variability in workmanship even for one building team (e.g. with regard to ventilation systems). Together with the detailed data collection approach, the uniformity within the neighbourhood also enabled statistical analysis to reveal the important correlation between set-point temperatures and real energy use that is often not identified in much larger datasets. However, with regard to the selection of the case-studies, as a result of the limited number of neighbourhoods, the study cannot claim to be exhaustive with regards to socio-demographic variations, technical variations or the association between them.

The two neighbourhoods differed not only with regard to their building properties, being representative of different building periods and corresponding energy performance levels, but also with regard to their household characteristics and the ownership status. This is symptomatic of underlying socio-demographic differences, as lower insulation levels are commonly found in the houses of elderly people and low-income households [10,139,162] and as lower income levels are more highly represented in rental houses, especially in rented social houses [162]. While this makes the case-studies representative for a considerable segment of the Flemish residential building stock [162], this strong association between technical and socio-demographic parameters questions the general applicability of this study's findings to other combinations of households and houses, e.g. to high performance social housings that will have presence profiles similar to cs1 but technical properties similar to cs2 or to the dataset from previous chapter. Furthermore, the study was limited to terraced and semi-detached single-family houses, while literature indicates that housing typologies (e.g. apartments versus detached houses) can also be a factor within user behaviour [52,163] and while many other technical variations were not included in the dataset (light weight construction types, balanced ventilation systems with heat recovery etc.). Therefore, additional complementary case-study neighbourhoods are needed to further disentangle the *causal* relationships between different parameters and results and to verify the applicability of the findings to other variations and combinations of types of buildings, systems and households.

3.5 Conclusion

The presented study corroborates findings from literature with regard to the large variation in real energy use associated with variations in user behaviour, but it also shows that user behaviour is not to all regards the most uncertain parameter. Almost all inhabitants used their mechanical ventilation system at the lowest flow rate, but the ventilation systems showed large variations in installed flow rates notwithstanding they were of the same type and installed by the same company in similar houses.

The study also confirms reports from literature with regard to the large gap between theoretical and real energy use, becoming smaller at better performance levels. The fact that the regulatory energy performance assessment method overestimates the building average temperature in uninsulated houses and that it does not take into account the difference in indoor temperature between uninsulated and insulated houses explains parts of the prediction gap and of the shortfall. An additional explanation is the overestimation of the ventilation flow rates in old houses with leaky building envelopes and no ventilation system. Bathroom and kitchen windows were opened more often in these old houses than in the new houses with mechanical ventilation systems, but there was no significant difference with regard to the window opening profiles in living rooms and bedrooms.

These and other differentiations of user profiles at room level further explain part of the prediction errors. With regard to the opening of windows, the single-zone calculation method does not only overestimate the total ventilation heat losses, it also does not take into account the fact that the windows that are opened by the inhabitants are mainly those of the unheated bedrooms and almost never those of the heated living room. With regard to the heating profiles, while the higher bedroom temperatures found in the insulated houses compared to the uninsulated houses confirm reports from literature about temperature take-back resulting in large part from the increase in temperature of those unheated rooms, the largest difference in indoor temperature and in heating profiles was found in the bathrooms. The inhabitants of the old houses used the electric heaters in the bathrooms only for short durations, when using the bathroom. Most inhabitants of the new houses with central heating systems let the central thermostat control the heating periods of the bathrooms. As a result, most bathrooms in the new houses were heated for as many hours as the living room, even when the bathrooms were not used. This further resulted in high daily average temperatures in these bathrooms, in some cases even higher than the living room, while the bathrooms were amongst the coldest rooms in the old houses. This shows that different user profiles found in different houses do not only result from the different performance levels of the houses and economic rebound. Different user profiles found in different houses can also result more directly from the different control options of their systems. This also explains why, in addition to the heating profiles, the bathroom window opening profile was found to be significantly associated with the prediction error in the new houses. These findings further indicate the importance of considering variations in user profiles not only on average at building level and not only in the living room, but more comprehensively at the level of the various types of room.

4

Heating profiles: comparison between datasets

This chapter closes the sequence of data-driven chapters by comparing data from the high performance houses discussed in Chapter 2 with corresponding data from the standard and old houses discussed in Chapter 3. It looks back at the differences in heating profiles found in the new neighbourhood compared to those in the old neighbourhood and verifies if it is corroborated by self-reported data from the inhabitants of the high performance houses. Subsequently, it analyses correlations between user and building related parameters on the one hand and the heating profiles on the other hand, helping to explain causes of variations in heating profiles.

4.1 General introduction

Chapter 3 discussed evidence of temperature take-back, based on measured indoor temperatures and differences between real and theoretical energy use in old and new houses. It also showed that the higher building average temperatures found in the new houses (neighbourhood cs2) compared with those found in the old houses (neighbourhood cs1) (3.3.4) did not only result from the higher insulation level causing a physical temperature take-back, but also from more rooms being heated (3.3.3 and 3.4.1). It can be argued that the more lavish heating profiles found in the new houses was the result of having a central heating system with central thermostat. The observed heating profiles were therefore the easiest way of heating the houses of cs2, and this difference in heating profiles is thus not necessarily linked to the higher energy *efficiency* of the system and the better insulated building envelope. In addition, the different socio-demographic characteristics of the households of the two neighbourhoods make the comparison between the two neighbourhoods more complex, because those differences could also explain in part the different heating profiles. It is therefore difficult to substantiate if this trend towards more demanding heating profiles in new houses would further continue and increase the total temperature take-back when looking at high performance houses. In fact, a second question can also be asked regarding the validity of the findings on those datasets for other cases. While the homogeneity of those two datasets was an advantage for the analysis of Chapter 3, it also limits their representativeness and one could wonder if sets of different houses would have resulted in the same findings. Other houses can further differ based not only with regard to their heating and ventilation systems and their insulation levels, but also with regard to their typologies. Regarding the latter, Shipworth et al. [52] found that inhabitants of detached houses reported heating their houses for more hours than inhabitants of terraced houses while Hunt and Gidman [72] found no statistically significant difference between different housing typologies with regard to measured indoor temperature. Shipworth et al. put forward the hypothesis "*that detached houses, with more exposed walls, are being heated for longer in order to provide the same internal temperatures as found in mid-terrace houses*". The dataset they analysed contained mainly data from old houses. Therefore, it is worth asking if more heating hours are also found in the detached houses when comparing only well insulated buildings, because higher insulation levels should reduce the difference in average or operative indoor temperatures resulting from different heat loss areas. These questions regarding possible additional parameters influencing the heating profiles are important for understanding how the gap between theoretical and real energy use evolves with improving performance levels and also for making more sound choices with regard to creating user profiles as input for building energy simulations.

In response, this chapter extends the comparison of heating profiles found at different building performance levels in Chapter 3 (cs1 and cs2) by including the available data from the high performance houses (HPH) discussed in Chapter 2. While half a century separates the construction of the recent houses of cs2 from that of the old houses of cs1, less than 5 years separates the high performance houses from cs2. Those houses, constructed over the last 10 years, all include centralized heating systems, making the high performance houses differ from the houses of cs2 mainly by the performance of their systems and of the building envelope.

4.2 Data on heating profiles: availability, processing and analyses

4.2.1 Comparison between the data sets: houses and households

The characteristics of the houses and of the households of cs1, cs2 and HPH were discussed in detail in Chapter 2 (HPH, see 2.2.4) and Chapter 3 (cs1 and cs2, see 3.2.1, 3.3.1 and 3.3.3). This paragraph only summarizes the main similarities and differences.

While the two neighbourhoods (cs1 and cs2) mainly consisted of terraced houses and a few semi-detached houses, the HPH-dataset mainly consists of detached houses that are, on average, larger than the houses of the two neighbourhoods. The variations in technical characteristics are low within cs1 and cs2 because each neighbourhood was built by one building team and with the same type of building envelopes and systems. The houses of cs1 are old houses with no insulation, mainly single glazing, no central heating system (except for one house) and no mechanical ventilation system. The houses of cs2 are built to more modern standards: they are insulated, have a central heating system with a gas boiler and a mechanical exhaust ventilation system. Compared with cs1 and cs2, the HPH-dataset is much larger and not as homogeneous. Similarly to cs2, the houses of HPH are modern houses built over the past 10 years, but they were built to higher performance standards. 83% of the HPH-houses have a mechanical, balanced ventilation system with heat recovery and 14% have a mechanical exhaust ventilation system. 33% have a heat pump and only 5 houses (1%) have no central heating, but local heaters.

Compared with the old houses of cs1, the new houses of cs2 and HPH are inhabited mainly by young families whose heads of the family, on average, have higher education levels and fewer of them are unemployed or retired. While most inhabitants of cs1 are social renters, cs2 has a mix of private renters and owners and 99% of the houses of HPH are inhabited by their owners.

The cases included in cs2 and HPH are thus more similar than those of cs1, not only with regard to the technical characteristics of the houses but also with regard to their households. They are thus more representative of current new buildings, though with a differentiation regarding their performance level. In addition to the technical difference between the cases of each dataset, the different data-gathering approaches also result in a differentiation with regard to the available data on the buildings and the households of the three datasets.

4.2.2 Availability and comparability of the data

Heating hours: number versus times

The inhabitants of cs1 and cs2 were asked to fill in a table indicating at which hours the heating was on in each room during an average week-day, enabling making the 24-hours profile charts discussed in 3.3.3 (see also 3.2.2). In addition, in cs2 they were also asked to do this for an average weekend-day. Less detailed data is available for the houses of HPH. Their inhabitants were only asked to report the number of hours the rooms were heated during an average week-day. Therefore, this chapter compares the available data at the minimal comparable level: that of the data from HPH, counting the number of reported heating hours in cs1 and cs2 to obtain comparable values. As opposed to cs1 and cs2 (see 3.3.3), comparison of the heating times or durations with similar data on presence or on ventilation is impossible in HPH, for no such data was collected at room level on HPH. The only data on presence available for HPH was the number of people being at home during day-time for each day of the week.

Room types

While the inhabitants of cs1 and cs2 were only questioned about their heating profiles for the living room, the kitchen, the bedrooms and the bathrooms, the inhabitants of HPH were asked for the heating hours of all the rooms present in their house. This resulted in complementary data on toilets, circulation areas, office-rooms, play-rooms, garages, attics and basements. Therefore, after comparing the data between the different neighbourhoods with regard to the living rooms, kitchens, bedrooms and bathrooms, a second analysis compares the values of all the rooms within HPH.

Self-reported set-point temperatures

That second analysis also looks at the self-reported set-point temperatures collected in the surveys on HPH. No temperatures measurements took place in that study. While previous chapter showed the lack of reliability on self-reported set-point temperatures (see 3.3.3 and 3.4.2), they are analysed here because for HPH they were reported not only for the living area (as was the case in cs2), but also for all other heated rooms. It is assumed that, while those self-reported absolute temperature values are probably inaccurate, the relative *difference* between the values reported for the different rooms can give valuable *qualitative indication* on the relative difference in target temperatures between the different rooms. The self-reported set-point temperatures of almost all rooms of corresponding houses (e.g. bedrooms and living rooms) were significantly correlated. This could result from the fact that the households demanding higher temperatures in the living room indeed also demand higher temperatures in the bedrooms, but, considering the large discrepancies between measured and self-reported temperatures, it could also result from the fact that one respondent overestimates all temperatures in general while the other does not. Therefore, when analysing the set-point temperatures in different rooms, comparisons are made based on the *differences* between the reported set-point temperature for the different rooms of the same house, serving as an indication of the differentiation between rooms instead of as an indication of the actual set-point temperatures in the rooms.

Statistics

SAMPLE SIZE

33 households of cs1 and 26 households of cs2 reported about their heating profiles in the living room, the kitchen, the bathroom and the bedrooms. For HPH, the number of cases that can be analysed depends on the considered parameter because not every room type was present in each house and because controlling the data revealed some erroneous entries that needed to be removed (see 2.2.2). Each statistical analysis is based on the maximum number of cases for which the required non-erroneous data was available ('pairwise deletion') and the resulting sample sizes are reported in the results section. Indicatively, 520 reported set-point temperatures and 499 reported numbers of heating hours are available with regard to the living rooms.

TESTS

While the HPH data set includes more variation with regard to its houses and households than cs1 or cs2, Chapter 2 showed it was still relatively homogeneous when compared to the whole building stock. Therefore and because of its still limited sample-size, the data set is not suited for defining representative sets of user profiles based e.g. on statistical cluster analysis. However, the sample is large enough for statistical analyses studying some hypotheses on correlations between characteristics of the heating profiles in the different rooms and of the users and their houses.

This was performed using statistical methods discussed in Chapter 2 and 3 (see 2.2.3 and 3.2.2). The data on the heating hours had multimodal distributions resulting in the residuals of statistical correlation analyses not meeting the parametric assumptions. Therefore, Kendall tau-b associations were used for the direct correlation analyses (see 2.2.3). In addition, partial rank-based correlations were also used, more specifically partial Spearman (rho) correlations, allowing for testing correlations between two variables while controlling for a third variable.

HYPOTHESES

The focus of the statistical analysis is based on findings discussed in Chapter 3 and additional literature.

This chapter verifies two correlations discussed in Chapter 3: the association between the presence of people and the heating hours, and the association between the heating hours of the living room and those of the other rooms in centrally heated houses. Chapter 3 argued that, from the data on cs1 and cs2, it could not be analysed if the more demanding heating profiles of cs2 compared to cs1 were caused only by the presence of a central thermostat or if those also resulted from behavioural rebound associated with the better performance of the houses of cs2 and the socio-economic situation of their households. The HPH-dataset is larger and more varied. Therefore, statistical analyses in this chapter also focus on the association between the heating profiles on the one hand and, on the other hand, the income of the households and the technical characteristics of the houses influencing their energy performance. The most important technical variations regard the ventilation system (exhaust systems versus balanced systems with heat recovery), the heating system (including high and low temperature gas based systems and heat-pumps) and the insulation level of the houses.

In addition, the set of analysed parameters also includes the differences in housing typologies (terraced, semi-detached or detached) because of Shipworth et al. [52] reporting that detached houses are heated for more hours.

4.3 Results

4.3.1 Comparison between datasets: daily heating durations

Figure 4.1, Figure 4.2 and Figure 4.3 compare the daily number of heating hours in the kitchens with the daily number of heating hours in the living rooms of the corresponding houses for the old neighbourhood (cs1), the recent neighbourhood (cs2) and the high performance houses (HPH), respectively. The sizes of the binned dots indicate the number of households they represent. Because of the different sample sizes, these dots are scaled in each chart separately to be representative of the percentages within each dataset. In total, only one household (from HPH) reported that they did not heat their living room. While the inhabitants of cs1 did not have a heating element in their kitchen, resulting in the dots forming a horizontal line at 0 heating hours for those kitchens (Figure 4.1), almost all households of cs2 (23 out of 26, 88%) and HPH (99%) made use of their possibility of directly heating their kitchen. Moreover, except for 4 households of HPH (less than 1%), all households who heated their kitchen did it for as many hours as they heated the living rooms, as indicated by the many dots forming a diagonal line. As argued in Chapter 3, those households supposedly used only the central thermostat for defining the heating times. While this makes the cases of cs2 and HPH similar, the living rooms and thus also the kitchens of HPH are heated for more hours per day, with 34% households of HPH heating their house for 24 hours a day, while only one of the 26 households of cs2 did so.

Figure 4.4, Figure 4.5 and Figure 4.6 make a similar comparison with the heating hours of the living rooms, but with regard to the bedrooms instead of the kitchens. As opposed to the findings on the kitchens, the fact that all bedrooms of cs2 had a heating element while this was not the case for all the houses of cs1 did not result in the bedrooms being heated by many more households in cs2: only 8 of the 26 households (31%) of cs2 heated at least one bedroom (see 3.3.3). However, 6 of the 8 households heating their bedrooms did so for as long as they were heating their living room. The bedroom heating profiles of HPH are very similar to those of cs2, except for the fact that more households heat their bedrooms (approximately 50%), but this difference is not statistically significant (Table 4.1). The fact that many households of HPH heated their living room 24 hours per day and that many of them also heat their bedrooms for as many hours as their living room results in almost one in every five households in HPH heating their bedrooms for 24 hours per day, while only one household did so in cs1 and not one household in cs2.

Figure 4.7, Figure 4.8 and Figure 4.9 extend the analysis by looking at the bathrooms. For cs1, the use of the decentralized, electric heaters in the bathrooms resembles the use of the decentralized, electric heaters in the bedrooms, both being used intermittently for brief durations. On the opposite, the centrally heated houses of cs2 and HPH show heating hours in the bathrooms that are more similar to the higher number of heating hours in their kitchens and living rooms. However, a higher number of households switch the heating of the bathrooms off while still heating the living area (35%).

Adding the data on HPH to the comparison of the heating hours thus appears to confirm the importance of the central heating in defining the heating hours not only of the living room, but also of the kitchen and the bathroom, as was discussed in Chapter 3. The main differences between the centrally heated houses of cs2 and HPH are the longer number of heating hours of the living room and the lower number of households heating the bathroom for as many hours as they heat the living room.

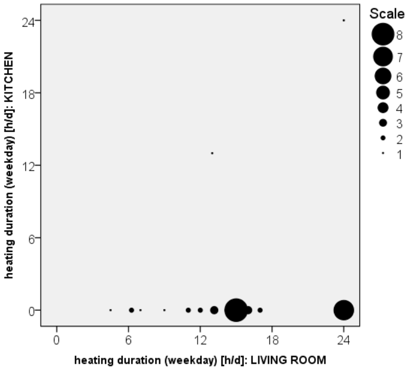

Figure 4.1: daily heating duration: kitchens vs. living rooms, cs1

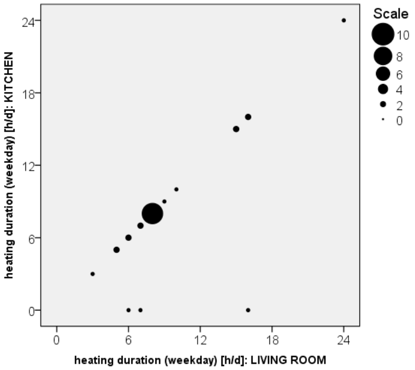

Figure 4.2: daily heating duration: kitchens vs. living rooms, cs2

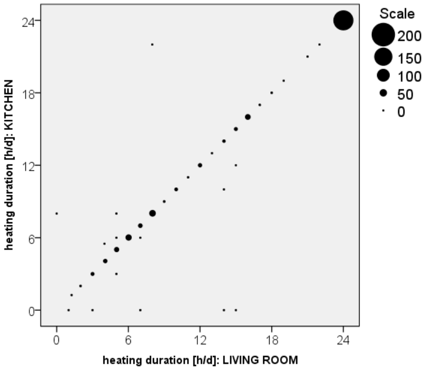

Figure 4.3: daily heating duration: kitchens vs. living rooms, HPH

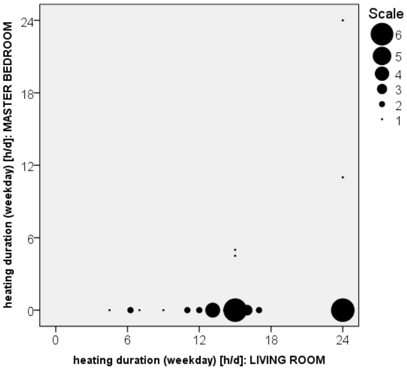

Figure 4.4: daily heating duration: <u>bedrooms</u> vs. living rooms, <u>cs1</u>

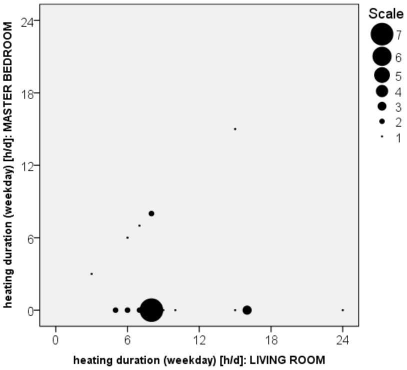

Figure 4.5: daily heating duration: <u>bedrooms</u> vs. living rooms, <u>cs2</u>

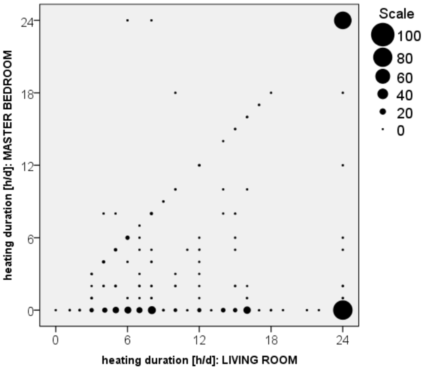

Figure 4.6: daily heating duration: <u>bedrooms</u> vs. living rooms, <u>HPH</u>

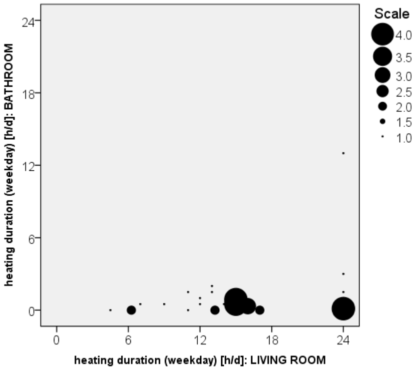

Figure 4.7: daily heating duration: <u>bathrooms</u> vs. living rooms, <u>cs1</u>

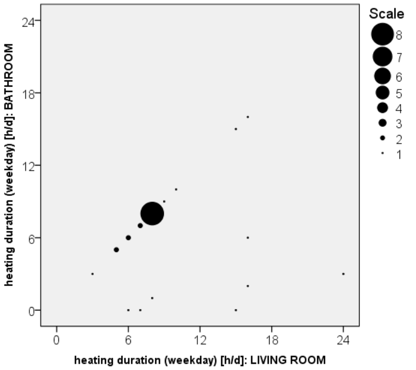

Figure 4.8: daily heating duration: <u>bathrooms</u> vs. living rooms, <u>cs2</u>

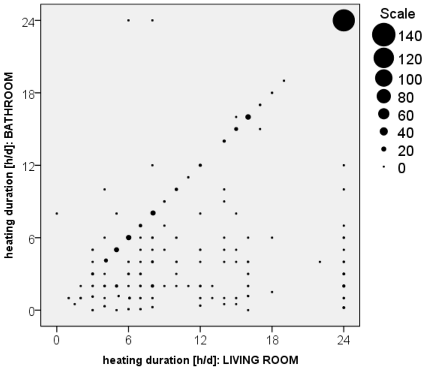

Figure 4.9: daily heating duration: <u>bathrooms</u> vs. living rooms, <u>HPH</u>

4.3.2 Comparison between rooms in HPH: daily heating times and set-point temperatures

Before investigating what parameters can explain that HPH shows a higher number of heating hours than cs1 and cs2, this section reports in more detail on the heating profiles of HPH. It extends the analysed dataset by including the self-reported set-point temperatures and also data on the other room types that were not documented with regard to cs1 and cs2. Rooms that were reported as not directly heated are included in the charts on the heating hours with a value of 0 hours. The charts showing the self-reported set-point temperatures only show values on the directly heated rooms, for which set-point temperatures can be defined and were reported. In addition to the thermostat-related approach of comparing the profile data of the different rooms with the data on the living area, this section also looks for further association between those other rooms directly.

4.3.2.1 Comparison with the living room

(Characteristic figures on the heating hours and on the heating set-point temperatures of HPH can be found in Table 4.1 and Table 4.2, respectively.)

In HPH, most self-reported set-point temperatures for the living room are in the range 20-22°C (86%) with a very large number of households reporting 21°C (39%) (Figure 4.10, Table 4.2). This range is approximately the same as the range of self-reported values of cs2 (see 3.3.3). The latter data set seemed to be less homogeneous (Figure 3.16), but this can be caused by the smaller sample size.

Figure 4.10, Figure 4.11 and Figure 4.12 show that most inhabitants reported the same set-point temperature as in their living room for their kitchens (97%), offices (77%) and playrooms (67%) and that only few of them report lower values (in the latter group on average 2°C and 2.3°C lower for the office and play rooms, respectively). As opposed to the kitchen, a considerable number of households heated the office rooms and playrooms only intermittently or not at all (see also *Table 4.1*).

The circulation area, toilets and storage or washing rooms (Figure 4.13, Figure 4.14 and Figure 4.15, respectively) have very similar heating profiles. For quasi all houses, they are either not heated or heated for as many hours as the living room, probably following the settings of the central thermostat. Households that heat their living rooms 24 hours per day are much more likely to follow the latter approach. This is further underpinned by the statistics in Table 4.3. The spread in reported set-point temperatures for these three rooms is larger than that for the kitchens, offices and playrooms (Table 4.2).

The variation in heating profiles is larger in the bedrooms (Figure 4.16) and in the bathrooms (Figure 4.17), as discussed in the previous section comparing these heating hours with those of cs1 and cs2 (see 4.3.1). While the bathrooms are heated by nearly all households, the bedrooms are not. The probability of heating the bedrooms is higher for households heating their living rooms for more hours, but that association is less strong than for the circulation area (Table 4.3). The difference is only significant when comparing the households heating their living room for 24 hours per day with the other households. With regard to the set-point temperatures, the bedrooms showed on average the lowest values of all heated rooms, with 18°C being the most frequently reported value. On the opposite, the highest set-point temperatures and the only set-point temperatures higher than those of the living rooms were found in the bathrooms, with a mode and median of 22°C and 5% reporting values of 24°C or more. Finding lower and higher self-reported set-point temperatures in the bedrooms and in the bathrooms of HPH, respectively, is congruent with the lower bedroom temperatures and higher bathroom temperatures measured in cs2 (see 3.3.4) and also in other studies (see 3.4.1).

Only 17, 6 and 22 households reported heating their garage, basement and attic respectively (Table 4.1). This corresponds to, respectively, 6%, 3% and 7% of the houses having those rooms. In addition to these very low numbers, no information was available on the characteristics of those rooms or on their use. It is e.g. unknown if the attics were mere crawl spaces that could be used for storage only, or fully accessible functional spaces. It is also unknown if those spaces were located within the insulated envelope of the building: the attics could have either loft insulation or roof insulation, the garages could be located in the house or adjacent to the house. For those reasons, the few reported heating hours and set-point temperatures of the garages, basements and attics are not further discussed in this chapter.

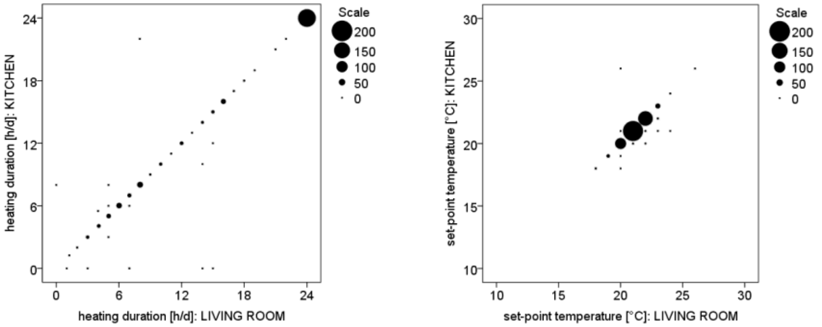

Figure 4.10: heating duration & set-point temperatures (HPH): <u>kitchens</u> vs. living rooms

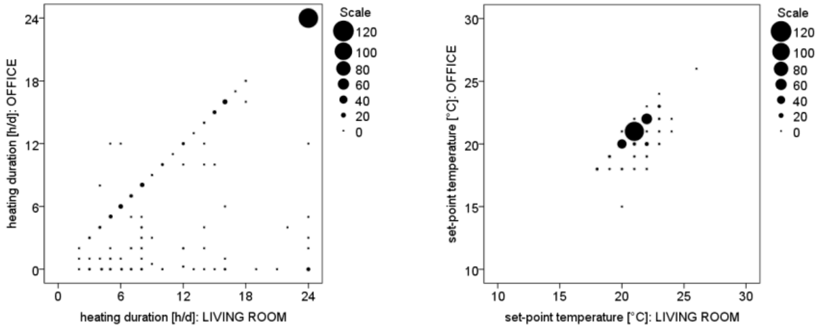

Figure 4.11: heating duration & set-point temperatures (HPH): offices vs. living rooms

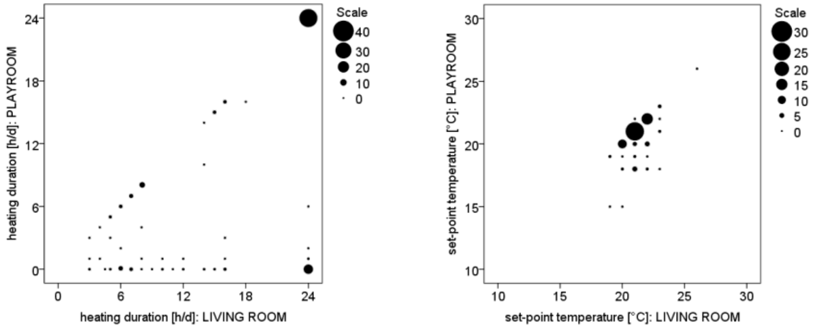

Figure 4.12: heating duration & set-point temperatures (HPH): play- vs. living rooms

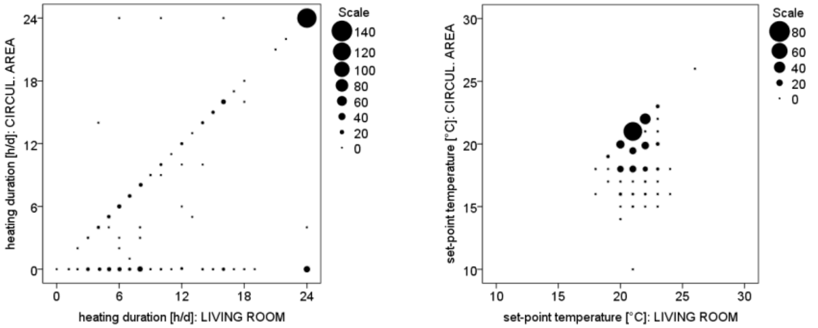

Figure 4.13: heating duration & set-point temperatures (HPH): circulation vs. living r.

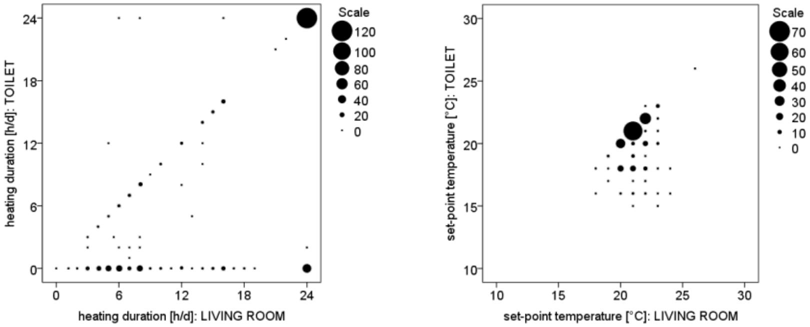

Figure 4.14: heating duration & set-point temperatures (HPH): toilet vs. living rooms

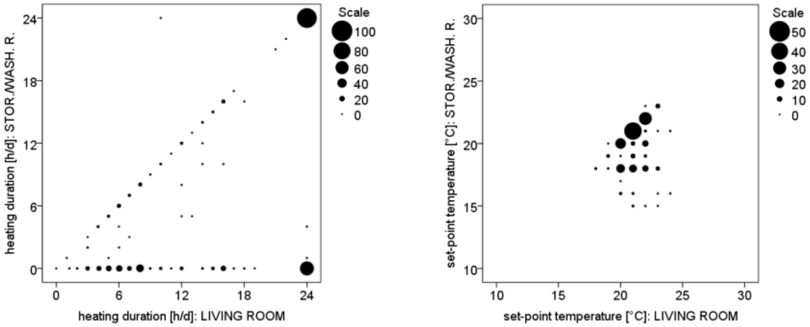

Figure 4.15: heating duration & set-point temperatures (HPH): storage/washing vs. living rooms

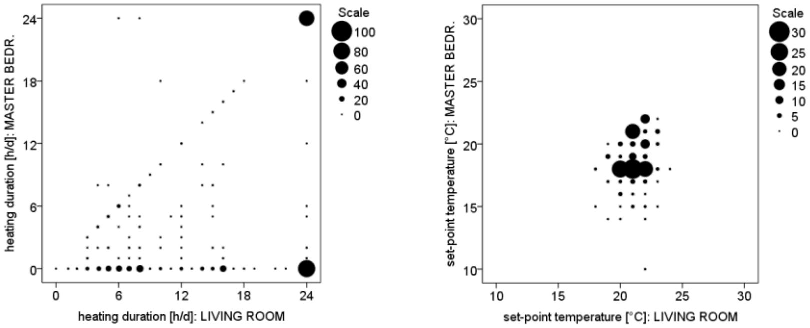

Figure 4.16: heating duration & set-point temperatures (HPH): bedrooms vs. living rooms

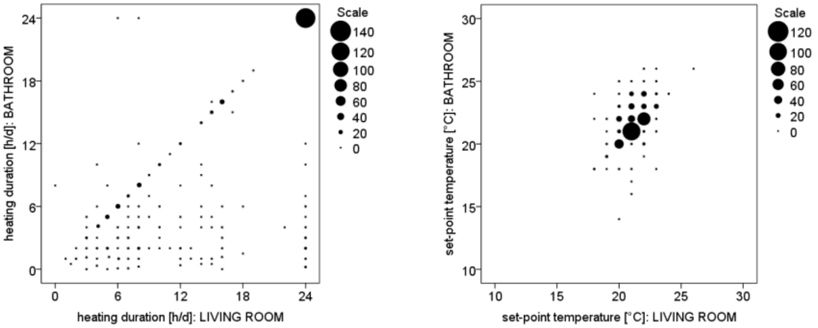

Figure 4.17: heating duration & set-point temperatures (HPH): <u>bathrooms</u> vs. living rooms

Table 4.1: heating durations per room: <u>HPH</u>

	Heated?	If heated:			
		Heating time compared to living r.			
	YES	N	less	equal	more
living r.	100%	499	0.0%	100.0%	0.0%
kitchen	99%	486	0.8%	98.4%	0.8%
play r.	66%	82	20.7%	79.3%	0.0%
office r.	84%	286	14.0%	85.0%	1.0%
hall	64%	298	6.0%	92.3%	1.7%
washing r./stor.	45%	206	9.2%	90.3%	0.5%
garage	6%	17	5.9%	88.2%	5.9%
basement	3%	6	33.3%	66.7%	0.0%
attic	7%	22	27.3%	68.2%	4.5%
toilet	50%	233	5.6%	92.7%	1.7%
bathr.	98%	478	34.9%	63.0%	2.1%
children bedr.	50%	222	37.8%	59.0%	3.2%
master bedr.	42%	195	32.8%	64.6%	2.6%

Table 4.2:self-reported heating set-point temperatures per room: HPH

	N	av. [°C]	Mdn. [°C]	5% [°C]	95% [°C]	Mode [°C]	%=Mode -
living r.	519	21.1	21	19	23	21	39%
kitchen	506	21.1	21	19	23	21	39%
play r.	87	20.5	21	18	22	21	32%
office r.	305	20.7	21	18	22	21	38%
hall	312	19.6	20	16	22	21	24%
washing r./stor.	218	19.7	20	16	22	18	27%
toilet	246	20.0	20	16	22	21	28%
bathr.	500	21.8	22	19	24	22	27%
children bedr.	234	19.1	19	16	22	18	37%
master bedr.	206	18.7	18	15	22	18	39%

NOTES: ‘5%’ and ‘95%’ = percentiles ; ‘%=Mode’ = percentage of households reporting the mode.

Table 4.3: association between the number of heating hours of the living room and the probability of heating another room: HPH

living rooms	heating hours:		[0:12[	[12:24[	24
	N:		224	105	171
	%:		45%	21%	34%
	N	p	percentage heated		
kitchen	493	*(n.s.?)*	*98%*	*98%*	*100%*
play r.	126	n.s.	*61%*	*61%*	*70%*
office r.	349	.003	76%	85%	90%
hall	480	< .001	48%	67%	80%
washing r./stor.	467	< .001	32%	45%	61%
garage	293	.002	2%	7%	11%
basement	194	*(n.s.?)*	*3%*	*3%*	*4%*
attic	350	*(n.s.?)*	*5%*	*5%*	*10%*
toilet	478	< .001	30%	52%	74%
bathr.	496	*(n.s.?)*	*97%*	*99%*	*98%*
children bedr.	458	.031	46%	48%	57%
master bedr.	490	.010	38%	34%	52%

notes:
N = number of cases with that reported to have that room type and also if they heated those rooms or not
n.s. = not significant (p > .050)
(n.s.?) = some sub-samples are too small to test significance

4.3.2.2 Statistical and quantitative association between the heating profiles of the different rooms

The figures from previous section 4.3.2.1 illustrated the strong association between the heating profiles of the living room and those of the other rooms without analysing if the households that chose to heat e.g. their hall are the same as the households that chose to heat e.g. their bedrooms. However, this information is important e.g. for defining realistic sets of heating profiles on building level, for use e.g. in stochastic analyses. The associations are documented statistically in Table 4.4. That table shows if the odds of heating one room type is associated with the odds of heating another room type. The table does not include values related to the living room, kitchen or bathroom because those rooms were heated by nearly all households, resulting in a lack of statistical power when analysing their odds of being heated. Similarly, the table does not include associations with the garage, the basement or the attic because not enough households reported heating those rooms. Comparing all other rooms one with the other always resulted in very significant associations, but some were much stronger than others. Only one direct combination of two rooms had odds of being heated that were not significantly associated: the play room and the toilet. Based on the strongest associations with regard to their probability of being heated (Table 4.4) and also on the differences between their heating hours (Table 4.5) and set-point temperatures (Table 4.6), rooms can be clustered into groups. Because the discrete choice of heating a room or not is already analysed by means of odds ratios in Table 4.4, the quantitative figures on the heating hours shown in Table 4.5 and those on the set-point temperatures shown in Table 4.6 only relate to the rooms that are heated, thus corresponding to all dots in the figures of section 4.3.2.1, except the ones forming a horizontal line at zero heating hours. The percentages connecting two room types (row and column, upper right side) in Table 4.5 show, for the households that heat both types of room, the percentage of those households that heat them for a *different* number of hours per day. The values connecting two room types on the lower left side of the table show, for that percentage of the households that heat both types of rooms for a different number of hours, the *average difference* in heating hours associated with each room. For example, 35% of the households that heat both the living room and the master bedroom (41% of all households according to Table 4.1) do not heat these rooms for the same number of hours per day. On average, those 35% heat their master bedroom 6.7 hours less than the living room. Table 4.6 follows the same approach but with regard to the set-point temperatures.

The first cluster was already indisputably recognisable in the previous section and consists of the living area and the kitchen. Respectively 100% and 99% reported heating those rooms. Of those 99%, only 2% report different heating hours and only 3% report different set-point temperatures (Table 4.5 and Table 4.6). For those rare cases, the kitchen is on average heated to 1.2°C higher temperatures but for 0.8 hours less each day.

A second, obvious room cluster consists of the children bedrooms and the master bedrooms. The odds of heating the children bedrooms if the master bedroom is heated are very high (OR=37.62, 95% CI[21.82, 76.71], p<.001) and less than 10% of the households that heat both types of bedrooms heat each type differently. They heat the master bedrooms on average 2 hours less and to 2°C lower temperatures.

A third, strongly correlated group consists of the hall, the toilet and the washing or storage room, with the hall being the most likely heated of all three (Table 4.1). Not only do they have very strong associations with regard to their odds of being heated (Table 4.4), if they are heated directly than their reported heating hours and set-point temperatures are rarely different (≤ 6% and ≤ 28%, respectively) and, when different, the difference is small (Table 4.5 and Table 4.6). By comparison, while their heating hours are also rarely different than those of the living room (≤ 10%), approximately 50% report heating those rooms to a lower temperature, on average by a difference of -3°C. This is also the reason why the office rooms are not included in this cluster: while their odds of being heated if the hall is heat are very high and while, in that case, the number of heating hours are rarely different (11%), their set point temperatures differ in 43% of those cases, showing values that are on average 2.5°C higher in the office rooms than in the halls.

The odds of heating the play room are much higher if the office room is also heated (Table 4.4), suggesting that these two room types could form a fourth strong cluster. They differ more with regard to their heating hours and set-point temperatures. If both are heated, 16% heat them for a different number of hours, heating the office rooms for on average 5.6 hours more (Table 4.5). 31% of those households also report a different set-point temperature, but some give higher values for the play room and others for the office room, resulting in no difference when taking the average (Table 4.6).

One room remains: the bathroom. 98% reported heating their bathroom, to on average less heating hours but higher temperatures than all other heated rooms. It is thus the room that is most likely being heated intermittently (see also Table 4.1).

Table 4.4: association (odds ratios OR) between the probabilities of heating different rooms: HPH

		office r.	hall	wash./stor. r.	toilet	child. bedr.	master bedr.
play r.	N	110	132	131	132	133	132
	OR	6.42**	3.38**	2.68*	n.s.	5.21	3.97
	95% CI	[2.14, 30.02]	[1.51, 8.15]	[1.25, 6.50]	n.s.	[2.32, 13.37]	[1.80, 10.35]
office r.	N	-	360	346	357	337	360
	OR	-	6.73	3.77	3.56	3.41	2.78**
	95% CI	-	[3.68, 14.13]	[1.97, 8.59]	[1.95, 7.43]	[1.79, 7.54]	[1.48, 5.87]
hall	N	-	-	474	487	463	495
	OR	-	-	5.10	12.96	2.30	2.59
	95% CI	-	-	[3.30, 9.15]	[8.14, 23.01]	[1.54, 3.48]	[1.74, 3.99]
wash../stor. r.	N	-	-	-	475	451	483
	OR	-	-	-	4.55	2.35	2.45
	95% CI	-	-	-	[3.07, 6.96]	[1.61, 3.51]	[1.68, 3.70]
toilet	N	-	-	-	-	464	495
	OR	-	-	-	-	1.97	2.09
	95% CI	-	-	-	-	[1.37, 2.94]	[1.46, 3.05]
child bedr.	N	-	-	-	-	-	474
	OR	-	-	-	-	-	37.62
	95% CI	-	-	-	-	-	[21.82, 76.71]

NOTE: all odds ratios are significant at the level $p < .001$, except **: $p \leq .010$; *: $p \leq 0.050$; n.s.: not significant

Table 4.5: difference between the heating hours of the heated rooms: percentage of cases with different self-reported values and average difference for those cases [h]: HPH

Δ heating hours	liv. r.	kitchen	play r.	office r.	hall	wash./stor.r.	toilet	bathr.	child. bedr.	master bedr.
living r.	-	2%	21%	15%	8%	10%	7%	37%	41%	35%
kitchen	1.2	-	20%	15%	7%	10%	6%	37%	41%	35%
play r.	-9.9	-10.2	-	16%	17%	15%	13%	33%	34%	31%
office r.	-6.4	-6.4	5.6	-	11%	10%	12%	33%	38%	31%
hall	-2.2	-2.5	8.5	4.2	-	6%	3%	32%	33%	30%
wash./stor.r.	-5.5	-5.4	-0.1	-0.7	-0.9	-	2%	27%	34%	30%
toilet	-1.9	-1.5	13.5	5.8	0.3	3.0	-	25%	31%	26%
bathr.	-7.9	-8.1	-0.3	-5.4	-8.8	-7.2	-9.4	-	33%	28%
children bedr.	-7.4	-7.2	-0.7	-5.5	-7.6	-5.7	-7.3	-1.8	-	6%
master bedr.	-6.7	-6.7	1.1	-4.9	-7.2	-5.4	-7.6	-1.5	-2.1	-

Table 4.6: difference between the heating set-point temperatures of the heated rooms: percentage of cases with different self-reported values and average difference for those cases [°C]: HPH

Δ set-p. temperature	liv. r.	kitchen	play r.	office r.	hall	wash./stor.r.	toilet	bathr.	child. bedr.	master bedr.
living r.	-	3%	33%	23%	51%	50%	43%	48%	75%	78%
kitchen	-0.8	-	31%	20%	49%	49%	41%	50%	73%	77%
play r.	-2.3	-2.4	-	31%	44%	48%	36%	54%	50%	51%
office r.	-2.0	-1.9	0.0	-	43%	45%	37%	56%	61%	67%
hall	-3.1	-3.2	-1.2	-2.5	-	28%	19%	65%	51%	53%
wash./stor.r.	-2.9	-2.9	-2.0	-2.2	0.2	-	24%	62%	52%	50%
toilet	-2.9	-2.9	-0.5	-2.2	1.4	1.0	-	62%	55%	56%
bathr.	1.3	1.3	2.8	2.1	3.4	3.4	3.0	-	73%	77%
children bedr.	-2.8	-2.9	-2.1	-2.4	-1.1	-0.8	-2.1	-3.7	-	9%
master bedr.	-3.2	-3.2	-2.9	-2.6	-1.4	-1.2	-2.2	-4.0	-2.1	-

4.3.3 Statistical analysis on the determinants of the heating profiles of HPH

Previous section 4.3.2 showed the strong association between the heating profiles of the different rooms, but it did not reveal the causes of the variations in heating profiles or why longer heating hours were found in HPH compared to cs2. This section presents answers to those questions based on additional statistical analysis. The analysis first focuses on the link between heating profiles and user and building related parameters before also considering the resulting energy use.

Presence of the inhabitants

Statistical analysis confirmed the association between presence and heating hours discussed in Chapter 3. Households reporting at least one person being present in the house during the day on a week-day also reported more heating hours in the living room and in the kitchen. Because it was asked to report the number of heating hours for an average week day, this association was not found with the reported presence of people on Saturdays and Sundays, but it was significant at the level of $p < .01$ for reported presence (yes/no) for every other day of the week. This association is illustrated for the presence on Monday in Table 4.7, with a median of 16 hours being reported by the households having someone staying at home compared with 9 hours for the households with no-one at home. Significant associations were also found with the heating hours in the other rooms because of those being associated with the heating hours of the living room (see 4.3.2.1). Except for the kitchen, those associations between heating hours and the presence of someone at home were weaker for those rooms than for the living room, because those rooms were not heated by every household. The limited data that was reported on the presence of people in the house did not show associations with the types of rooms being heated or with the self-reported set-point temperatures.

Ventilation and heating systems

The system related parameters that were analysed were the characteristics of the ventilation system and those of the heating systems. There was no significant difference between the heating profiles found in the houses with an exhaust ventilation system and the houses with a balanced ventilation system with heat recovery. However, the heating profiles proved to be associated with the characteristics of the heating system. A higher number of heating hours was found for houses with a heat-pump and for houses with lower return-water temperatures being reported in the EPB-assessment (Table 4.7). By consequence, a significant correlation was found between the number of heating hours of the living room and the reported efficiency of the space heating generation system ($\tau = .289$, 95%CI [.222;.354], N=471, $p < .001$) (see also Table 4.9). Because the reported return-water temperature includes both detailed, calculated values and default values (see 2.2.3 and 2.3.2), the values were recoded into a dichotomous variable for further analysis. It differentiates ‘low-temperature’ (LT) heating systems from the other systems. LT-systems were defined as having a reported return water temperature of 45°C or lower, with 45°C being the default return-water temperature for surface heating (floor, ceiling and wall heating) defined in the EPB-method (see 2.3.2, [80]). The remainder mainly includes cases with reported return water temperatures of 70°C (Figure 4.18), being the default value for the other types of systems. There was a significant association between having an LT-system and having a heat-pump (N = 405, OR = 2.90, 95%CI [1.72; 4.89], $p < .001$), but analyses showed that both heat-pumps and LT-systems were separately associated with a higher number of heating hours (Table 4.7). No significant association was found between the heating hours and the return-water temperature for cases that had a heat-pump (Table 4.7). This can be caused by the small sample size (N=65) resulting from the fact that the return-water temperature was not documented for all heat-pumps and it can also be caused by the fact that more than 50% of those households with heat-pumps heated their house 24 hours per day in both the group with and without LT (see median values in Table 4.7).

Combining all cases with a LT-system or a heat-pump results in a subsample with a drastically higher number of households heating their living room and kitchen for 24 hours per day, independently of someone being at home during day-time or not. In fact, a higher number of heating hours in the living room is associated more strongly with the presence of a low-temperature heating system or a heat-pump than with the fact that someone stays at home (Table 4.7). This is illustrated by Figure 4.19 and Figure 4.20, showing the subsample without heat-pump or LT-system and the subsample with one of both, respectively. Their sub-groups with no one at home on Monday (left side of the figures) have a higher percentage of houses heated for less than half a day compared to the subsample with someone staying at home (right side of the figures). However, the average difference between the two groups is much smaller for the sub-sample with a heat-pump or a LT-system (Figure 4.20) because of their high number of households leaving the heating system on 24 hours per day.

In addition to their association with the heating hours, the different types of heating systems were also associated with the odds of heating other rooms than the living room and the kitchen, but those associations are small (Table 4.8). The odds of heating office rooms, halls, washing or storage rooms, toilets and children bedrooms were higher in houses with a heat-pump. Houses with LT-heating systems only had higher odds of heating the halls and the toilets.

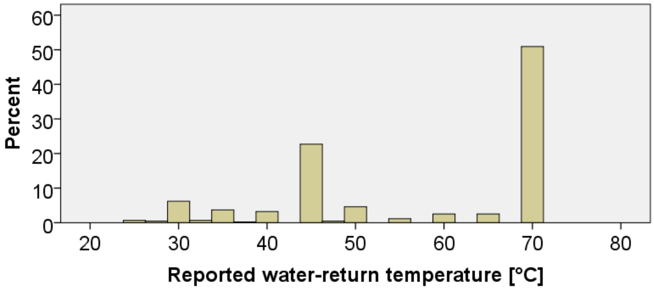

Figure 4.18: distribution of the reported return-water temperatures (HPH)

Table 4.7: associations (Mann-Whitney U-test) between the number of heating hours in the living room [h] and the kitchen on the one hand, and, on the other hand, the presence of someone at home on Monday, of a low temperature heating system (LT), of a heat pump (HP) ('LT/HP' = yes if LT = yes or if HP = yes)

		N	NO		YES		U	z	p
			Mdn.	Av.	Mdn.	Av.			
		[-]	[h]	[h]	[h]	[h]	[-]	[-]	[-]
LIVING ROOM									
	Monday	499	9.0	13.2	16.0	15.9	20906	-3.829	< .001
	LT	416	9.5	12.1	16.0	15.9	14532	-4.836	< .001
	HP	452	9.0	12.1	24.0	19.7	9073	-8.179	< .001
	LT/HP	459	8.0	11.2	24.0	17.4	14910	-8.214	< .001
if LT =									
yes	HP	141	15.5	14.8	24.0	18.1	1482	-2.153	.030
no	HP	249	8.0	11.0	24.0	19.6	1304	-5.022	< .001
if HP =									
yes	LT	65	24.0	19.6	24.0	18.1	n.s.	n.s.	.497
no	LT	325	8.0	11.0	15.5	14.8	7980	-4.475	< .001
KITCHEN									
	Monday	487	10.0	13.4	16.0	15.9	19907	-3.585	< .001
	LT	406	10.0	12.2	16.0	15.8	14079	-4.514	< .001
	HP	451	10.0	12.2	24.0	19.6	8903	-7.971	< .001
	LT/HP	449	8.0	11.3	24.0	17.3	14551	-7.914	< .001

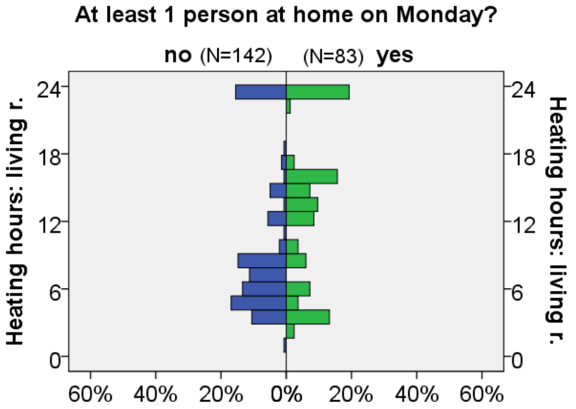

Figure 4.19: houses without heat pump and without low temperature heating system (N=233): heating hours of the living rooms vs. someone being at home on Mondays

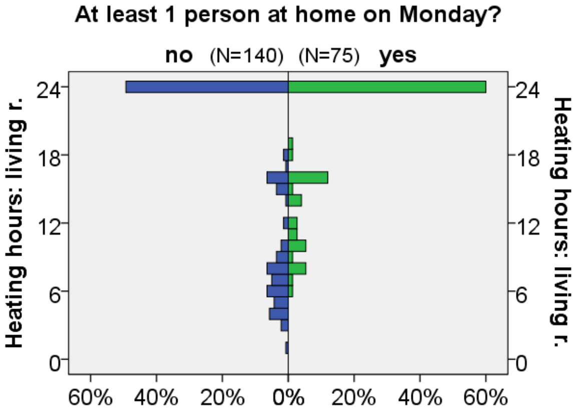

Figure 4.20: houses with a heat pump or a low temperature heating system (N=229): heating hours of the living rooms vs. someone being at home on Mondays

Table 4.8: associations (odds ratios) between the presence of a heat-pump or a LT-heating and the heating or not of specific rooms

	N	p	OR	95% CI
HEATPUMP				
office r.	327	.003	1.45	[1.45, 7.69]
hall	453	< .001	1.81	[1.81, 4.95]
washing/stor. r.	444	< .001	1.77	[1.77, 4.27]
toilet	452	< .001	2.77	[2.77, 7.30]
master bedr.	464	.001	1.33	[1.33, 3.13]
LT-HEATING				
hall	416	.003	1.28	[1.28, 2.99]
toilet	416	< .001	1.43	[1.43, 3.20]

Building characteristics and income

The characteristics of the constructions were also significantly associated with the heating profiles. Larger houses (volume and floor area), houses of a less compact typology (e.g detached), with more glazing or with better insulation levels were heated for more hours (Table 4.9). A less compact typology was also associated with higher odds of heating play rooms, office rooms, halls, storage rooms and toilet (Table 4.10). Except for the office room, this also applied for larger houses (Table 4.10). Furthermore, houses with more glazing also had higher odds of heating the hall of the toilet (Table 4.10).

While most of these associations had very low p-values (p < .010), these associations were small. Furthermore, these associations are no proof of causal relation and they might be indirect. In fact, there were also significant associations between these construction parameters (Table 4.11). More specifically, all these construction parameters were significantly associated with the building typology (Table 4.11). Furthermore, larger houses, more glazing and less compact typologies were also associated with better efficiencies of the heating system, which was discussed in the previous paragraph (Table 4.11).

Additionally, the construction and system characteristics were also significantly associated with the income levels and these income levels were also associated with the heating profiles: higher household income levels were associated with larger, less compact, more glazed and better insulated buildings and also with higher odds of heating halls, play rooms, office rooms and storage rooms and with more heating hours in the living room (Table 4.12). While the association between higher income levels and *more* heating hours is small, this association is noteworthy considering that higher income levels were associated with a *smaller* probability of someone being at home on week-days (except on Wednesdays) (Table 4.12).

This maze of correlations between system characteristics, building characteristics and income levels made it impossible to determine if one of the reported parameters is more directly associated with the heating profiles than the others. The heating system characteristics were more strongly associated with the heating profiles than were all other parameters (Table 4.9), which did not show graphs differentiating heating profiles as strongly as Figure 4.19 and Figure 4.20. This suggests that those system characteristics are probably the most important parameters worth investigating for explaining the associations with the heating profiles. A series of factorial Spearman correlations correcting for one parameter and testing the others never made the associations of those other parameters with the heating profiles become not significant. However, because of the sample size, the nature of these statistical tests and the statistical tools that were used, the factorial analyses could only be performed correcting for one single parameter and without bootstrapping, thus with no information on the confidence intervals.

Table 4.9: associations between the heating hours of the living room on the one hand and, on the other, the construction and system characteristics and household income levels.(‘terr.’=terraced, ‘semi-d.’=semi-detached; ‘det.’=detached)

HEATING HOURS, LIVING ROOM	τ	95% CI	N	p
generation efficiency	.289	[.222, .354]	471	< .001
typology (1=terr.,2=semi-d, 3=det.)	.185	[.107, .258]	434	< .001
volume	.134	[.074, .190]	499	< .001
floor area	.092	[.032, .150]	499	.004
window area/floor area	.139	[.076, .199]	499	< .001
average U-value	-.075	[-.141, -.011]	499	.022
average U-value,opaque	-.140	[-.207, -.077]	499	< .001

Table 4.10: associations between the probability of heating a room on the one hand and, on the other, the construction characteristics. ('terr.'=terraced, 'semi-d.'=semi-detached; 'det.'=detached)

HEATING YES(=1)/NO(=0)?	τ	95% CI	N	p
PLAY ROOM				
typology (1=terr., 2=semi-d, 3=det.)	.254	[.437, .065]	115	.006
volume	.210	[.060, .337]	134	.003
OFFICE				
typology (1=terr., 2=semi-d, 3=det.)	.231	[.341, .105]	314	< .001
HALL				
typology (1=terr., 2=semi-d, 3=det.)	.132	[.228, .039]	436	.005
volume	.093	[.022, .163]	502	.011
floor area	.076	[.004, .144]	502	.037
window area/floor area	.147	[.080, .215]	502	< .001
STORAGE				
typology (1=terr., 2=semi-d, 3=det.)	.173	[.263, .084]	427	< .001
volume	.100	[.029, .171]	488	.007
floor area	.079	[.006, .150]	488	.034
TOILET				
typology (1=terr., 2=semi-d, 3=det.)	.133	[.225, .041]	437	.005
volume	.117	[.044, .188]	500	.001
window area/floor area	.165	[.098, .237]	500	< .001

Table 4.11: associations between construction and system characteristics. ('terr.'=terraced, 'semi-d.'=semi-detached; 'det.'=detached)

CONSTRUCTION & SYSTEMS	τ	95% CI	N	p
generation efficiency				
typology (1=terr.,2=semi-d, 3=det.)	.140	[.066, .214]	456	< .001
volume	.113	[.056, .172]	495	< .001
floor area	.088	[.033, .142]	495	.004
window area/floor area	.146	[.085, .205]	495	< .001
average U-value	n.s.	n.s.	495	.275
average U-value,opaque	n.s.	n.s.	495	.065
typology (1=terr.,2=semi-d, 3=det.)				
volume	.236	[.169, .299]	456	< .001
floor area	.191	[.121, .260]	456	< .001
window area/floor area	.146	[.076, .216]	456	< .001
average U-value	-.117	[-.186, -.040]	456	.002
average U-value,opaque	-.126	[-.196, -.054]	456	.001
volume				
floor area	.637	[.592, .678]	499	< .001
window area/floor area	n.s.	n.s.	499	.467
average U-value	n.s.	n.s.	499	.353
average U-value,opaque	-.072	[-.132, -.012]	499	.016
average U-value,opaque				
window area/floor area	-.207	[-.261, -.155]	499	< .001

Table 4.12: associations between household income levels on the one hand and, on the other, heating profiles, presence and system and construction characteristics. ('terr.'=terraced, 'semi-d.'=semi-detached; 'det.'=detached)

INCOME LEVEL	τ	95% CI	N	p
HEATING HOURS LIVING ROOM	.107	[.029, .180]	390	.005
HEATING YES(=1)/NO(=0)?				
play room	.227	[.056, .375]	113	.006
office	.106	[-.005, .204]	290	.040
hall	.105	[.021, .191]	391	.017
storage	.128	[.040, .212]	380	.004
PRESENCE (>=1person)				
Monday (1=yes, 0=no)	-.124	[-.212, -.034]	395	.005
Tuesday (1=yes, 0=no)	-.167	[-.257, -.078]	395	< .001
Wednesday (1=yes, 0=no)	n.s.	n.s.	395	.660
Thursday (1=yes, 0=no)	-.162	[-.245, -.076]	395	< .001
Friday (1=yes, 0=no)	-.088	[-.172, .004]	395	.045
CONSTRUCTION & SYSTEMS				
generation efficiency	.124	[.050, .195]	388	.001
typology (1=terr.,2=semi-d, 3=det.)	.110	[.022, .197]	355	.016
volume	.159	[.092, .231]	410	< .001
floor area	.121	[.050, .192]	410	.001
window area/floor area	.189	[.118, .260]	410	< .001
average U-value	n.s.	n.s.	410	.101
average U-value,opaque	-.174	[-.238, -.112]	410	< .001

Theoretical and real energy performance

THEORETICAL ENERGY PERFORMANCE

Houses with a lower theoretical primary energy use for space heating (normalized per floor area) showed more demanding heating profiles, while the theoretical net energy use for space heating was found not to be associated with the heating profiles, even though those two theoretical performance characteristics are very strongly correlated (Table 4.13). This can be explained by the fact that the largest association with the heating profiles on component level was found with regard to the space heating system, which differentiates to a large extent the net demand from the primary demand. Furthermore, the association between the heating profiles and the average U-value was lower and the presence of a ventilation system with heat recovery, strongly influencing the theoretical net energy use, was not found to be associated with the heating profiles.

Table 4.13: associations between the heating hours of the living room and the theoretical building performance (net and primary energy use for space heating)

	τ	95% CI	N	p
HEATING HOURS, LIVING R.				
Qheat,net	n.s.	n.s.	293	.219
Qheat,net/floor area	n.s.	n.s.	283	.304
Qheat,prim	-.068	[-.137, .001]	468	.037
Qheat,prim/floor area	-.146	[-.214, -.085]	468	< .001
generation efficiency				
Qheat,net/floor area	.114	[.031, .193]	293	.004
Qheat,net/floor area				
Qheat,prim/floor area	.641	[.726, .833]	295	< .001

REAL ENERGY PERFORMANCE

The associations between prediction errors on the one hand and building and user characteristics on the other were analysed in detail in Chapter 2 and revealed the importance of the reported return-water temperature of the heating system and of the heating of the bedrooms. This section reported a very significant correlation between the return-water temperature of the heating system and the heating profiles. It results from this that the more demanding heating profiles found in houses with LT-heating will probably have increased the association that was discussed in Chapter 2 (see 2.3.2) between the same return-water temperatures on the one hand and the gap between real and theoretical energy use on the other hand. Vice versa, the former association might also have increased the association discussed in Chapter 2 (see 2.3.2) between the probability of heating the master bedroom and the prediction gap. Still, factorial analyses combining the different variables confirmed the statistical significance of both the return-water temperature and of the heating of the bedrooms with regard to the prediction gap (see also the regression analyses and diagnostics in 2.3.2). The difference between households heating their circulation area and toilets and households not heating those rooms did not prove to be significant in those analyses, but power analysis showed that their significance could not be rejected either. Larger datasets would be needed for the tests to have enough statistical power.

4.4 Discussion and conclusion

4.4.1 Heating profiles at room level versus single-zone modelling assumptions

The larger amount of literature on heating profiles in living rooms compared with other rooms (see 3.1 and 3.4.1) can in part be explained historically, by the use of decentralized heating systems in houses with the heating element in the living area being the only or at least the main heating element of the house. Also now, with most new heating systems being central heating systems, the heating profile of the living room remains key in understanding the heating profiles of the other rooms. The living room is the most common location of the central thermostat and many households have their central thermostat define also when the other rooms are heated. This resulted e.g. in the heating profiles of the kitchens in the new houses (cs2 and HPH) being almost always the same as those of the living room. However, more differentiation is found with regard to the other rooms. First, some room types are not heated by all households. This is not only the case for the more technical spaces like the garages, the attics and the basements. More than one out of three households did not heat the play rooms and circulation halls and approximately one out of two households did not heat the bedrooms, the toilets and the washing or storage rooms. Secondly, approximately 40% of the households that heat their bathrooms and bedrooms do so for fewer hours than the living room. Thirdly, a significant number of households reported lower set-point temperatures in rooms that are not living rooms or kitchens, while higher set-point temperatures were often reported for the bathrooms. Compared with old houses, modern insulated houses show smaller temperature differences between different heating profiles. Still, the measured indoor temperatures discussed in Chapter 3 (see 3.3.4) show differences of several degrees Celsius between different room types in the recent houses of cs2. Taking these zonal differentiations into account in energy calculation models could therefore improve the accuracy of the theoretical values compared with the results from single-zone models, like e.g. most models used for EPB-calculations. This will be even more important when analysing energy savings associated with energy renovations or tightening building standards, because of the associated physical temperature take-back.

4.4.2 Associations between room types and heating profiles at building level

Taking not only the physical temperature take-back into account in the models but also variations and changes in heating profiles is more complicated. This chapter gave detailed information on variations in heating profiles that could help building more realistic sets of heating profiles for e.g. stochastic multi-zone simulation analyses. It analysed associations between heating profiles at the level of the different rooms, allowing for sound choices when defining the heating profiles of different rooms for a house and a household. Not only were associations found between the probabilities of different rooms being heated, but also between the number of heating hours in e.g. the living room and the probability of heating other rooms, accentuating the difference between more and less demanding profiles. Defining realistic heating profiles at building level still need additional research, including e.g. accurate data on set-point temperatures instead of only self-reported values. It would also benefit from a more diverse and larger data set to build the findings on. In fact, the latter is foremost needed for further research that should focus on explaining what drives users to select different heating profiles, looking both at characteristics of the users and at characteristics of the buildings and the systems.

4.4.3 Understanding user profiles and using that knowledge

Literature often refers to the importance of behavioural rebound, the theory of which originates from economic research. It associates an increase of efficiency or a decrease of cost per unit on the one hand with an increase of the demand on the other hand, offsetting part of the savings that would have been obtained if the demand did not increase. Chapter 3 showed more frugal heating profiles in the new houses inhabited by households in better socio-economic position than in an older neighbourhood with higher unemployment figures. This chapter found that higher reported income levels, larger but also better insulated houses and lower theoretical primary energy performance levels were associated with more demanding profiles, within a set of well insulated houses. These findings suggest that, indeed, people might increase their demand if they can afford it because of a higher income or a better efficiency of the system supplying the demand. However, findings from both chapters indicate that such associations could in large part be indirect and that the shortfall that is found based on the comparison between real and theoretical energy savings might not only be caused by behavioural rebound or by physical temperature take-back. Technical changes to the building systems might also influence user behaviour not because of the improved efficiency reducing the cost associated with a demand of the user, but because of the type of control and feedback that they offer. The presence of a central heating system was shown to be associated with more rooms being heated and for more hours. As argued, this heating pattern probably also results from the fact that it is the easiest way of controlling the heating in a centrally heated house. This chapter showed that more demanding heating profiles (heating more rooms and for more hours per day) were found in the centrally heated houses with the most efficient, low-temperature heating systems and heat-pumps. Part of this increase of the demand could be due to behavioural rebound, because those heating systems are more efficient and also because their presence was found to be associated with higher household incomes. However, it is unlikely to be the only explanation because no such strong association was found between the heating profiles and e.g. the presence of balanced ventilation with heat recovery. Also, the association with higher insulation levels was not as strong. Two additional explanatory hypotheses are put forward. Firstly, low-temperature heating systems having not only lower return-water temperatures but also lower emission system temperatures might not give the same feedback to the users with regard to their energy use: feeling the heat of a very hot radiator could make you more aware of your energy use than the fact that the floor stays at a comfortable but not hot temperature thanks to low-temperature floor heating. Secondly, low-temperature systems such as floor heating can have longer response-times or seem to respond more slowly because of the lower temperature of the emission system. Therefore, a less intermittent heating profile might just be an answer to this (apparent) lack of responsiveness to intermittent heating profiles.

Verifying these hypotheses cannot be done based solely on the datasets available for this study because of the limited sample size compared to the number of correlated parameters and because of the lack of more detailed data, including e.g. measured data, data on the sizing of the heating systems or direct information from the households on their motivation and awareness regarding their heating profiles. This would require further studies and would be valuable not only for making more accurate predictions e.g. in building stock analyses, but also for system and building designers. Their goal should not be that of selecting the most efficient components when tested under controlled test-environments in labs, but that of giving the users whole building and systems concepts that will make it more easy or natural for them to reduce their energy use while keeping good comfort levels. One example is the possibility in Ireland of receiving a grant reimbursing part of the cost of upgrading the heating system for allowing zonal differentiation between e.g. ‘upstairs’ and ‘downstairs’ or between the living areas and the bedroom area [164,165].

5

Heating profiles in quasi-steady-state models: single versus multi zone models, *theoretical analysis and new model*

This chapter initiates the model-driven section of this dissertation. Based on the findings from the data-driven analyses from the previous Chapters 2, 3 and 4, it analyses different approaches for modelling heating profiles in simplified energy calculation models which could be used both for fast estimation of the energy use in the framework of building projects and for evaluations at building stock level in the framework of policy making. Firstly, the background of many countries' energy performance calculation models is summarized: the single-zone quasi -steady-state modelling approach described in ISO 13790. Secondly, this chapter reports on existing approaches for taking into account, in single-zone models, intermittent heating patterns and the fact that most households do not heat all the rooms of their houses. Thirdly, this chapter discusses the coupled multi-zone variation on the quasi-steady model that is also described in ISO 13790. Fourthly, corrections to this coupled multi-zone model are presented. This chapter is limited to the theoretical analysis of the modelling equations. In the next chapter, Chapter 6, these models will be analysed and compared based on a case-study analysis before presenting, in Chapter 7, an integrated way for using multi-zone models for fast estimation of space heating demands with only a limited added workload compared to single-zone models.

5.1 Introduction

5.1.1 Using simplified quasi-steady-state methods: from performance assessment to predicting energy use

Theoretical calculation models are often used for verifying the compliance of building projects with the energy performance regulation, for giving financial incentives based on the achieved performance levels and for giving information to potential buyers on the energy performance of houses [21,22]. An important part within this assessment procedure is that of calculating the final energy use for space heating, starting with calculating the net space heating demand. Many countries use simplified models for calculating the net space heating demand, based on two international standards [21,22]. The main equations for calculating the transmission and ventilation heat transfer coefficients are defined in ISO 13789 [166] while the overall heat balance equations are most commonly based on the single-zone quasi-steady state approach described in ISO 13790 [20] and discussed further in the following sections. The simple formulation of this calculation approach requires very little computing power and no iterative procedure, resulting in fast and stable calculations. On the side of the user and of the regulatory framework, this type of model also reduces the workload and complexity of implementation by reducing the number of inputs compared to more complex dynamic models. The thermal time constant for example is specified at the zonal level, and can be defined in function of the size of the building and on predefined classes of thermal capacity associated mainly with the construction type. This avoids the need for additional information about the thermal capacity of each layer within the building envelope (insulation layer, finishing layer etc.). More specifically, simplifying the building into a single-zone model reduces the workload considerably by requiring no detailed inputs about the interior boundaries between rooms, inter-zonal air flows etc. Furthermore, it makes the regulatory framework less dependent on personal interpretation and more robust against fraud. Indeed, defining one thermal zone for each room, with different user profiles (heating profiles, internal heat gains etc.) depending on the function of each room, would lead to discussions about how to define a room’s function, especially before the building is being inhabited or before it is even known who will inhabit it and how they will use it, making a robust legal implementation difficult.

These benefits of simplified single-zone models explain why they are so widely used in regulatory frameworks, including in the countries where most of the studies referred to in the previous chapters were conducted (Germany, The Netherlands, The United Kingdom, Belgium…). As a result of being compulsory, the use of these models has become familiar to the building sector and these models are being used more than only for verifying compliance to regulations. The theoretical energy use calculated by these models has become an argument for companies and design teams for commending products, designs and technical solutions, comparing the predicted energy use and associated financial costs of one option with those of the alternatives. Building stock analyses on residential energy use are also often based on the official calculation method or similar approaches (see Chapter 7: 7.1.1 [34,36,37,40,42]). This is explained by the limited computing power those models require, the reduced number of necessary inputs and the availability of data that matches those modelling requirements, thanks to the fact that the regulating instances store data on the official performance assessments (see Chapter 2 and Chapter 7). However, as shown in the previous chapters, the theoretical energy use calculated using those regulatory performance assessment methods suffer from a systematic prediction error.

5.1.2 Accuracy of simplified methods versus their use

It is argued in literature that using simplified quasi-steady state models for energy performance assessment is a sensible choice, provided the dynamic parameters defining the thermal constant of the building and the utilization factor are correctly determined [167–170]. Numerous studies have focussed on the accuracy of the statistical correlations of physical dynamic parameters used in single-zone quasi-steady state models, more specifically regarding those utilization factors [167,169,171–174], showing that accurate results compared to more detailed dynamic simulations can be obtained, if needed with calibrated utilization factors (e.g. in function of the glazing area and climate [167]). These positive verifications of the reliability of single-zone quasi-steady state models seem to contradict the findings discussed in previous chapters, showing large discrepancies between results from such models used in regulatory contexts and real energy use, but one must not forget that the aims of energy performance assessments are not the realistic estimation of the real energy use in each house, considering the specific inhabitants. As discussed in sections 2.4.3 and 3.4.1, energy performance assessment methods aim at evaluating the building performance under standardized assumptions (e.g. standard climate and user profiles), making it possible to verify compliance with regulation and to compare the performance of different buildings, not the behaviour of their users. Considering the large variation in user profiles, it is therefore normal that discrepancies are found at the level of the individual case. However, this argument of standardization should not be used to explain away the large discrepancies that are also found on average between real and theoretical values when considering large numbers of houses, including large variations in user profiles. As discussed in 3.4.1, these large average discrepancies between real and theoretical values can be explained in part by non-realistic modelling assumptions, like general overestimations of the ventilation flow rates and not considering zonal differentiation regarding presence, heating and ventilation profiles (3.3.3, 4.3.1, 4.3.2): the fact that large parts of the houses often remain unheated and that this results in different average indoor temperatures at different insulation levels, the fact that the windows that are opened are mostly those in the unheated rooms etc.

For obtaining more accurate predictions, more realistic modelling assumptions must thus be made, also with regard to these user related zonal differentiations and, first of all, the models must be able to take these more realistic assumptions into account. This is not verified by most simulation based studies comparing results from the quasi-steady state approaches with dynamic simulations of residential buildings. Those studies commonly make simplified assumptions similar to those considered in the regulatory framework, using dynamic models that do not consider zonal differentiation or barely: simplified 'shoe-box' models [170], a single-zone model of a single-family house [167], a multi-zone model but considering the same user profile in all zones [169] or furthermore considering the heating and ventilation settings to remain constant 24 hours per day [171]. A comparison between single-zone quasi-steady state calculations and multi-zone dynamic simulations was made by Deurinck et al. [68]. They showed that the single-zone model with fixed set-point temperature as used in Flanders (see 3.4.1, [80]) results in an overestimation of energy savings associated with higher insulation levels because it does not take into account the physical temperature take-back, the increase of the indoor temperature in indirectly or intermittently heated zones at increased insulation levels. Deurinck et al. also made a small comparison with single-zone calculations using correction factors from other, national standards that take into account intermittent heating and the fact that part of the house is only indirectly heated. They showed that using these correction factors results in a realistic estimation of the average temperature increase at better insulation levels when compared to the multi-zone dynamic simulation, even though the calculated temperatures differed. However, the comparison was only illustrative of the potential of such correction factors for taking physical temperature take-back realistically into account in quasi-steady state methods because the single-zone quasi-steady state method and the multi-zone dynamic simulation were not compared considering the exact same heating profiles. For the multi-zone simulations, a specific case-study building and a stochastic distribution of heating profiles were considered while for each single-zone quasi-steady state approach only the default heating profile from the corresponding national standard was considered, resulting in different assumptions on the heating set-point temperature, the number of heating hours and the heated fraction of the house. Furthermore, the multi-zone model that was used still considered some important simplifications, e.g. differentiating only two thermal zones and with ventilation heat losses and internal heat gains considered as spread uniformly over these zones, assumptions that resemble single-zone assumptions and contradict findings discussed in Chapter 3, e.g. the large differences in ventilation profiles between room types (3.3.3, 3.4.1, [56,57,59,60]).

5.1.3 Analyses on simplified calculation methods: aims and approach

This and the following chapters pursue the analyses on simplified models by focussing on their ability of taking different user profiles into account. The better their ability to take these profiles into account, the better not only their validity in the framework of building performance assessment, but also their validity for analyses considering real energy use. Ultimately, the aim is making it possible to take the most important variations between user profiles into account in simplified, pragmatic simulation approaches that could be used in the framework of building stock analyses or in the daily practice of small residential building projects. The previous chapters showed the large variation in user profiles, with important differentiations at room level regarding presence, ventilation and heating and with large differences in set-point temperatures and in the number of heating hours in different rooms (3.3.3, 4.3.1, 4.3.2). Furthermore, differences in heating profiles were found between the old non insulated houses with local heating and insulated houses with central heating systems, with more rooms being heated and for more hours per day in the latter houses, especially in those houses with low-temperature heating systems. These differences can explain part of the variation in energy use between households and part of the observed shortfall. Therefore, for taking different residential user profiles into account, a model must be able to take into account zonal differentiations, different set-point temperatures and different heating durations.

After presenting the basis single-zone quasi-steady state modelling approach, this chapter will focus on additional modelling approaches. First, additional approaches that apply those single-zone models are discussed. These are found in national performance assessment standards from other countries and consist of correction formulas taking into account night-time set-back and the fact that only a part of the house is heated. In addition, a simplified yet multi-zone modelling approach is presented, making a more detailed differentiation at room level possible, not only with regard to the corresponding heating profiles, but also with regard to their heat gains, window opening profiles etc. It builds on the existing coupled multi-zone quasi-steady state approach from ISO 13790, correcting for some limitations of that approach.

This chapter is limited to the physical description of the modelling approaches, to their implementation and to related theoretical discussions. In the following Chapter 6 these models will be used for simulation-based analyses. Chapter 6 will analyse to what extent the accuracy of theoretical values can be improved by using these more advanced yet simplified models taking zonal differentiation of user profiles into account in more or less detail. Subsequently, Chapter 7 will focus on the usability of the multi-zone model. It will present a practical approach for using the more detailed multi-zone model in situations where the required additional information about the building, on multi-zone level, might not be available. That approach aims at benefitting from the added flexibility of the multi-zone for considering different user profiles in building stock analyses or during fast and preliminary evaluations of building designs.

5.2 Monthly quasi-steady-state calculation methods: ISO 13790 and national implementations

5.2.1 Single zone formulation from ISO 13790

In the monthly quasi-steady state method described in ISO 13790, the net energy demand for space heating during a specific month in a zone 'x', $Q_{heating,x}$, is written as a function of the heat-losses $Q_{H,losses,x}$, the heat-gains $Q_{H,gains,x}$ and a utilization factor for those heat gains $\eta_{H,x}$ (Eq. (5.1)). The heat losses are a function of the heat transfer coefficient (transmission and ventilation) of the zone to the outside and of the indoor-outdoor temperature difference (Eq.(5.2)). The heat transfer coefficient from zone 'x' to the outside ('e') $H_{H,xe}$ is a transformation of the sum of the heat transfer coefficient from zone 'x' to all adjacent zones 'y' (including the outside) based on their reduction factors b_{xy} (Eq. (5.4)). These reduction factors are defined in ISO 13789 as a function of the interior and exterior temperatures in case of heat losses towards adjacent heated buildings ('i') (Eq. (5.5)) and, in case of heat losses to adjacent, unconditioned spaces ('u') as function of the heat transfer coefficients between the zones and between the adjacent space and the outdoor environment (Eq. (5.6)). The reduction factor equals 1 in case of heat losses directly towards the outside environment ('e'). The heat gains consist of the direct internal and solar heat gains, increased by an amount of 'transmitted' solar and internal heat gains from adjacent unconditioned zones 'u' (Eq.(5.3)). The utilization factor used in Eq. (5.1) is defined as a function of the ratio of heat gains to heat losses and of the time constant of the heated zone itself, based on its internal heat capacity and heat transfer coefficient [20]. It accounts for the fact that not all heat gains can be fully utilized for reducing the space heating demand, due to the asynchrony between those heat gains and the heating demand. For example, high solar gains at noon might cause an unnecessary temperature increase (overheating) at noon in the bedrooms, while those heat gains will be partially lost by the time the bedrooms are in use in the evening. While parts of the heat gains are not utilized for reducing the heating demand, they do cause temperature increases that result in higher average temperatures (Figure 5.1). The monthly average temperature can thus be defined using Eq.(5.7) or using Eq. (5.8), taking into account all heat losses, active heating and heat gains, without utilization factor. It is important to note that, as the solar and internal heat gains of unheated spaces are attributed directly to their adjacent, heated zone, the thermal capacity of unheated zones is not taken into account in this uncoupled method.

$$Q_{heat,x} = Q_{H,losses,x} - \eta_{H,x} * Q_{H,gains,x} \tag{5.1}$$

With

η_x= gain utilization factor ([0;1]) for heating of zone x

$$Q_{H,losses,x} = H_{xe} * (T_{H,set,x} - T_{av,e}) * dt \tag{5.2}$$

$$\begin{aligned} Q_{H,gains,x} = {} & (Q_{H,sun,x} + Q_{H,internal,x}) \\ & + \sum_{u} (1 - b_{xu}) * (Q_{H,sun,u} + Q_{H,internal,u}) \end{aligned} \tag{5.3}$$

With

$Q_{H,sun}$= solar heat gains (for the space heating calculation)

$Q_{H,internal}$= internal heat gains (for the space heating calculation)

x = considered heated zone

u = an adjacent unconditioned zone

e = exterior environment

H = heat transfer coefficient between two zones or environments

dt = time duration

$$H_{xe} = \sum_{i} b_{xy} * H_{xy} \tag{5.4}$$

With

y = an adjacent zone (including heated and unheated zones as well as the outside environment)

Where for adjacent heated zones (‘i’):

$$b_{xi} = \frac{T_{H,set,x} - T_{av,i}}{T_{H,set,x} - T_{av,e}} \tag{5.5}$$

And for adjacent unheated zones (‘u’):

$$b_{xu} = \frac{H_{ue}}{H_{ui} + H_{ue}}, \textit{ or a predefined default value} \tag{5.6}$$

$$T_{av,x} = T_{H,set,x} + \frac{(1 - \eta_{H,x}) * Q_{H,gains,x}}{H_{xe}.dt} \tag{5.7}$$

$$T_{av,x} = T_{av,e} + \frac{Q_{H,gains,x} + Q_{heat,x}}{H_{xe}.dt} \tag{5.8}$$

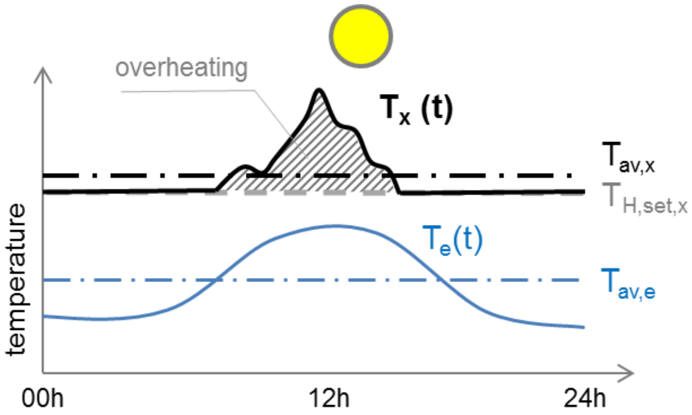

Figure 5.1: illustration of overheating caused by unutilized heat gains and resulting in an average temperature higher than the set point temperature

5.2.2 Correction formulas for heating profiles

ISO 13790 leaves it to the countries to define a standard heating profile as input in the calculation method. However, filling in the real set-point temperature of the central thermostat or of the main, heated room (e.g. the living room) in Eq. (5.2) would neglect any temperature setback (intermittency, e.g. at night) as well as the fact that some rooms are not heated, or at least not directly (spatial reduction, e.g. bedrooms, toilets). ISO 13790 proposes correction formulas for intermittent heating, but not for the presence of unheated rooms. In response, different countries have developed their own correction formulas for their national standards, both for intermittency and spatial reduction. Also, these different approaches apply their corrections at different steps within the calculation of the net heating demand. ISO 13790 multiplies the net space heating demand (Eq. (5.1)), calculated with a fixed set-point temperature, with a correction factor $a_{H,red}$ for intermittency. The Dutch standard NEN 7120 multiplies the heat losses (Eq. (5.2)) with two reduction factors $a_{H,red,night}$ and $f_{int,set,H,adj}$ for intermittency and spatial reduction, respectively. The German standard DIN 18599 corrects the set-point temperature before using it to calculate the heat losses. The Flemish method does not add any correction formula but implicitly considers that any intermittency and spatially reduced heating is accounted for in a fixed space and time averaged ‘equivalent’ set-point temperature of 18°C that lies below average set-point temperatures found in houses (see e.g. 3.3.3 and 4.3.2.1) and that is not dependent on any building characteristic.

These different approaches and standard user profiles for residential buildings are now discussed in more detail, focusing first on heating intermittency (time reduction) and subsequently on the presence of unheated or indirectly heated spaces (spatial reduction). For further evaluation of the approaches from these international and national standards which are based on monthly quasi-steady state models, another set of correction formulas will be presented that was defined for use in seasonal calculations [175].

Correction factor for intermittency

For residential buildings as opposed to e.g. school and office building, both DIN 18599 and NEN 7120 only take night-time set-back periods into account, assuming no weekend or holiday periods with reduced heating demand. Also, Chapter 3 and Chapter 4 showed that, when weekend heating profiles differed from week-day heating profiles, in houses, it were most commonly the weekend-profiles that showed the most heating hours per day. Therefore, only corrections for night time set back are further discussed here. DIN 18599 considers a heating set-point temperature of 20°C and 7 hours of night-time heating set-back while NEN 7120 also considers 20°C but 10 hours without heating. The intermittency correction formulas from ISO 13790 (Eq. (5.9)), DIN 18599 (Eq.(5.10) and (5.11)) and NEN 7120 (Eq.(5.12)) all take into account that the reduction of the heating demand due to setback decreases as the length of the setback period decreases and the thermal time constant of the building increases.

ISO 13790: INTERMITTENCY CORRECTION FACTOR ($A_{H,RED}$) FOR THE NET HEATING DEMAND ($Q_{HEAT,X}$)

$$a_{H,red} = max\left[1 - b_{H,red}\left(\frac{\tau_{H,0}}{\tau_H}\right)\gamma_H\left(1 - f_{H,hr}\right) ; f_{H,hr}\right] \tag{5.9}$$

With

$f_{H,hr}$ = the daily time fraction with a normal heating set-point (no reduced set point temperature or switch-off) [-]

γ_H = the dimensionless heat-balance ratio (heat gains divided by heat losses) for the heating mode [-]

$b_{H,red}$ = an empirical factor (= 3) [-]

τ_H = thermal time constant [h]

$\tau_{H,0}$ = the reference thermal time constant [h] (default from ISO13790, also used in the Flemish method: 15h)

DIN 18599: INTERMITTENCY CORRECTED, EQUIVALENT SET POINT TEMPERATURE

$$T_{H,set,equivinterm,x} = max \begin{bmatrix} T_{H,set,main,x} - f_{NA}\left(T_{H,set,main,x} - T_{av,e}\right); \\ T_{H,set,main,x} - \Delta T_{i,NA}\,\frac{t_{NA}}{24} \end{bmatrix} \tag{5.10}$$

With, for full switch-off of the heating system at night

$$f_{NA} = 0.26\,\frac{t_{NA}}{24}\,exp\left(-\frac{\tau_H}{250}\right) \tag{5.11}$$

$T_{H,set,main,x}$ = the primary heating set-point temperature [°C]

$T_{av,e}$ = the average outdoor temperature [°C]

τ_H = thermal time constant [h]

t_{NA} = the daily reduced heating time [h]

$\Delta T_{i,NA}$ = the permitted internal temperature reduction during setback periods [°C]

NEN 7120: INTERMITTENCY CORRECTION FACTOR ($A_{H,RED,NIGHT}$) FOR THE HEAT LOSSES ($Q_{LOSSES,X}$)

$$if\ \frac{t_{H,hr,low}}{\tau_H} > \frac{c_{H,red,2}}{2\,c_{H,red,3}}$$

$$than{:}\ a_{H,red,night} = \frac{\left(24 - t_{H,hr,low}\right) + t_{H,hr,low}\left[c_{H,red,1} - \left(\frac{c_{H,red,2}{}^{2}}{4\,c_{H,red,3}}\right)\right]}{24} \tag{5.12}$$

$$else{:}\ a_{H,red,night} = \frac{\left(24 - t_{H,hr,low}\right) + t_{H,hr,low}\left[c_{H,red,1} - c_{H,red,2}\frac{t_{H,hr,low}}{\tau_H} + c_{H,red,3}\left(\frac{t_{H,hr,low}}{\tau_H}\right)^{2}\right]}{24}$$

With

$c_{H,red,1}$, $c_{H,red,2}$ and $c_{H,red,3}$ = empirical correlation factors (respectively 1, 0.5 and 0.075)

τ_H = thermal time constant [h]

$t_{H,hr,low}$ = number of hours per day at reduced set point temperature or full switch-off [h]

Correction factor for spatial reduction

To account for the fact that not all the rooms of a house are heated, both DIN 18599 and NEN 7120 include spatial heating correction factors. Both methods result in a lower heating demand if a smaller part of the house, considered as the living area, is directly heated (Eq. (5.13), (5.14), (5.15)). The standards differ with regard to their assumption about the remaining area. DIN 18599 states a clear distinction between the directly heated area and the remaining, not or only indirectly heated area. The Dutch standard assumes that the remaining area is still heated, but only moderately, for 20% of the time. The ratio between the unheated or moderately heated area and the total floor area is represented by a constant default value in both national standards. However, the Dutch standard considers a ratio of 0.5 for residential buildings, while the German standard considers a ratio of 0.25 or 0.15 for single-family houses and apartment buildings, respectively. The Dutch standard assumes that the internal heat transfer coefficient per floor area equals 2W/(m².K). The German standard does not specify similar assumptions, but takes into account the maximum required heating power per floor area. As that maximum heating power decreases, the equivalent set-point temperature increases. DIN 18599 does not explain why the maximum heating power is taken into account. If the real, installed heating power was considered, it could be argued that as the installed power decreases, the set point temperature might not be reached in the living room during cold winter days without additional a minimal heating of the adjacent secondary spaces (e.g. bedrooms). However, the considered maximum heating power is a calculated value that equals the total heat transfer coefficient (transmission and ventilation) times the difference between predefined design internal and external temperatures [176]. Therefore, the inclusion of this maximum heating power in the German correction formula is similar to the inclusion of the heat transfer coefficient in the Dutch correction formula, taking into account that switching off the heating in some rooms will have a larger effect on the average indoor temperature and on the heat losses in poorly insulated houses compared to well insulated houses.

DIN 18599: EQUIVALENT SET POINT TEMPERATURE CORRECTED FOR SPATIAL REDUCTION

$$\begin{aligned} T_{H,set,equivSpatialInterm,GE,x} &= T_{H,set,equivInterm,x} \\ &- f_{tb}\left(T_{H,set,equivInterm,x} - T_{av,e}\right) \end{aligned} \tag{5.13}$$

With, for full switch-off of the heating system at night

$$f_{tb} = 0.8 \left[1 - exp\left(-\frac{\dot{Q}_{h,max}}{A_b \, 35 \, W/m^2}\right)\right] a_{tb}{}^2 \qquad (5.14)$$

$Q_{h,max}$ = the calculated maximum heating power [W]

A_b = the total floor area of the building zone [m]

a_{tb} = the fraction of the total floor area taken up by the indirectly heated area [-] (default values 0.25 and 0.15 for single-family houses and for apartments respectively)

NEN 7120: SPATIAL REDUCTION CORRECTION FACTOR ($F_{INT,SET,H,AJD}$) FOR THE HEAT LOSSES ($Q_{LOSSES,X}$)

$$f_{int,set,H,adj} = \frac{(1 - f_{mod,t} f_{mod,sp})(f_{mod,sp} H_{e,spec}) + H_{int,spec}}{(f_{mod,sp} H_{e,spec}) + H_{int,spec}} \qquad (5.15)$$

$f_{mod,t}$ = time fraction that the moderately heated area is not heated (default value = 0.8, thus heated for 4h and 48min)

$f_{mod,sp}$ = the fraction of the total floor area taken up by the indirectly heated area [-] (= a_{tb} in DIN 18599) (default value = 0.5)

$H_{e,spec}$ = the external heat transfer coefficient per floor area [W/(m²K)] (= the total external heat loss coefficient divided by the total floor area)

$H_{int,spec}$ = the internal heat transfer coefficient per floor area [W/(m²K)] (default value = 2W/(m².K)) (calculation method not further defined)

Seasonal reduction factors: Loga et al. 1999

While no detailed information could be found on how exactly the correction factors from ISO 13790, DIN 18599 and NEN 7120 were defined, a research report by Loga et al.[175] explains in detail how they defined another set of correction factors. As opposed to those from the international and national standard presented in the previous paragraphs, those factors were defined for use in a seasonal calculation model that followed the seasonal method from EN 832 [19], which is also document in the more recent ISO 13790. That model and the corresponding correction formulas are used in the energy calculation tool of the Institut Wohnen und Umwelt (IWU) [177]. Similarly as the correction factors from NEN 7120, these factors are applied on the calculated heat losses. However, using those factors in a monthly method would result, especially for houses with no or little insulation, in an overestimation of the heat losses and thus of the heating demand during the colder months [175]. Nevertheless, comparing these factors with the factors from the standards can help evaluate the different formulas from the standards, as will be illustrated after reporting their mathematical formulation. In a later report [43], Loga et al. added a third, empirical correction factor the ‘use factor’ (‘Nutzungsfaktor’) to the equation, which is included in the following description after the intermittency and the spatial reduction factors.

CORRECTION FOR INTERMITTENCY

Single-zone dynamic simulations were used for defining the intermittency correction factors, varying the insulation level, thermal capacity, the duration of the set-back (between 4 and 16 hours), the set-back temperature (5°C or 15°C). The results showed that thermal time constant is the dominant parameter influencing the reduction factor. However, the reduction factor was summarized in the following equation:

$$f_{ze} = 0.9 + \frac{0.1}{1 + h} \tag{5.16}$$

With

h = the specific external heat transfer coefficient = $H_{e,spec}$ as defined in NEN 7120 for Eq.(5.15)

As opposed to the formulas from the standards, only the specific external heat transmission coefficient ($H_{e,spec}$) is considered, and not the thermal capacity, the duration of the set-back period or, as in DIN 18599, the set-back temperature. This is because the formula considers an average typical thermal capacity per floor area (100Wh/(m².K)) with 8 hours of set-back and a set-back temperature of 15°C as a standard profile, thus reflecting only part of the simulation work.

SPATIAL REDUCTION FACTOR

The correction factor for spatial reduction was defined from a simulation study using a coupled multi-zone quasi-steady state model. While the correction factors were defined so as to be used in a seasonal model, the multi-zone model used for defining them was a monthly model. It was based on EN 832 [19], the predecessor of ISO 13790 and is very similar to the coupled multi-zone model from ISO 13790 discussed in following sections 5.2.3 and 5.3. A detached single-family house, modelled in 4 zones, was used as a case-study, with as fixed (24 hours per day) set-point temperatures 20°C for the main heated zones and 12°C for the other zones, which could also reside in free-floating status depending on the heat balance. The selection of which zones where heated and which were not was varied, as well as the specific external heat transfer coefficient (between 0.49 and 4.9 W/(m².K)). Based on these simulations, the following Eq.(5.17) was derived:

$$f_{re} = \frac{1}{0.5\sqrt{h}\, {n_V}^2 + 1} \tag{5.17}$$

With

h = the specific external heat transfer coefficient = $H_{e,spec}$ as defined in NEN 7120 for Eq.(5.15)

n_V = area fraction of the indirectly heated zones, limited to ≤ 0.5 (Defined as a_{tb} in Eq.(5.14) of DIN 18599 and as $f_{mod,sp}$ in Eq.(5.15) of NEN 7120)

USE FACTOR 'NUTZUNGSFAKTOR'

Noticing that the seasonal calculation method using these correction factors for intermittency and spatial reduction still overestimated the real energy use especially in the less insulated houses, a third, empirical factor was later added to the equation: the use factor or 'Nutzungsfaktor' (Eq.(5.18) [43]). It ranges from a value of 0.7 for houses with low insulation levels to 1.5 for passive houses, becoming thus in the latter case a magnification factor rather than a reduction factor [43]. It is not a purely physical factor, for it is based on comparisons between real and calculated values, including behavioural rebound and other aspects explaining prediction errors. In fact, Loga et al. report a few possible, physical and not physical causes for the remaining discrepancy between real and calculated values that has to be bridged with this factor:

- The heat transfer at inner and outer surfaces of the building envelopes is lowered in practice by closets, shelves, carpets, vegetation etc.
- In old, not insulated houses, thermal bridges are usually only found at the junctions with the basements. Thus using external dimensions for calculating the heat loss area is more likely to result in an overestimation of the heat losses.
- The higher cost of heating not insulated buildings might push the inhabitants to a more economical heating behaviour.

$$f_n = 0.5 + \frac{1}{0.5\, h} \tag{5.18}$$

With

h = the specific external heat transfer coefficient = $H_{e,spec}$ as defined in Eq.(5.15) of NEN 7120

Illustration of the equivalent set-point temperature corrected for intermittency and spatial reduction

COMPARISON ON MONTHLY LEVEL

By correcting the main set-point temperature for taking into account intermittency and spatial reduction, the German approach corresponds to calculating an equivalent set-point temperature to be used in Eq.(5.2) when calculating the heat losses. That equivalent set-point temperature can thus be compared directly to the fixed equivalent set-point temperature of 18°C considered in the Flemish calculation method. If the heat loss coefficients are independent of the set-point temperature, the Dutch approach can also be included in the comparison. This requires calculating the equivalent set-point temperature that corresponds to the reduction factors of NEN 7120 (Eq.(5.12) and Eq.(5.15)) using Eq.(5.19) and Eq. (5.20) (derived considering Eq. (5.2)). An equivalent set-point temperature that corresponds to the intermittency correction approach of ISO 13790 can be defined using an iterative solution procedure, calculating what equivalent set-point temperature would be needed in Eq. (5.2) for Eq. (5.1) to result in the same heating demand without multiplication with $a_{H,red}$ from ISO 13790 (Eq. (5.9)).

$$T_{H,set,equivSpatialInterm,NL,x} = T_{H,set,main,x} - f_{NA\&tb,NL}\left(T_{H,set,main,x} - T_{av,e}\right) \tag{5.19}$$

With

$$f_{NA\&tb,NL} = (1 - a_{H,red,night}\ f_{int,set,H,adj}) \tag{5.20}$$

Figure 5.2 and Figure 5.3 illustrate the principle of these reduction factors for intermittency and spatial reduction by means of these equivalent set-point temperatures and of the corresponding average temperatures (Eq. (5.8)). The figures show monthly temperatures calculated for the months of January to December for one of the old not insulated terraced houses from Chapter 3 (neighbourhood cs1). Figure 5.2 compares the equivalent set-point temperatures and the average indoor temperatures, resulting from the different formulas and their corresponding standard user profiles. During summer, as the heat losses decrease and the heat gains increase, the utilization factors decrease, reaching a status where there is no heating demand. As a result, the average temperatures (Eq.(5.8)) are the same for all calculation approaches, notwithstanding their different equivalent set point temperatures. On the opposite, during winter, the equivalent set-point temperatures and their respective average temperatures closely match due to the high utilization factors resulting from the low outdoor temperatures and the lack of insulation. During the coldest months, in these not insulated houses, the 18°C from the Flemish standard closely matches the values from the German approach, as opposed to the much lower values obtained by using the Dutch formulas and user profile. Figure 5.3, which does not show the average temperatures, shows that the difference between the equivalent set-point temperatures (and by consequence also the average temperatures) is much smaller when the same (Dutch) user profile is implemented in both the German and the Dutch formulas, with the highest difference being 0.3°C for January, the coldest month. Figure 5.3 also includes the equivalent temperatures if only the intermittency or only the spatial correction formulas are applied, showing that there is a close fit for both corrections formulas separately between the Dutch and the German approaches, for this specific case. Both the Dutch and the German formulas assert a larger reduction of the equivalent set-point temperature and thus of the resulting space heating demand to the spatial reduction (not heating all the rooms) than to time reduction (switching of the heating system at night). Both the Dutch and German intermittency correction formulas also assert that temperature drops during set-back periods and savings due to not heating all the rooms will be more pronounced as the outdoor temperature decreases, thus resulting in lower equivalent set point temperatures and average indoor temperatures. However, this is not the case when following the intermittency correction approach from ISO 13790.

While for this house the results based on ISO 13790 are in the same range as the results from the German and Dutch formulas, the equivalent set-point temperature reaches two local minima, in October and in March, and increases again during the colder winter months. This error is caused by the correction factor a_{hred} (Eq. (5.9)) being linearly, positively correlated with the heat balance ratio while it is applied to the net heating demand that on the opposite, via the utilization factor, is negatively and non-linearly related to the heat balance ratio. This is better illustrated by deriving the average temperature for a simplified example. Including the intermittency correction from ISO 13790, the average temperature can be calculated using Eq.(5.21) instead of Eq.(5.8). Illustratively, considering 8 hours of night-time setback (f_{Hh}=2/3) and an old, non-insulated building with a thermal time constant of 15h ($\tau_H = \tau_{H,0}$), further derivation of Eq.(5.21), using Eq. (5.9) results for the average temperature in the reduced and case-specific Eq. (5.22). For this low performance house, the heat balance ratio will be low and the utilization factor very high as we get deeper into winter season, resulting in $\eta_H(1 - \gamma_H)$ being close to its maximum value of one. Moving further to even lower outdoor temperatures as well as lower solar heat gains will not significantly increase that value anymore, causing the lowered heat gains to result in a higher average temperature according to Eq. (5.22). Because of this error in the intermittency correction from ISO 13790 and because of the lack of any spatial correction formula in ISO 13790, the correction approach from ISO 13790 will not be considered in the following analyses.

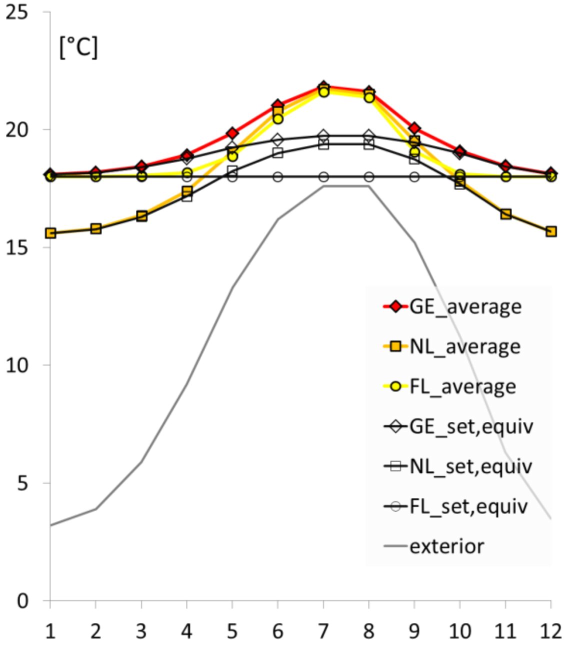

Figure 5.2: monthly equivalent set-point and average temperatures calculated using <u>the formulas and the corresponding standard heating profiles from the different national standards</u> as discussed in 5.2.2 (FL=Flanders [80], GE=Germany=DIN 18599 [176], NL=the Netherlands=NEN 7120 [78]) Climate: standard Belgian climate as defined for the EPB-calculations [80]. Case-study: old, not insulated terraced house from Chapter 3('cs1').

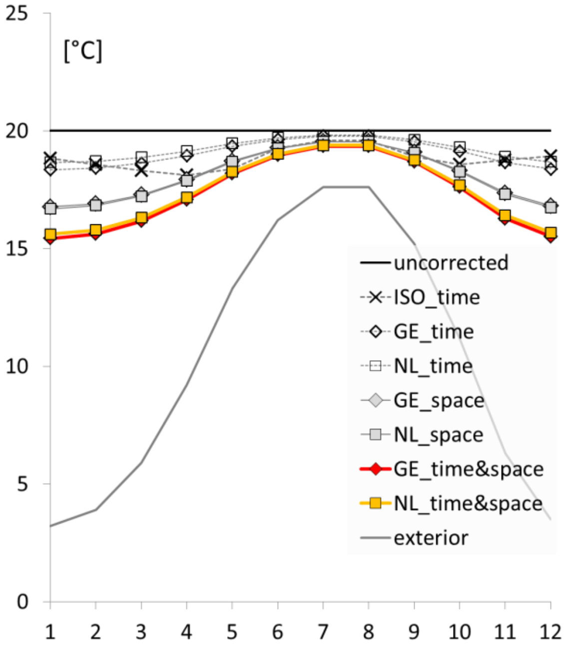

Figure 5.3: monthly equivalent set-point and average temperatures calculated using the the formulas from the different national standards as discussed in 5.2.2 (FL=Flanders [80], GE=Germany=DIN 18599 [176], NL=the Netherlands=NEN 7120 [78]), but the same heating profile (from NEN 7120). Climate: standard Belgian climate as defined for the EPB-calculations [80]. Case-study: old, not insulated terraced house from Chapter 3('cs1').

$$T_{av,x} = T_{av,e} + \frac{Q_{H,gains,x} + a_{H,red}\left(Q_{H,losses,x} - \eta_{H,x} * Q_{H,gains,x}\right)}{H_{xe}.\,dt} \tag{5.21}$$

$$T_{av,x} = T_{H,set,x} - \frac{Q_{H,gains,x}\,\eta_{H,x}(1 - \gamma_H)}{H_{xe}.\,dt} \tag{5.22}$$

COMPARISON WITH THE SEASONAL APPROACH

Eq.(5.19) and Eq. (5.20) can also be used to transform the seasonal correction factors from Loga et al. into correction factors for calculating an equivalent set-point temperature, by replacing in Eq. (5.20) the intermittency and spatial reduction factors from NEN 7120 by those defined by Loga et al. (Eq.(5.16) and Eq.(5.17)). In the following comparison, an average outdoor temperature of 4.55°C is considered. This is considered to be an average for the heating season (see also 6.2.2), allowing for a more solid comparison between the equivalent set-point temperature resulting for the seasonal correction formulas and those for the monthly approaches. Figure 5.4 compares the equivalent set-point temperatures for the same terraced house as in previous paragraph, however under different assumptions. To make the direct comparison valid, the assumptions are the same as those defined by Loga et al. [175] for the physical correction formulas: a set-point temperature of 20°C, 8 hours of night-time set-back, a set-back temperature of 15°C, 50% of the house being indirectly heated and a thermal capacity per floor area of 100Wh/(m².K). These equivalent set-point temperatures are calculated for different building average U-values. For the approaches from DIN 18599 and NEN 7120, values are also calculated considering different thermal capacities. While the previous paragraph showed no significant difference between the two approaches from the national standards when considering the same heating profile (Figure 5.3), Figure 5.4 shows that differences will be found at other levels of insulation and thermal capacity. The approach from NEN 7120 proves to be more sensitive to changes to the thermal time constant resulting from different levels of thermal capacity (offsets between the lines) or different insulation levels (steeper slope of the lines) . The steeper slope traced by the values from NEN 7120 shows that this approach will take a larger share of temperature take-back into account by considering a larger temperature increase when improving the insulation level. However, the lowest values should not be compared directly with the value from the other methods. The intermittency formula from NEN 7120 does not take a set-back temperature into account, considering instead a full switch-off of the heating system at night. Because of that, at the lowest thermal time constants (high Um and low thermal capacity), the values obtained considering only intermittency are below what would have been obtained considering a weighted average of 14 hours at 20°C and 10 hours at 15°C. Therefore, one line has been added to the chart ('NL_25Wh/(K.m²)_corr.'). It was calculated following the procedure from NEN 7120, but adding as a lower limit to the intermittency corrected set-point temperature the mentioned time weighted average, similarly to the approach from DIN 18599 (Eq.(5.10)). The values calculated with the physical correction formulas from Loga et al. but without the empirical correction factor are in between the values from DIN 18599 and NEN 7120. However, the values calculated using also the 'use factor' ([43], Eq.(5.18), 'Loga_adapt.') show that the total shortfall (including e.g. behavioural rebound), will probably still be much larger than acknowledged by any of the different physical correction factors. This will be analysed in further detail based on simulations in Chapter 6.

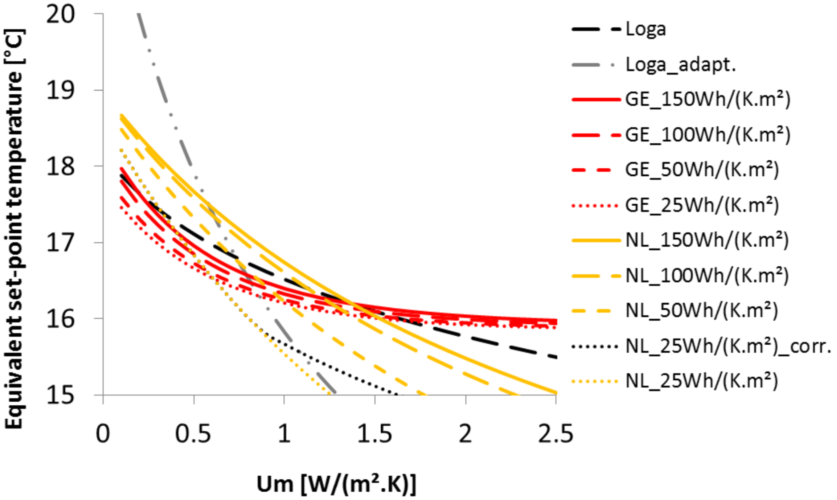

Figure 5.4: equivalent set-point temperatures, using formulas from the different standards and from Loga et al., with heating set-point=20°C, set-back temperature=15°C, set-back duration=8h, indirectly heated area fraction=50% (GE=Germany, DIN 18599 [77], NL=the Netherlands, NEN 7120 [78], ISO=ISO 13790 [20], Loga=physical correlations from Loga et al. [175], Loga_adapt.=including the additional 'use factor'[43])

5.2.3 Coupled, multi-zone formulation from ISO 13790

The spatial and time reduction factors from ISO 13790, DIN 18599 and NEN 7120 allow taking into account the fact that the whole area of a house is not heated all the time. However, they do not allow taking into account specific heating profiles in the multiple different zones, the specific heat transfer coefficients between those zones or other zonal differentiation regarding e.g. internal heat gains, ventilation profiles or the different thermal performance of the external building envelope surrounding those zones. Such, more detailed and case-specific differentiations require the use of multi-zone models. This is illustrated by Loga et al. [175] acknowledging that their multi-zone simulations used for defining the spatial heating reduction factors were sensitive to different assumptions on the inter-zonal heat transfer coefficients, but they did not analyse it in further detail, referring to the uncertainty about these parameters (e.g. caused by opening the doors) and the fact that these do not significantly change after energy refurbishment. Also, varying the selection of heated and unheated rooms influenced the correlations, indicating the importance of the non-homogeneity of the building envelope. This indicates that not taking these parameters into account by using single-zone models could lead to significant errors. Before analysing these errors by means of simulations in the next chapter (Chapter 6), this chapter first analyses the multi-zone heat balance equations required for those simulations. This section analyses two existing quasi-steady state multi-zone approaches: the uncoupled and coupled approaches of ISO 13790 [20], the latter being comparable to the approach used by Loga et al. [175] which was based on EN 832 [19], the predecessor of ISO 13790.

When several heated zones are adjacent to each other, their heat balance equations can be simplified into the decoupled formulation, using the formulas summarized above and assuming either no heat exchange between the zones or assuming a predefined internal temperature in the adjacent, heated zone. This decoupled formulation allows calculating the net heating demand of each zone separately. This however neglects the mutual influence that two connected zones have on their temperatures and energy use for space heating. This interaction is increasingly important as different, unstable heating profiles occur in the different zones or as some zones are not heated at all. Furthermore, when an unheated zone is connected to several other, heated zones, the uncoupled method does not supply a solution on how its heat gains have to be divided towards the different adjacent, heated zones. ISO 13790 states that, in such case, those heat gains shall be divided weighted according to the floor areas of the heated zone. This, of course, is an important simplification, taking into account neither the heat transfer coefficients between the zone nor their interior temperature.

Those more complex relations can only be solved through more complex models, taking into account the coupling of all zones. Annex B of ISO 13790 gives some limited indications on how to extend the quasi-steady state method to a coupled, multi-zone model, based on the TCM-heat method [178]. The proposed solution resides in using the untransformed heat transfer coefficient between two adjacent heated zones (reduction-factors b_{xy}=1) and, when calculating the heat losses of one zone (‘x’), assuming that all adjacent zones ('y') are at their respective average indoor temperature (Eq. (5.23), Figure 5.5). Therefore, the average temperature of the adjacent zones ('y') has to be calculated using Eq. (5.24) and (5.25) which itself is a function of the average temperature of its adjacent zones, including zone 'x'. Due to the gain utilization factors, which depend on the heat transfer coefficients and gain-loss ratios, the resulting set of equations is non-linear and requires an iterative solution process, summarized in Figure 5.6. In a first step, the heat losses are calculated for each zone separately using Eq.(5.23) and considering that the average temperature in each adjacent zone is equal to the set-point temperature of that zone. Subsequently, the space heating demand is calculated using Eq.(5.1). Finally, the average temperature in each zone is calculated using Eq. (5.24). These steps are than repeated, but using these calculated average temperatures in Eq.(5.23), until their values have converged. This method still contains some modelling limitations. Next section discusses these limitations and proposes some corrections to this coupled multi-zone method.

$$Q_{H,losses,x} = \sum_{y} H'_{xy} * \left(T_{H,set,x} - T_{av,y}\right) * dt \tag{5.23}$$

Where

$$T_{av,x} = \frac{(Q_{H,sun,x} + Q_{H,internal,x}) + Q_{heat,x} + \sum_y H'_{xy} * T_{av,y} * dt}{\sum_y H'_{xy} * dt} \tag{5.24}$$

$$H'_{xy} = H_{xy} * b_{xy} \tag{5.25}$$

With

'y' = all adjacent zones, including the external environment

For all adjacent zones 'y' that are modelled in detail: $b_{xy} = 1$

For all default, uncoupled adjacent zones 'y' (e.g. basements not modelled in detail) or for heat losses via the ground: definitions of b_{xy} are kept unchanged and $T_{av,y} = T_{av,e}$

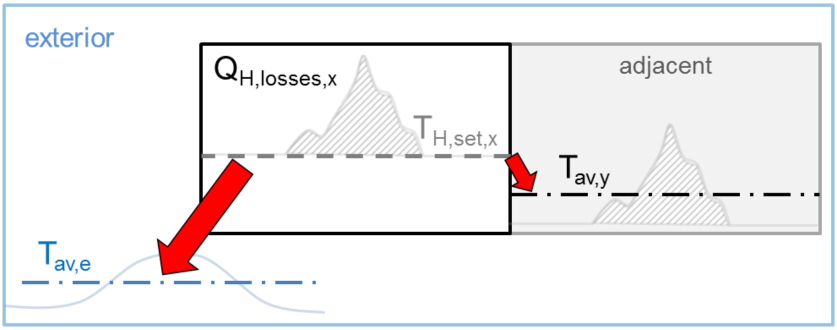

Figure 5.5: coupled multi-zone approach from ISO 13790 [20]: heat losses calculated between the set-point temperature of the considered zone and average temperatures of adjacent zones

(1) Assume initially that the actual mean temperature in each zone is the set-point temperature for heating for that zone
(2) Calculate the heat losses of each zone using Eq.(5.23)
(3) Calculate the space heating demand of each zone using Eq.(5.1)
(4) Calculate the average temperature of each zone using Eq. (5.24)
(5) Check the convergence of the average temperature. If the convergence criteria are not reached, repeat from step (2)

Figure 5.6: workflow of the coupled multi-zone approach from ISO 13790 [20]

5.3 Coupled multi-zone model: issues with the ISO 13790 formulation and improved model

5.3.1 Issues with the coupled, multi-zone formulation from ISO 13790

Transmitting directly versus buffering heat gains

In the coupled model, the division of the heat gains of an unheated zone towards adjacent, heated zones can be calculated in a physically more correct way. Indeed, the heat gains of an unheated zone can be included in its energy conservation balance (Eq. (5.24)) and will therefore result in an increase of the calculated average temperature of the unheated space. This temperature increase will in turn affect the heat losses of the adjacent heated space based on the different thermal heat loss coefficients rather than the floor areas. However, the coupled model still neglects the thermal capacity of the unheated space. This means that e.g. the choice between massive concrete or lightweight timber frame floor- and wall-slabs in an adjacent, unheated space (e.g. a veranda) will have no effect not only according to the uncoupled model, but also according to the coupled model. While this problem seems to apply only to spaces without heating system, it also applies to conditioned spaces where, during certain months, there is no heating demand. This can be the case e.g. in a bedroom with low set-point temperature in an insulated building during mid-season. In such case, the bedroom has no direct space heating demand and its thermal buffering capacity has no influence within the coupled model.

The formulated heat balance equations are based on the simplifying assumption that only the average temperature of an adjacent space defines the heat losses to that space and that the amplitude of the temperature fluctuations has none or only negligible effects or that those effects are fully included in the utilization factor. Indeed, a similar simplifying assumption is made regarding the outdoor temperature, defined in the calculation method only by its monthly average value. However, modelling the heat losses towards adjacent spaces based on their average steady-state temperature (Eq. (5.24)) results in additional errors.

Average versus set point temperatures

ISO 13790 correctly states that replacing the average temperature of the adjacent zones in Eq. (5.23) by their set point temperatures would result in significant errors if there are strong interactions between the zones. The above mentioned example of the bedroom is a good illustration: calculating the heat loss from the living area towards the bedrooms based on low set point temperature of e.g. 15°C in the bedrooms might not make sense if the adjacent, heated living area indirectly heats the adjacent bedroom to a higher temperature. However, using the average temperatures of the adjacent zones can also cause significant errors. Consider two rooms that are perfectly identical (having the same geometry, orientation, heating profile, internal heat gains, and surroundings) and that are adjacent to each other (Figure 5.7). The centre of their common wall will thus act as an adiabatic boundary. Unless their utilization factor equals one, their average temperature will be higher than their set point temperature. However, using Eq. (5.23) will result in both spaces having a negative transmission heat loss towards each other or, in other terms, each room will heat the other while none of both rooms will lose heat to the other, thus infringing the law of conservation of energy. While this formulation error might be negligible in barely insulated houses with high thermal mass during the coldest months, the error will grow in high performance houses or mid-season, as utilization factors decrease due to increased insulations levels, lowered thermal capacities and higher ambient temperatures, making the average temperature differ more from the set point temperature.

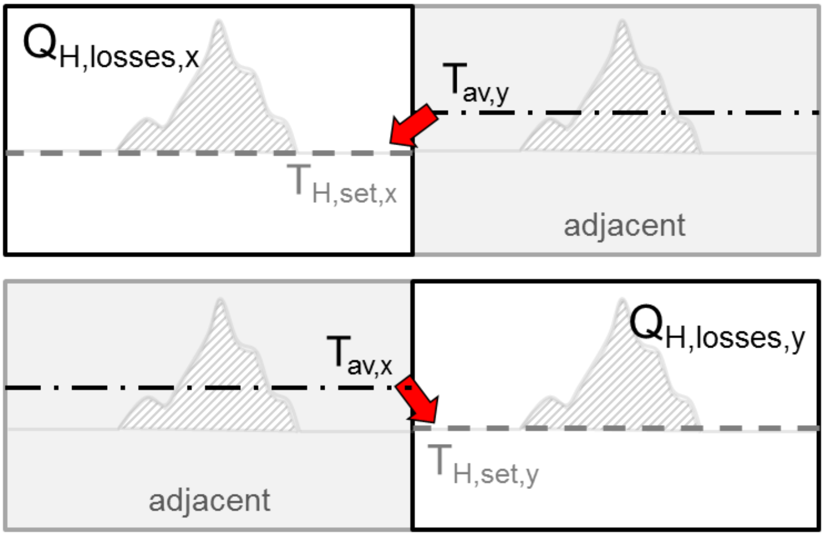

Figure 5.7: coupled multi-zone model from ISO 13790: the use of set-point and average temperatures infringing the law of conservation of energy

Boundless overheating versus the indirect influence of space cooling on space heating

As will be described in this paragraph, the simplification error caused by the use of average temperatures in Eq. (5.23) is further increased by the possibility of boundless overheating that is assumed in Eq. (5.24) by not considering any active or passive cooling strategy. The utilization factors account for the fact that a part of the heat gains does not contribute to lowering the heating demand. The main reason is the asynchrony in time between the (peak) heat gains and the (peak) heat losses that cannot always be levelled out by the thermal time constant of the building. Several methods exist to define the correlation formulas and their physical constants defining the utilization factors [17,20] or even to apply Bayesian calibration methods to correct the constants for a specific building [168,173,179]. Common to all approaches, the correlation formulas and constants are defined based on sets of dynamic simulations that do take into account both heating and cooling requirements, considering both heating and cooling set points. Using regression analysis based on those simulation results, the utilization factors are calculated for use within single zone quasi-steady state calculations. They are defined for use within quasi-steady state heating demand calculations by assuming the building is being used as during winter (e.g. sun shadings never lowered, ventilation heat recovery units not bypassed) or for use within cooling demand calculations by assuming the building is being used as during the summer (e.g. sun shadings in normal use and ventilation heat recovery units bypassed). Because a cooling set-point and infinite cooling power is considered in the dynamic simulations, the correlations of the utilization factors take into account the direct effect that cooling measures have on the space heating demand of a zone even though the cooling demand is not calculated within the quasi-steady state space heating demand calculation and vice versa. Within a single zone calculation, this approach is sound for calculating the space heating energy use. However, the multi-zone calculation of the space heating demand from ISO 13790 neglects the fact that cooling measures in one zone can also have an indirect effect on the space heating demand in another, coupled zone and vice versa. Annex B of ISO 13790 asserts the fact that overheating might occur and result in increased average indoor temperatures during the heating season. Therefore, all the solar and internal heat gains are fully taken into account when calculating the average temperatures (Eq. (5.24)). Indeed, heat gains can make the interior temperature peak above the heating set point temperature. However, when uncomfortably high temperatures are reached, inhabitants will take measures (e.g. opening the windows or lowering sun shadings) and active or passive cooling mechanisms can be automatically activated (e.g. bypassing the heat recovery unit). However, these passive and active ways of reducing the heat gains (e.g. sun shadings) or cooling the building (e.g. additional ventilation or cooling systems) are not taken into account in Eq. (5.24). As a result, the calculated average indoor temperature can reach unrealistically high values. This will in turn artificially lower the heating energy use of the adjacent spaces calculated using Eq. (5.23) and increase the error caused by the infringement of the law of conservation of energy discussed in the previous paragraph. When simulating the passive-house scenario for defining their spatial reduction factors, Loga et al. [175] indeed obtained very high temperatures, far above 26°C in all the zones of the house, already from the month of April and until the month of September (included), but these were considered being outside the heating season and therefore causing no significant errors on the results. However, one can wonder if the calculated heating season would not have been a little extended if these errors did not occur or if the error would not have been significant in case of larger differentiation between the zones, considering e.g. a well insulated extension to an uninsulated old house, the former with overestimated indoor temperatures influencing the calculated heating demand of the latter.

5.3.2 Alternative coupled, multi-zone formulation

The following changes are proposed to handle the issues identified within the coupled method and close the set of equations.

Set-point and average temperatures

A first change to the formulations addresses the issues regarding the utilization of heat gains and the resulting difference between set point and average temperatures. The effect of the heat gains is first considered to affect the heat balance of the respective zones, resulting, in case of a utilization factor lower than one, in both a 'lower temperature' and an average temperature. The lower temperature of a zone ($T_{low,y}$) will be defined differently depending on it being heated or not (Eq. (5.28)): the equivalent heating set point temperature ($T_{set,y}$ including any intermittency corrections) in case of a zone with a heating demand or, in case the corresponding heating demand of that zone is zero (including all unconditioned zones), the highest equivalent set point temperature at which there would still be no heating demand in that zone ($T_{y,setH=0}$, from Eq.(5.1)=0). During winter in most heated rooms (e.g. the living room) the former definition applies, while in an unheated zone the latter definition applies. Especially in well insulated houses, the latter can still prevail when the outdoor temperature increases and the temperatures within the adjacent rooms are high enough to compensate the heat losses to the outside, like e.g. for bedrooms adjacent to a heated living room. Following the monthly quasi-steady state equations from ISO 13790, $T_{setH=0,y}$ can be calculated using Eq.(5.29), resulting on multi-zone building level in a linear set of equations, with additional inequalities from Eq. (5.28).

The fluctuation of the internal temperature of the zone, resulting in a difference between the average and the lower temperature, causes a fluctuating heat exchange between adjacent zones. These are considered as the fluctuating part of the heat gains that can be transmitted to the adjacent zones and which might not be fully utilized in the adjacent zones mainly due to asynchrony between the gains and the demand.

To take overheating into account, the difference in heat losses between Eq. (5.23) and Eq. (5.26) is taken into account in the heat gains (Eq. (5.27)). In other words, the heat losses are calculated considering the lower temperatures of the adjacent zones while, in addition, the temperature fluctuations in the adjacent zones are considered as heat gains that might not be fully utilized, due e.g. to asynchrony, when thermal time constants and heating demands are low. As a result, the thermal time constants of both zones will influence the utilization of heat gains to lower the heating demand.

$$Q_{H,losses,x} = \sum_{y} H'_{xy} * \left(T_{H,set,x} - T_{low,y}\right) * dt \tag{5.26}$$

$$Q_{H,gains,x} = (Q_{H,sun,x} + Q_{H,internal,x}) + \sum_{y} H'_{xy} * \left(T_{av,y} - T_{low,y}\right) * dt \tag{5.27}$$

Where

$$T_{low,y} = MAX(T_{H,set,y}; T_{setH=0,y}) \tag{5.28}$$

And

$$\begin{aligned} &T_{setH,y=0} \\ &= fictive\ set\ point\ temperature \\ &of\ zone\ 'y'\ for\ wich\ Q_{heat,y} is\ zero \\ &= \frac{\sum_y H'_{xy}\ T_{low,y}}{\sum_y H'_{xy}} \end{aligned} \tag{5.29}$$

Boundless overheating and indirect effect of cooling measures

A second change to the multi-zone method addresses the issue of the boundless overheating. The effect of passive and active overheating protection and cooling is difficult to implement in the quasi-steady-state calculation of the heating demand. Indeed, those measures occur at the level of the heat loss coefficient (e.g. bypassing the ventilation heat recovery units, additional ventilation), at the level of the heat gains (e.g. solar shading) and at the level of active systems (e.g. active cooling). However, the basic consequence of all forms of overheating protection and cooling strategies, both active and passive, could be implemented in the calculation procedure by introducing a fictive cooling load $Q_{cooling,x}^{fictive}$ within Eq. (5.24), resulting in Eq. (5.30). This fictive cooling load is defined as the calculated net cooling demand assuming that the building resides in its winter status (e.g. no solar shading, heat recovery unit not bypassed), as for the space heating calculation. Therefore, this $Q_{cool,x}^{fictive}$ (Eq.(5.31)) should not be confused with the theoretical net energy demand for cooling (Eq.(5.33)), which will be lower due to e.g. solar shading and the bypassing of ventilation heat recovery units. This method allows taking into account the fact that inhabitants will do what they can to avoid any overheating, without taking into account inefficient control strategies. Therefore, it is an underestimation of the total effect of all cooling strategies (reduction of the heat gains, additional heat losses and net active cooling combined). It is important to note that this fictive cooling can only be implemented within the boundaries of the available cooling options. Therefore, a realistic cooling set-point temperature for the fictive cooling should be chosen. If active cooling is present, the choice will purely depend on its cooling power and the inhabitants comfort criteria. If no active cooling is present, but e.g. windows can be opened, a reasonable choice should be made for each month, based on the outdoor temperature and the comfort criteria used. When considering this fictive cooling load for a zone, the set-point temperature considered for that fictive cooling load must also be imposed as an upper limit for the lower temperature of that zone, replacing Eq.(5.28) by Eq.(5.34).

Note that including “$-\ Q_{cool,x}^{fictive}$” in the formula only affects the average temperature of the considered zone and thus the heating demand of the adjacent zones, but not (directly) its own heating demand. Eq. (5.30) thus takes into account the indirect effect that overheating protection and cooling strategies have on the heating demand of a coupled zone. Indeed, the direct effect of heating and cooling interactions within a zone was already taken into account in Eq. (5.1) by the utilization factor.

In case of building zones with high thermal capacity, low heat gains and with low thermal transmittance between the zones, this indirect effect might be negligible. In cases of e.g. lightweight timber frame buildings with high solar gains and strong zonal differentiations, the passive or active cooling needed during mid-season might have an important effect on the resulting average indoor temperature and thus on the heating demand occurring during the same season.

$$T_{av,x} = \frac{(Q_{H,sun,x} + Q_{H,internal,x}) + Q_{heat,x} - Q_{cool,x}^{fictive} + \sum_y H'_{xy} * T_{av,y} * dt}{\sum_y H'_{xy} * dt} \tag{5.30}$$

$$Q_{cool,x}^{fictive} = Q_{H,gains,x} - \eta_{C,ls,x} * Q_{fict.C,losses,x} \tag{5.31}$$

$$Q_{fict.C,losses,x} = \sum_y H'_{xy} * \left(T_{C,set,x} - T_{low,y}\right) * dt \tag{5.32}$$

$$Q_{cool,x} = Q_{C,gains,x} - \eta_{C,ls,x} * Q_{fict.C,losses,x} \tag{5.33}$$

$$T_{low,y} = MIN\left[MAX\left(T_{H,set,y}; T_{setH=0,y}\right) ;\ T_{C,set,y}\right] \tag{5.34}$$

With

$Q_{H,gains,x}$= the heat gains for the heating calculation resulting from Eq.(5.27)

$\eta_{C,ls,x}$ = heat loss utilization factor ([0;1]) for cooling calculations, further defined in ISO 13790 [20] and calculated using the corresponding gains and losses mentioned in the equation it is used

H'_{xy} = heat transfer coefficient resulting from Eq.(5.25), thus considering winter conditions (e.g. with heat recovery units being used)

$T_{C,set,x}$ = the set-point temperature for cooling

$Q_{C,gains,x}$= the heat gains for the cooling calculation, considering e.g. the use of solar shading [20]

$Q_{C,losses,x}$= the heat losses for the cooling calculation, considering e.g. bypassing ventilation heat recovery units [20]

Equivalent set point temperature accounting for intermittency

The intermittency correction formulas from NEN 7120 were implemented for taking night-time reduction into account in this multi-zone model. They are applied on the set-point temperature used in Eq.(5.26) and (5.28), using the formulation from Eq.(5.20). However, in the multi-zone formulation, intermittency profiles can be strongly different from the assumptions in the national standards. Indeed, the standards apply these correction formulas on heating profiles for the main living area with respectively realistic heating periods of approximately half a day (see 5.2.2). However, in the multi-zone model intermittency corrections also apply on e.g. bathrooms, heated for e.g. only one hour a day and located next to the unheated sleeping area. Applying an intermittency correction based on Eq.(5.12) to those rooms in a multi-zone model sometimes results in unrealistically low equivalent set point temperatures and consequently in no calculated heating demand in the bathroom notwithstanding its set point temperature being high, sometimes even higher than the main set-point and average temperatures in the living area. In response, an additional lower limit was imposed to the equivalent set-point temperature, notwithstanding this is only needed for rare combinations of short heating periods in small parts of barely insulated houses. That lower limit is calculated as the time weighted average of the main heating set-point temperature, the exponentially decaying temperature when the heating is switched off and the set-back temperature (if that temperature is reached) (Eq.(5.35)). It considers the exponential decay of the temperature of the room starting from the set point temperature and assuming no heat gains, neither solar nor internal, and convergence to the exterior temperature. Therefore, this calculated temperature can be considered as a lower limit for the average indoor temperature, without any overheating and thus applicable as a lower limit for the equivalent set point temperature. The decaying temperature after the heating is switched off can be calculated based on the thermal time constant of the room using Eq.(5.36). Consequently, the duration of the temperature decay can be calculated according to Eq.(5.37). Subsequently, the average temperature during the decay period is found by integrating Eq.(5.36) over that duration (Eq.(5.39)).

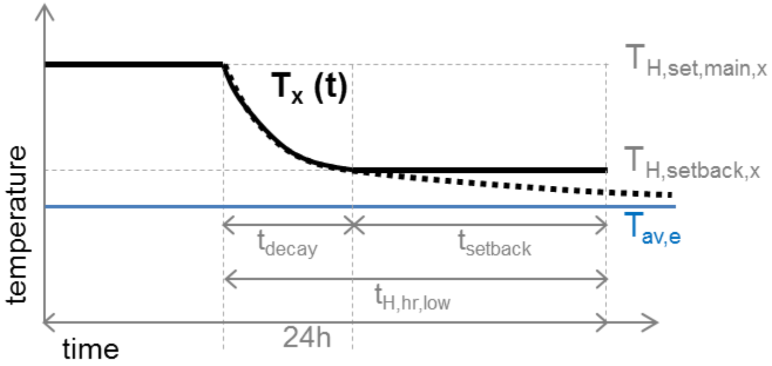

Figure 5.8: exponential decay of the indoor temperature during night-time set-back

$$T_{H,set,equiv,minimum,x} = \frac{(24 - t_{H,hr,low})}{24} T_{H,set,main,x} + \frac{t_{decay}}{24} T_{av,decay,x} + \frac{t_{setback}}{24} T_{H,setback,x} \quad (5.35)$$

With

$t_{H,hr,low}$ = the number of hours per day at reduced set point temperature or full switch-off [h] (see also section 5.2.2, Eq. (5.12))

t_{decay} = the duration of the temperature decay until the set-back temperature is reached or until the start of the next heating cycle [h]

$t_{setback}$ = the duration that the heating system is active for maintaining the set-back temperature [h]

$T_{H,set,main,x}$ = the main heating set point temperature [°C]

$T_{H,setback,x}$ = the heating set-back temperature (if applicable) [°C]

and from

$$T_{toff,x} = T_{av,e} + (T_{H,set,main,x} - T_{av,e}) e^{-t_{off}/\tau_H} \quad (5.36)$$

with

t_{off} = the time elapsed since the heating is switched off [h]

$T_{toff,x}$ = the temperature at that moment (t_{off}) [°C]

τ_H = thermal time constant [h]

results

$$t_{decay} = minimum\left[t_{H,hr,low}\ ;\ \ -\tau\ln\left(\frac{T_{H,setback,x} - T_{av,e}}{T_{H,set,main,x} - T_{av,e}}\right)\right] \tag{5.37}$$

$$t_{setback} = t_{H,hr,low} - t_{decay} \tag{5.38}$$

$$T_{av,decay,x} = T_{av,e} + \frac{\tau\left(T_{H,set,main,x} - T_{av,e}\right)\left(1 - e^{-t_{decay}/\tau}\right)}{t_{decay}} \tag{5.39}$$

Inter-zonal heat loss coefficients

ISO 13790 notes that a coupled multi-zone model, compared to single-zone models, *"requires significantly more, and often arbitrary, input data (on transmission properties and air flow direction and size)"*. Estimating the thermal resistance of interior walls and floors can be done in a similar way as for the exterior building envelope, using measured, calculated or default values. In addition, calculating the inter-zonal heat transfers coefficients requires much more geometrical information than needed in a single-zone model. However, approaches using Building Information Models (BIM) can drastically reduce the related workload, as is further discussed in Chapter 7. In a similar way as for calculating the transmission heat losses, directional inter-zonal air flows induced by mechanical ventilation systems can be estimated based on the design values and on common, often lowered user control settings reported in literature and surveys (see 3.3.3, [47,96,116,117,158–161]). The inter-zonal air flows will also be largely influenced by the inhabitants opening and closing the doors. In reality, all inter-zonal air flows can also be influenced significantly by the temperature differences between zones, wind pressure and the air permeability of the envelope and of the partition walls [138,180]. However, modelling these additional aspects requires more complex air flow models. Going far into detail on those aspects outreaches the goal of this study and would require considerable amount of extra input data (e.g. regarding types of vent holes), opposing the aim of a pragmatic and simple simulation tool. The choice of the modelling approach regarding these inter-zonal air flows will thus depend on the presence or type of mechanical ventilation system, the availability of data on the use of those systems and considerations regarding the required accuracy of the model and the workload for building it. One approach regarding the modelling of air flows through open doors will be presented in section 6.2.2, where the use of the multi-zone model is described for the case-specific simulation of old houses without ventilation system.

Summary of the iterative calculation process

Before briefly discussing the software implementation of the different models, this paragraph summarizes the mathematical implementation of the presented multi-zone model. An overview of the workflow of this adapted multi-zone approach is given in Figure 5.9. Compared to the single-zone models and similarly to the original coupled model, the adapted coupled model includes parameters that can only be calculated through an iterative solving procedure. That solving procedure is more complex than that of the original coupled multi-zone model from ISO 13790. Still, optimized formulations of the iteration routines, supplemented with an adaptive relaxation method (Aitken-method) resulted in efficient calculation algorithms, allowing strict convergence criteria. The convergence criteria used in the mathematical implementation consist of maximum absolute differences comparing results of subsequent iteration steps, required to be achieved over a minimum number of consecutive iterations (Table 5.1). Convergence checks are applied for the most important calculated values: the supplied average power and the lower and average temperatures from Eq. (5.28) and (5.30). By checking the lower temperature from Eq. (5.28), the applicable equivalent set point temperatures are also checked. For the heating demand, the values are checked both per zone as well as for the cumulated value over all zones. While these convergence criteria appear very strict, the value of the convergence criterion does not guarantee the calculation error due to the iterative procedure to be as small. Furthermore, in part thanks to algorithm optimizations like the use of adaptive relaxation and code optimization, increasing the convergence criteria for the temperature and power values to 0.01°C and 1W respectively, thus by a factor of 10 and 100, did only reduce the number of iterations by approximately 1/3. This was considered negligible, firstly because an efficient mathematical and programming implementation of the algorithm already resulted in very fast calculations. Secondly, considerable parts of the calculation procedure do not take place within the iteration loops and become more important in terms of total simulation time: reading in and checking inputs, exporting results, calculating the solar heat gains based, for each month, on an hourly calculation of the solar irradiance on each separate window during a reference day etc. In its final implementation, calculating the yearly space heating demand (thus 12 monthly heat balances) for the multi-zone model of an average multi-bedroom house containing around 15 rooms, each modelled as a separate thermal zone, takes less than 0.1s on an average portable computer. This timing includes calculating the solar heat gains but excludes pre-processing of the inputs (e.g. calculating geometries) or post-processing of the outputs, which depend on the integration of the model in other software and on their interface.

1. (1) Assume initially that the lower temperature ($T_{low,x}$, required in step 2) and the average temperature of each zone (required in step 4) are equal to the set-point temperature for heating of that zone.
2. (2) Calculate for each zone the highest set-point temperature for which the space heating demand would be zero ($T_{setH=0,x}$, Eq.(5.29))
3. (3) Define $T_{low,x}$ using Eq.(5.28). If $T_{low,x}$ has changed compared to the values considered in step 2, repeat step 2.*
4. (4) Calculate the heat losses and the heat gains of each zone using Eq.(5.26) and Eq.(5.27)
5. (5) Calculate the fictive cooling energy demand of each zone using Eq.(5.32)
6. (6) Calculate the space heating demand of each zone using Eq.(5.1)
7. (7) Calculate the average temperature of each zone using Eq.(5.30)
8. (8) Check the convergence of the average temperatures, and of the space heating and cooling demands. If they have not converged to the predefined criteria, return to step 4

NOTES:

*Iterating between step 2 and step 3 does not require defining numerical convergence criteria. The set of equations required in step 2 is linear but contains inequalities (Eq.(5.28)). Iterations can be needed because of these inequalities when a room that was considered being heated when initializing step 2 appears to be free-floating or cooled because of the higher temperatures in the adjacent zones, or vice-versa. This will thus require redoing step 2 with these new assumptions. When the correct assumptions are found, the linear set of equation can be solved directly instead of iteratively.

Figure 5.9: workflow of the adapted coupled multi-zone approach

Table 5.1: Convergence criteria

	$T_{low,x}$	$T_{av,x}$	$\frac{Q_{cool,x}^{fictive}}{t}$	$\frac{Q_{heat,x}}{t}$	$\frac{\sum_x Q_{heat,x}}{t}$
Δmax,abs. ≤	0.001°C	0.001°C	0.001W	0.001W	0.001W
Ncons.it. ≥	4	4	4	4	4

5.4 Implementation of the different modelling approaches

This chapter presented different single and multi-zone modelling approaches, analysing and comparing them theoretically, based on their formulas. Further evaluation of the models requires using them on case-studies for validation and in scenario analyses exploring the flexibility and limitations of the different models. These analyses are presented in the following chapter (Chapter 6). Before moving on to that simulation based chapter, this paragraph briefly summarizes how the model algorithms were implemented for using them in the simulation analyses.

The algorithms were coded in VB.NET and compiled in a dynamic link library (DLL) for easy implementation within different applications. The single-zone approach (5.2.1) was also implemented in the DLL with the options of using the intermittency and spatial reduction factors from DIN 18599 or from NEN 7120 (5.2.2) and the option of overriding the standard heating profiles, making it possible to perform the comparative analyses of the different modelling approaches discussed in the following chapter.

.NET DLL's can be called from varying software ranging from simple Excel-files (through COM-interop calls in VBA-codes) onto many commercial or custom software tools. Native interaction on any computer running on Windows is easily achievable, without local compiling or access to the registry, with software running on the .NET-framework, thus allowing interaction with codes programmed in several common programming languages (C#, VB.NET, C++/CLI …), requiring only the .NET-framework to be installed.

For the analyses in the following Chapter 6, an Excel-file was used as an interface and to do necessary pre-calculations (e.g. of the heat transfer coefficients) and for post-processing the results. The .NET-algorithms in the DLL are called by a custom VBA-function (using COM Interop and thus registry access) that can be called as a custom Excel-formula from any cell in the Excel-file. This results in seamless integration in Excel and in automatic updates of the results when changing any input-cell. Further VBA-codes automated the process of scenario and sensitivity analyses. This calculation library has also been implemented in a more user friendly BIM-based software tool, as is further discussed in Chapter 7.

6

Heating profiles in quasi-steady-state models: single versus multi zone models, *simulation study*

This second chapter on the modelling approaches analyses and compares the approaches presented in Chapter 5 by using them for simulating case-studies. The models are now thus compared not based on their formulas and implementation, but based on simulation results. The neighbourhood of old houses analysed in Chapter 3 (‘cs1’) is used as a case-study, considering also the actual user profiles found in the different houses. Firstly, this chapter looks at modelling the houses in their existing, not insulated state, comparing simulation results of the different models with one another and with real values (energy use and temperatures). Subsequently, different renovation scenarios are analysed by means of simulations using the different models. The simulation results are analysed and compared to identify the biases that different modelling approaches can cause when using them for predicting energy savings and for comparing different renovation measures.

Parts of this chapter were presented at the International Building Physics Conference 2015 and published in the proceedings [181].

6.1 Introduction

6.1.1 General introduction and approach

Previous Chapter 5 discussed different approaches from national standards for taking heating profiles into account in quasi-steady models and presented an extended, multi-zone approach. These approaches were discussed because of the findings from the field studies and statistical studies referenced and discussed in Chapters 2, 3 and 4. Those chapters showed the large variations in heating profiles between houses and room types and the fact that these heating profiles were significantly associated with the variations in real energy use and with the prediction errors from regulatory energy performance assessment methods which consider standard user profiles. Those chapters also discussed additional variations in user profiles at room level regarding mainly the ventilation and presence of people, which could be taken into account in multi-zone models.

The current chapter analyses to what extent the different modelling approaches discussed in Chapter 5 succeed in improving the accuracy of the theoretical models on two levels: making a more realistic prediction of the variation in real energy use associated with different user profiles and reducing the average overestimation of the energy use. This simulation based study is done on a set of houses for which detailed information about the houses, the user profiles and the resulting indoor temperatures and energy use are available: the neighbourhood of old, not insulated houses analysed in Chapter 3 ('cs1'). Additional renovation scenarios are considered for further comparison between the different models with regard to predicted energy savings and associated physical temperature take-back. Considering those scenarios, the difference in results between the most detailed models and the regulatory approach are also compared with correlations found in literature relating real energy use and theoretical energy use considered in the framework of regulatory performance assessments. The following introduction section summarizes the references from literature that will be used for the latter comparisons. The subsequent introduction section lists the different modelling parameters that are analysed and the corresponding hypotheses that are verified.

6.1.2 Selected references with regard to the gap between theoretical and real energy use

Sunikka-Blank and Galvin [29] made a comprehensive literature review on the gap between real energy use for heating and theoretical values from regulatory energy assessment calculations. They defined what they called the 'prebound' factor as Eq.(6.1), which equals what was defined by Hens et al. [31,45] as the 'direct rebound' factor. The names 'direct rebound' and 'prebound' might thus be considered misleading in their reference to 'rebound' because what this factor accounts for is the average prediction gap between theoretical and real consumption values expressed as a percentage of the theoretical value. It can thus account for any modelling error or simplification, regarding user profiles, building or system characteristics etc. and is not necessarily related to changes in user behaviour being associated in building performance. They showed that not only in Germany, where most of the data they analysed came from (incl. data on over 3400 houses), but also in other countries (Belgium, France, the UK, the Netherlands) large overestimation errors occurred at poor theoretical performance (an estimated 60% at theoretical values of 500kWh/(m².year)) while small overestimations were found at better performance levels (around 17% at 150kWh/(m².year)) shifting even further to underestimation at high performance levels (below 100kWh/(m².year)). This was also discussed in Chapters 2, 3, with the data on the old and new neighbourhoods from Chapter 3 showing comparable overestimations for the not insulated houses (an overestimation by on average 53% at 321kWh/(m².year)). However, the overestimation in the new neighbourhood was still 30% at theoretical values of 97kWh/(m².year). When comparing such values, the differences between the datasets should be considered. Obviously, the dataset analysed in Chapter 3 was a specific case-study, much smaller and more homogeneous than the large dataset and thus less representative for average values at building stock level. Furthermore, different countries have different climates, building traditions etc. Another important difference is the calculation method used as a reference value in the different studies, being mostly the regulatory assessment methods from the respective counties. As was discussed in Chapter 5 and will be further illustrated in this chapter, the modelling approaches used in different countries show significant differences, making a direct comparison between the values from different countries difficult and mainly illustrative of the fact that 'similar' relations are found between prediction errors and performance levels.

Because of these differences between calculation methods, findings only from two studies are discussed here and will be used for comparison with the simulation results. These two studies are also selected because, instead of giving an average percentage of overestimation at one or two performance levels, they present a correlation defining the values of Eq.(6.1) at different performance levels. When such empirical correlation has been defined statistically, it can be used at different performance levels to find a more accurate or probable estimation of the real energy use based on a theoretical calculation by reversing Eq.(6.1). This of course gives a result that should be considered as an average value considering large numbers of cases and not as a value to be considered accurate for each specific household. Having such correlations also allows analysing their trends (e.g. are they linear, exponential etc.) and comparing those. The first study is one by Loga et al.[44] based on data from Germany. Therefore, comparing their correlation between real and theoretical values with our correlations between results from more detailed models and results from standard approaches should be considered solely as indicative. Using as a reference model our model that includes the German correction approaches and user profiles from DIN 18599 would not make a quantitative comparison more valid, because another (seasonal) calculation method was considered in the data analysed by Loga et al. [44,182]. The second study is one by Hens et al. [31,45] based on data from Belgium.

$$P = \frac{Q_{h,theory} - Q_{h,real}}{Q_{h,theory}} \tag{6.1}$$

With

P = dimensionless 'prebound' factor

$Q_{h,theory}$ = theoretical final energy use for space heating

$Q_{h,real}$ = real final energy use for space heating

The correction factor found by Loga et al. [44] is formulated in function of the theoretical energy use ($Q_{h,theory}$) normalized per floor area, expressed in kWh/(m^2.year) and equals Eq. (6.2). It was derived from data on energy use in houses with a central heating system. Based on '(subjective) experience', they state this factor should be corrected for houses with local stoves to take into account the lower temperatures found in these houses, an experience that corroborates the findings from Chapter 3 comparing the old houses with local gas stoves with the new houses with central heating systems. Since the necessary quantitative evidence was not available for defining this value empirically, they propose increasing the value from Eq. (6.2) with a flat rate of 10 percent points, at all performance levels. Using Eq. (6.2) and Eq.(6.1), Figure 6.1 shows the corresponding empirical relation between real and theoretical energy use and illustratively includes the real and theoretical energy use of the old houses analysed in Chapter 3 ('cs1).

$$P_{Loga2013} = 1.2 - \frac{1.30}{\left(1 + \frac{Q_{h,theory,psfl}}{500}\right)} \tag{6.2}$$

With

$Q_{h,theory,psfl}$ = theoretical final energy use for space heating per floor area [kWh/(m^2.year)]

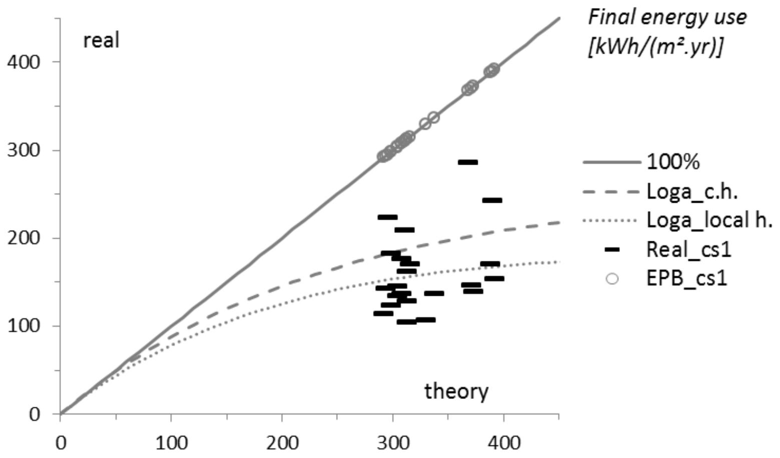

Figure 6.1: The gap between real and theoretical energy use for space heating according to Loga et al. [44] ('c.h.': original correlation based on houses with central heating; 'local h.': correlationcorrection for local heating) with real and theoretical final energy use of the old houses of cs1 from Chapter 3.

Hens et.al [31,45] did not define their correlation directly in function of the theoretical energy use calculated using a standard performance assessment model. They started from the observation that the energy use for space heating can be expressed in function of the transmission heat transfer coefficient after a normalization per cubic meter of volume (Eq.(6.3)). Considering the theoretical energy use based on simulations with the equivalent set-point temperature of 18°C in the EPB-methods in Belgium, this function was found to be linear (b=1 in Eq.(6.3)). In a first paper [31], the linear coefficient ('a' in Eq.(6.3)) was reported to be 311, while in a second paper [45] discussing the same approach it was reported to be 363. In both cases, these values were compared with the same dataset on real consumption data which proved that, in reality, the relation was not linear but following a power function, with for Eq.(6.3) a=229.6 and b=0.84.Figure 6.2 shows these correlations and illustratively includes the real and theoretical values of the old houses analysed in Chapter 3 ('cs1'). Based on these correlations and on Eq.(6.1), the 'direct rebound' or 'prebound' factor corresponding to the theoretical linear correlations can be formulated as Eq.(6.4) and Eq. (6.5), respectively. These can be used according to Hens et al. as an average correction factor on the results from official EPB-calculations. Eq. (6.4) differs from the equation reported in the original paper [31] (and copied in [29]) because it was found that the theoretical and real values had been mixed up in that paper when using Eq.(6.1).

$$\frac{Q_{h,**}}{V} = a\left(\frac{H_t}{V}\right)^b \tag{6.3}$$

With

Q_{h**} = the final energy use for space heating, theoretical or real [MJ]

a, b = regression coefficients defined based on simulations or real data

H_t = the transmission heat transfer coefficient [W/K]

V = the volume of the building [m³]

$$P_{Hens2010} = 1 - 0.633\left(\frac{H_t}{V}\right)^{-0.16} \tag{6.4}$$

$$P_{Hens2013} = 1 - 0.738\left(\frac{H_t}{V}\right)^{-0.16} \tag{6.5}$$

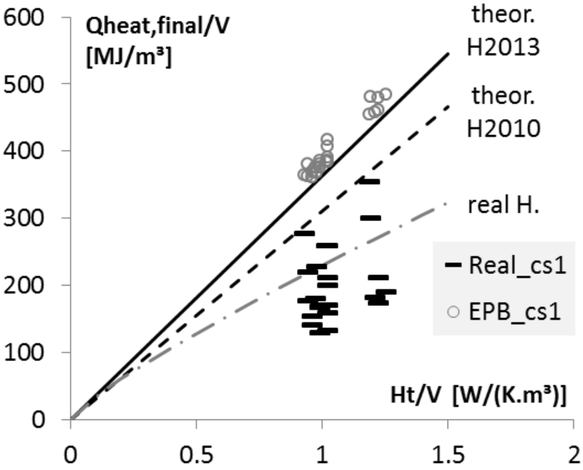

Figure 6.2: the gap between real and theoretical energy use for space heating according to Hens et al.2010 [31] and Hens et al.2013[45], with real and theoretical final energy use of the old houses of cs1 from Chapter 3.

6.1.3 Parameters and hypotheses

The overall hypothesis is that shifting from a single-zone model with fixed equivalent set-point temperature (as considered in Belgium) to a single-zone model with correction factors for intermittent and spatially reduced heating (as considered in the Netherlands and Germany) and further to a multi-zone model can result in a significant reduction of the discrepancies between real and theoretical values. The single and multi-zone approaches presented in Chapter 5 are different with regard to which aspect they can or cannot take into account. Some are considered to explain part of the prediction error described in literature and in the previous chapters, being characterised by an average overestimation of the energy use that increases at low performance levels (see previous section) and also by a large spread in prediction errors at all performance levels when comparing values at the level of the individual house and household.

Chapter 3 puts forward the hypothesis that part of the large overestimation of the energy use in old houses results from the fact that, by considering a fixed equivalent set-point temperature of 18°C, the official calculation method that was used overestimates, on average and at building level the average indoor temperature. The low indoor temperatures at building level found in the old houses proved to result mainly from the low temperatures of the indirectly heated night zone. The first hypothesis of this chapter therefore focusses on taking the zonal differentiation of the heating profiles into account: using the approaches from DIN 18599 and NEN 7120 (5.2.2) or the multi-zone model (5.3.2) should result in more accurate calculated indoor temperatures and space heating demands. However, this will probably not explain the full extent of the prediction gap. Firstly, Chapter 5 (5.2.2) showed that the equivalent set-point temperature resulting from the German and Dutch approach do not always result in values below 18°C. Secondly, large overestimations of the real energy use by regulatory energy calculation models were found not only in Belgium, but also in countries where the single-zone calculation methods include these types of correction factors: Germany, the Netherlands, the UK [29,32,97].

Therefore, a second hypothesis from Chapter 3 is analysed: considering the real window opening profiles should result in lower calculated air flow rates than considered in the standard EPB-model and therefore in lower heat losses, a lower theoretical energy demand and a smaller prediction gap (3.4.1).

Considering the heating profiles and window opening profiles together leads to the third hypothesis from Chapter 3. The windows that were opened by the inhabitants were mainly those of the unheated bedrooms and of the bathrooms, but not those of the heated living rooms. Therefore, single-zone modelling approaches, which do not consider this behavioural relation between ventilating and heating at room level, will overestimate the energy demands even when realistic building average temperatures and total air flows are considered (3.4.1). Taking this zonal differentiation into account in the multi-zone model should thus result in smaller overestimations.

Two additional differences between rooms are not taken into account in single-zone models with correction formulas: the different internal heat gains and the different performance levels of the external envelope of each room. In a similar way as for the ventilation heat losses, all internal heat gains of a house are summed up in single-zone models, without considering if those heat gains originated in the directly or in the indirectly heated areas. However, the most heated area is the living area, where cooking takes place and where people are active, using electrical appliances (e.g. televisions) and, especially during winter when nights are long, requiring active lighting. Taking into consideration this zonal match between heat gains and thermal comfort requirements in a multi-zone model may remove one more part of the prediction gap. Similarly, while corrected for taking into account the fact that not all rooms are heated, the single-zone approaches from DIN 18599 and NEN 7120 still simplify the thermal properties of the envelope into one average heat loss coefficient and the spatial differentiation into one single equivalent set-point temperature. This simplification can be compared to the assumption of a homogeneous occurrence of heat losses over the total heat loss area. However, walls, windows, roofs, floors etc. have different thermal properties and are not distributed uniformly over the whole building envelope. Loga et al. [175] reported that making different modelling assumptions on which zones of their model were heated and which were not, influenced the correlation between the unheated area fraction and the correction factor for spatially reduced heating (see 5.2.2). Using a multi-zone model of the considered house instead of a single-zone model with correction factor based on other housing typologies and zonal heating patterns should thus reduce the errors on the individual case-level. Moreover, it could also reduce the average overestimation of the energy use in not insulated houses because of the common lay-out of houses having their heated living area on the ground floor and their unheated night zone on the first floor. In a house where walls, roofs and floors are not insulated, the uninsulated floor will have the lowest equivalent thermal transmittance because of the thermal resistance and buffering capacity offered by the ground.

Another zonal differentiation that is not considered in the regulatory performance assessment models does not regard the different user profiles in adjacent rooms of the house, but the different user profiles in adjacent houses. In a simulation based study on apartment blocks by Nielsen And Rose [183], lowering the temperature of an apartment by 2°C was found to increase the energy demand of the adjacent apartments by 10 to 20%. Apartments are more compact than single family houses and therefore the relative effect of heat losses through party walls on their energy demand is supposedly higher, but a statistical association found in Chapter 3 gives sufficient ground for a small additional analysis using the multi-zone model. Chapter 3 showed that part of the variation in real energy use found for the (inhabited) houses of the old neighbourhood (‘cs1’) was associated with the fact some of the adjacent houses were not inhabited, thus causing heat losses through the party walls while the assessment method does not consider heat losses through those party walls. The large variations in heating profiles discussed in the first chapters makes it likely that not considering any heat transfer through party walls could also cause significant prediction errors if the adjacent houses are inhabited even though not necessarily biased errors leading to systematic under or overestimations.

One last parameter that is analysed is how the inter-zonal air flows through doors affect the simulation results. Loga et al. [175] referred to the errors that could be caused by uncertainties regarding the inter-zonal heat transfer because of the uncertainty regarding the opening and closing of doors by the inhabitants. ISO 13790 [20] also mentions this additional complexity of considering inter-zonal air flows when shifting from single-zone to multi-zone models. Furthermore, Chapter 3 found that some living rooms were heated also at night or at high temperature and put forward the hypothesis made also by Weihl and Gladhart [142] that these types of behaviour are found to be used in uninsulated houses with local heating systems as a necessary solution for reaching bearable temperatures in the coldest spots. This puts the use of doors in the list of options a user has for conditioning different zones of the house. A sensitivity analysis is therefore included to see to what extent assumptions on the door opening profiles influence the calculated indoor temperatures, the theoretical energy use and the associated temperature take-back.

6.2 Simulation study approach: case-study, models and analyses

6.2.1 Case-study

This study requires a direct comparison between simulation results and real values and therefore case-studies that are well documented with regard to the different inputs, both building and user related and to the outputs of the models, the theoretical energy use and indoor temperatures. Furthermore, enough cases have to be included in the analysis to include variations in heating profiles while the number of different building designs has to be limited to keep the detailed modelling of all buildings a feasible task. Therefore, the case-study that is used for this chapter is the old neighbourhood of nearly identical social houses discussed in Chapter 3 (cs1, Figure 6.3 and Figure 6.4, see also sections 3.2.1 and 3.3).

For the analyses in this chapter, only the cases of cs1 are used for which all necessary information was available with regard to the user profiles in order to build the models (3.3.3) and, depending on the analysis, also with regard to the actual energy use (3.3.2) or to the measured indoor temperatures (3.3.4) in order to make comparisons between calculated and real values. This resulted in 23 cases for the analyses on the energy use and 30 cases for the analyses on the indoor temperatures.

Figure 6.3: case-study neighbourhood: old, not insulated single-family houses

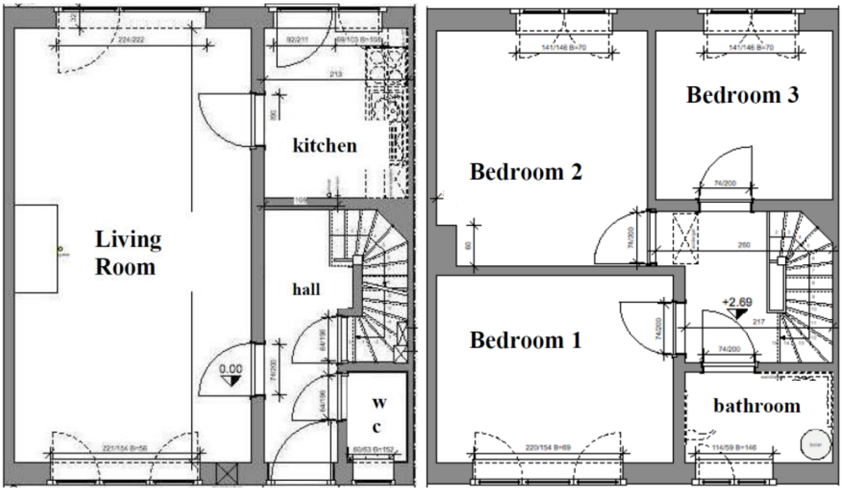

Figure 6.4: floor plans: living area on ground floor, sleeping area on first floor

6.2.2 Modelling approach and description

User related inputs

The aim of building the multi-zone model was to enable taking user profiles better into account when calculating the energy demand for space heating while still using simplified and computationally light models. The surveys and measurements supplied regarding three user related aspects whose zonal modelling implementations are analysed: the heating profiles (heating hours and set-point temperatures), the ventilation profiles (the use of windows) and the internal heat gains (defined in part by the presence of people). The modelling implementations of these three parameters are discussed in the following paragraphs, distinguishing single-zone modelling approaches from multi-zone modelling approaches where each room is modelled as a separate zone. One user related parameter influencing the multi-zone model is added to this list: the opening of doors between rooms.

HEATING PROFILES

LIVING AREA: DIRECTLY HEATED AREA

To distinguish variations in simulation results due to different modelling approaches from variations due to different heating profiles (heating hours and set-point temperatures), the different models are used with their respective standard heating profiles and with the same set of real heating profiles. Figure 6.5 summarizes the different heating profiles of the living area. The heating profile considered in the Flemish approach [80] is not shown in Figure 6.5

because it consists of a time and space average equivalent set-point temperature of 18°C that applies on the building level, without specification of the underlying assumption regarding the living area. The multi-zone method is applied only in combination with the real heating profiles, as the predefined heating area fractions from the regulation frameworks (GE: 75% or NL: 50%) do not fit with the multi-zone models. On the opposite, the Flemish approach includes all assumptions about the heating profile implicitly within the official equivalent set point temperature of 18°C, thus making it impossible to consider the other standard or real heating profiles.

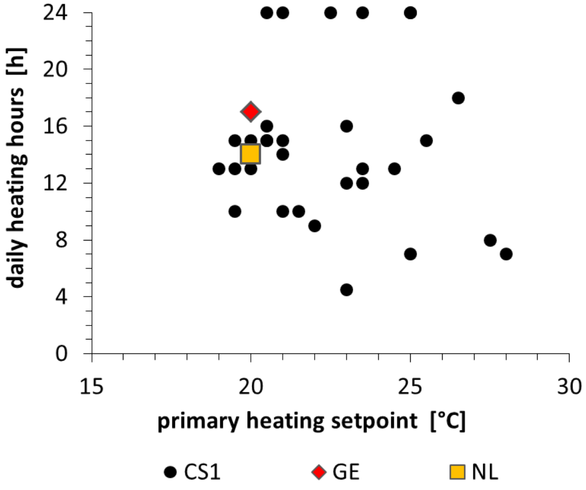

Figure 6.5: Real versus standard heating profiles from DIN 18599 (GE) and NEN 7120 (NL): heating set point temperatures and daily heating hours in the living area

OTHER ROOMS

The households barely heated the other rooms (see 3.3.2 and 4.3.1). The circulation area and the toilet were heated in none of the analysed cases. The small bathrooms were heated using electric heaters, but only for short durations, with only four households reporting to heat their bathroom for more than one hour per day but still for less than two hours per day. Only two of the 23 households included in the analysis on the heating demand and five of the 30 households included in the analysis on the indoor temperatures reported using an electric heater in one of their bedrooms. Four of them heated only one bedroom and only in the evening before going to sleep, for less than three hours per day. The fifth household reported heating two bedrooms for 11 hours but the measurements showed the target temperature was 5°C lower than in their living room. Therefore, when considering the real heating profiles in the modelling approaches of NEN 7120 [78] (from the Netherlands, further indicated as ‘NL’) and DIN 18599 [176] (from Germany, further indicate as ‘GE’), the considered fraction of directly heated spaces (see 5.2.2) is defined as being 40%, consisting only of the 32% and 8% of the floor area taken by the living room and the kitchen, respectively. While the kitchen had no electric heater, it is also considered as a part of the directly heated area because of the large permanent opening between the kitchen and the living room (see further in this section).

DIN 18599 makes a strict distinction between the directly heated building area and the *indirectly* heated area, but NEN 7120 differentiates the main heated living area from the remaining moderately heated area, considering that this moderately heated area is also heated directly, but only for 20% of the time or thus for 4.8 hours per day (see 5.2.2). This time fraction (parameter $f_{mod,t}$ in Eq.(5.15)) can be overridden when considering the real profiles, but the underlying assumption of the Dutch approach is that this time fraction applies to the whole of the area that is not included in the main heated living area, thus including all bedrooms, the circulation area etc. Because for most cases the bathroom is the only of those rooms that is heated, it would be an significant overestimation of the real heating profile to take the heating time fraction of the bathroom as $f_{mod,t}$. Instead, when considering the real heating profiles, $f_{mod,t}$ is defined for this study as the area weighed heating time fraction of the moderately heated area, using Eq.(6.6).

$$f_{mod,t,real\,profile} = \sum_{r} f_{t,heat,mhz,r} \frac{A_{fl,mhz,r}}{A_{fl,mhz,tot}} \tag{6.6}$$

With

$f_{t,heat,mhz,r}$ = heating time fraction of room ‘r’ of the moderately heated zone (= 0 if never heated directly) [-]

$A_{fl,mhz,r}$ = floor area of room ‘r’ of the moderately heated zone [m^2]

$A_{fl,mhz,tot}$ = total floor area of the moderately heated zone [m^2]

HYGIENIC VENTILATION FLOW RATES

The energy performance calculation method in Belgium considers the same hygienic ventilation flow rates in a house without ventilation system as in a house with a ventilation system [122,148], using Eq. (6.7). For the analysed houses, this results in an air change rate (ACH) of 0.77. However, as discussed in Chapter 3 (see 3.3.3 and 3.4.1) the analysed houses had no ventilation system and the inhabitants stated to rarely open their windows during winter (Table 6.1). Therefore, based on literature, the real air change rate is expected to be much lower (see 3.3.3, [57,151,152]). Furthermore, windows were not opened to the same extent in all rooms, with mainly the bedroom windows and the bathroom windows being used. To take more realistic air change rates into account in the models and to take into account the differentiation between rooms in the multi-zone model, the air flows through windows were calculated based on the data from the surveys. The simplified approach considered single-sided ventilation and was based on Eq.(6.9), Eq.(6.10), Eq.(6.11) and Eq.(6.12) from EN 15242

[184]. These formulas allow calculating the average air flows through open windows taking into account wind speed, stack effect and wind turbulence. Based on these calculated air flows, the corresponding heat transfer coefficients were calculated using Eq.(6.8), at room level or at building level for the multi-zone models and the single-zone models, respectively. Using these equations in combination with a monthly quasi-steady state model simplifies the dynamics of air flows by assuming that the average temperature difference and wind speeds when the windows are open equal the monthly average temperature differences and wind speeds.

$$q_{v,airing,EPB} = m_{heat} \left[0.2 + 0.5\, e^{-V/500}\right] \mathrm{V} \tag{6.7}$$

With

m_{heat} = a multiplication factor, related to the type of ventilation system and the quality of the workmanship [80]. When assessing the energy performance of houses, using the default value (=1.5) is allowed for new houses and it is the only approach for existing houses [122] [-]

V = the volume of the building [m^3]

$$H_{v,airing,windows} = \sum_{w} \rho_a\, c_a\, f_{open,w}\, q_{v,airing,w} \tag{6.8}$$

$$q_{v,airing,w} = 3.6\;\; 500\;\; A_{ow} V^{0.5} \tag{6.9}$$

$$V = C_t + C_w\, v_{met}^2 + C_{st}\, H_{window}\;\; abs(T_i - T_e) \tag{6.10}$$

$$A_{ow} = C_k(\alpha)\, A_w \tag{6.11}$$

$$C_k(\alpha) = 2.6\;\; 10^{-7}\, \alpha^3 - 1.19\;\; 10^{-4}\;\; \alpha^2 + 1.86\;\; 10^{-2}\;\; \alpha \tag{6.12}$$

With

$H_{v,airing,windows}$ = time averaged heat loss coefficient caused by window openings [W/K]

ρ_a = density of air [kg/m^3]

c_a = specific heat capacity of air [J/(kg.K)]

$f_{open,w}$ = opening time fraction of window ‘w’ [-]

$q_{v,airing,w}$ = air flow rate through the open window ‘w’ [m^3/h]

A_{ow} = window opening area [m^2]

Ct = constant taking into account wind turbulence (=0.01)

C_w = constant taking into account wind speed (=0.001)

C_{st} = constant taking into account stack effect (=0.0035)

H_{window} = free area height of the window [m]

v_{met} = meteorological wind speed [m/s]

T_i = room air temperature [K]/[°C]

T_e = outdoor temperature [K]/[°C]

$C_k(\alpha)$ = ratio of the air flow through the opened area (at angle α) and the air flow through the window when totally opened [-]

A_w = window opening area when totally opened [m²]

α = opening angle of the bottom hung window [°]

These air flows through open windows depend on the climatic conditions and on the indoor temperatures (Eq. (6.10)) while the air flows influence the heat balance of the house and the resulting average indoor temperatures. For more accurate results, the calculation of the air flows should thus be integrated in an iterative solution process calculating for each month all air flows and all indoor temperatures. However, this would result in different calculated air flow rates and corresponding heat loss coefficients between the building and the outdoor environment in the single-zone models compared with the multi-zone model. This would make a direct comparison of the heat balance equations of the two types of models less clear. Instead of calculating the air flows per month in an iterative solution process, the average air flow rates for the heating season were calculated before building the models considering the average indoor and outdoor climates of an average heating season. This approach is similar to the calculation approach used by Wouters and De Baets [57], however now the formulas from the more recent standard EN 15242 [184] are used.

The heating season was considered to last 5 months, from 1 November until 31 March. The corresponding average outdoor temperature was considered being 4.55°C, for average values of 4.56°C and 4.52°C were found for those months based on the Belgian standard EPB-climate [80] and based on data recorded by a nearby weather station during winter period 2010-2011, respectively. It is during that winter period that the measurements and the surveying were done. The standard climate considered for the Flemish EPB-calculations does not specify values for wind speed. The corresponding average wind speed was thus calculated based on data on the same months from that same weather station, resulting in 3.3 m/s. For each window of each house, the average indoor temperature was defined based on the corresponding measured room temperatures (see Chapter 3). The measurements were done during different weeks, at different outdoor temperatures. To obtain average indoor temperatures for the heating season, those were corrected to correspond with an outdoor temperature of 4.55°C. This was calculated using a linear regression between the daily average indoor temperatures and the daily average outdoor temperatures (see 3.3.4).

The numbers of opening hours of the windows were reported by the inhabitants for the living room, the kitchen, the bathroom and the three separate bedrooms (Table 6.1). No data was collected about the use of the toilet windows. For the calculation models, these were assumed to be open two hours per day. The dimensions of the operable window panes were measured from the building plans. No detailed information was collected with regard to the position of the windows when open: if they were bottom hung or side hung and to what angle. Therefore, one common assumption was made for all windows of all houses. The windows were considered being tilted with a distance of 15cm between the top of the tilted window and the fixed window frame, resulting thus in a smaller opening angle for the taller windows to be used in Eq.(6.12) (between 16° for the bathroom and toilet windows and 4.2° for the tallest living room window).

Inhabitants might open some windows wider resulting in larger air flow rates, but studies showed that windows are most often opened ajar during colder periods [57,60]. Larger air flow rates could also result from cross ventilation if e.g. the doors are left open simultaneously. On the opposite, smaller air flow rates could result from the fact that the reported values referred to an average winter day, not taking into account days with weather precipitation: 61% of the households reported closing all windows during weather precipitation and 30% reported closing some windows. Because of these numerous uncertainties, the calculated values were compared with values from literature to verify if the calculation results are realistic. The calculated ACH at room level and at building level are summarized in Table 6.2. The median ACH through windows at building level (0.16) is lower than the median values of 0.24 measured by Kvisgaard et al. in Denmark [151] but it lies very close to the even lower median value of 0.14 calculated by Wouters and De Baets based on more extensive survey data collected in old Belgian social houses [57]. Considering also that an average total ACH (including infiltration trough the building envelope) of 0.20 was measured by Stymne et al. in houses in Sweden [152], the total calculated values at building level are considered realistic. As a result of the small number of window opening hours reported in the living areas and of the larger size of the living rooms compared to the other rooms (Table 6.1), the living rooms have the lowest air change rates (Table 6.2). In fact, the very low living room values on neighbourhood level result from the fact that only three households reported opening the windows in their living room. Table 6.3 shows the percentage of the total air flow that is associated with each room, corresponding thus also to the allocation to the different rooms of the heat loss coefficients corresponding to the window openings. The bedrooms will, on average, account for 63% of the total air flow between the building and the outdoor environment and for some houses they will account for more than 90%.

Table 6.1: User reported daily opening times of the windows (cs1), heating season

	open windows: number of opening hours per day [h/d]					
	av.	min.	25%	mdn.	75%	max.
living r.	0.36	0.00	0.00	0.00	0.00	4.00
kitchen	1.12	0.00	0.00	0.00	1.00	8.00
toilet	(Not reported. Assumption for all models: 2 h/d)					
bathroom	4.06	0.00	0.00	1.00	6.00	24.00
bedr. 1	5.91	0.00	1.00	4.00	6.00	24.00
bedr. 2	4.88	0.00	0.00	1.00	6.00	24.00
bedr. 3	4.21	0.00	0.00	1.00	6.00	17.00
TOTAL	**20.55**	**1.00**	**7.00**	**19.00**	**28.00**	**68.00**

Table 6.2: Calculated air change rate caused by window openings (cs1), heating season

	open windows: time weighed average air change rate [1/h]					
	av.	min.	25%	mdn.	75%	max.
living r.	0.02	0.00	0.00	0.00	0.00	0.23
kitchen	0.12	0.00	0.00	0.00	0.12	0.84
toilet	0.63	0.55	0.59	0.63	0.66	0.73
bathroom	0.49	0.00	0.06	0.12	0.39	2.97
bedr. 1	0.37	0.00	0.06	0.24	0.39	1.62
bedr. 2	0.27	0.00	0.00	0.07	0.35	1.39
bedr. 3	0.39	0.00	0.00	0.11	0.55	1.70
TOTAL	**0.18**	**0.02**	**0.07**	**0.16**	**0.26**	**0.59**

Table 6.3:Percentage of the total calculated air flow through windows per room (cs1)

	open windows: percentage of total air flow [%]					
	av.	min.	25%	mdn.	75%	max.
living r.	4.0%	0.0%	0.0%	0.0%	0.0%	45.1%
kitchen	9.3%	0.0%	0.0%	0.0%	11.6%	46.8%
toilet	12.6%	1.8%	4.1%	6.3%	14.7%	53.7%
bathroom	10.9%	0.0%	8.3%	5.2%	30.8%	61.5%
bedr. 1	26.8%	0.0%	8.3%	24.1%	30.8%	91.0%
bedr. 2	19.6%	0.0%	0.0%	13.7%	26.1%	76.3%
bedr. 3	16.8%	0.0%	0.0%	11.8%	25.4%	93.7%

INTER-ZONAL AIR FLOWS THROUGH DOORS

In addition to defining the air flows between the indoor environment and the outdoor environment, the multi-zone model requires defining the air flows between the rooms. Because the houses have no mechanical ventilation system, the main inter-zonal air flows will be caused by opening the interior doors. During the measurement and surveying campaign, no detailed information was collected regarding the opening of the doors. However, in most houses, the door between the kitchen and the living room was either removed or said to be left open all day. Furthermore, both from observation and from talking to the inhabitants during the visits, it appeared that the doors of the living room were often left open, at least at night, in order to have a minimum of indirect heating to the sleeping area. Therefore, the air flows through doors were modelled based on some assumptions.

In a similar way as for the air flows through windows, a simplified approach was chosen for calculating the heat transfer coefficients (Eq.(6.13)) associated with the air flows through open doors (Eq.(6.14) [185,186]). As opposed to the formulas used for calculating the window air flows, these formulas from EN 13465 [185] for calculating the air flow through doors only consider Buoyancy-induced air flows and no increase of the air flows caused by wind (see also [186]). Because of that and because the temperature difference between the rooms is much lower than between the indoor and the outdoor environment, the relative errors caused by estimating the air flows before modelling the houses instead of calculating them during the iterative solution process will be larger than for the windows. In addition, compared to the modelling of the air flows between the indoor and the outdoor environment, modelling the inter-zonal air flows (within the building) in the iterative solution process raises no concern regarding the comparability of the single-zone and multi-zone models. In fact, taking into account the zonal differentiation in a house and thus the heat exchanges between zones is the aim of the multi-zone model that is analysed and compared with the single-zone models. These formulas were thus included in the iterative solution process, updating the calculated heat transfer coefficients and indoor temperatures at each iteration.

For use in Eq.(6.14), different discharge coefficient for open doors can be found in literature [186,187], ranging mainly between 0.6 and 0.8. For this study, the default value of 0.6 from EN 13465 is used. However, Shaw et al. noted that the air flow rate stabilizes at small temperature differences, explained by the turbulence of the air in the rooms [186]. Those values will strongly depend on the presence of fans, on the wind and the air permeability of the envelope etc. For the simulated old houses, a minimal average air velocity of 0.05m/s was assumed as a lower limit for the average air velocity through the open doors (in opposite directions on both sides of the neutral pressure plane). This corresponds approximately to a temperature difference of 0.125°C in Eq.(6.14).

$$H_{v,airing} = \rho_a \, c_a \, f_{open,d} \, q_{v,airing} \tag{6.13}$$

$$q_{v,airing} = C_D \, H_{WD} \, W_{WD} \frac{1}{3} \sqrt{\frac{abs(\theta_1 - \theta_2)}{\frac{\theta_1 + \theta_2}{2} + 273} \, g \, H_{WD}} \tag{6.14}$$

With

$H_{v,airing}$ = equivalent heat loss coefficient of the open door [W/K]

ρ_a = density of air [kg/m^3]

c_a = specific heat capacity of air [J/(kg.K)]

$f_{open,d}$ = opening time fraction of door ‘d’ [-]

$q_{v,airing}$ = air flow rate through an open door [m^3/s]

C_D = coefficient of discharge (default value = 0.6) [-]

H_{WD} = height of the opening [m]

W_{WD} = width of the opening [m]

θ_1 and θ_2 = temperature on each side of the opening [°C]

g = acceleration due to gravity [m/s^2]

The possibility of taking user related inter-zonal heat exchanges into account differentiates the multi-zone model from the single-zone models, but, as opposed to window opening profiles and heating profiles, there was no detailed information on the real opening and closing of the doors. To assess the influence of the assumptions regarding the opening of the doors, a sensitivity analysis is performed. For each door, four different options are considered:

- (option 0) no air flow is considered through the door
- (option 1) the door is wide open 10 minutes per day
- (option 2) the door is wide open for 8 hours per day
- (option 3) the door is removed or fully open 24h/day

Selecting one of these four options for each door, four profiles were defined at building level (Table 6.4):

- considering no internal air flows (*no flow,* all doors at option 0),
- a *low flow* user profile, leaving all doors mostly closed (option 1)
- an intermediate *default profile* leaving only the door to the living room open for longer durations (option 2)
- a *high flow* profile leaving also the bedroom doors open for a longer duration (option 2).

Except for the scenario without air flows, the kitchen door is always considered fully opened all day long because of the observation on site, while the doors to the basement, the toilet and the bathroom are always considered to be opened for no more than 10minutes per day. Using Eq.(6.14) and Eq.(6.13), option 1 and option 2 equal the door being open to 1/3 of its full opening area 30 minutes or 24hours per day respectively.

Table 6.4: door airing profiles (option 0 = no air flow; option 1 = 100% open 10minutes/day; option 2 = 100% open 8h/day=1/3 open 24h/day; option 3=100% open 24h/day)

	no flow	low flow	default flow	high flow
kitchen < > living room	option 0	option 3	option 3	option 3
circulation area <				
> living room	option 0	option 1	option 2	option 2
> bedrooms	option 0	option 1	option 1	option 2
> toilet/bathroom/basement	option 0	option 1	option 1	option 1

INTERNAL HEAT GAINS

For use in energy performance assessment models, internal heat gains in houses are calculated based on the floor areas or on the volumes of the buildings in the international standard ISO 13790 (Eq.(6.15) [20]), in the energy performance calculation method for new and old houses in Flanders (Eq.(6.16) [80,122]), in the Dutch standard NEN 7120 (Eq.(6.17) [78]) and when making a passive house performance assessment in Belgium (PHPP) (Eq.(6.18) [188]). The corresponding heat gains for the analysed houses are summarized in Table 6.5. The highest values, obtained by the formula from ISO 13790 are 75% higher than the lowest values, obtained by the formula from PHP. The latter considers modern high performance houses and is based on the assumption of ditto appliances and lighting. The Flemish and Dutch calculation methods consider approximately the same internal heat gains result in only 13% lower values than ISO 13790. These values could be used for defining the internal heat gains in the single-zone methods, but they lack the differentiation at room level needed for the multi-zone method. The only of these approaches making a differentiation at a more detailed level than that of the whole house is ISO 13790, which considers 9W/m² for the living room and kitchen and 3W/m² for all the other rooms. In addition to the lack of differentiation at room level, these approaches do not enable taking into account the variation in heat gains associated with the variation in households. In response, a simplified calculation of the heat gains was made.

$$\Phi_{internal,ISO\ 13790} = 9\ A_{fl,liv\&k} + 3\ A_{fl,other} \tag{6.15}$$

$$\Phi_{internal,FL\ EPB/EPC} = 220 + 0.67\ V_b \tag{6.16}$$

$$\Phi_{internal,NEN7120} = 230\ N_w + 1.8\ A_{fl,b} \tag{6.17}$$

$$\Phi_{internal,PHPP} = 78 + 2.1\ A_{fl,b} \tag{6.18}$$

With

$\Phi_{internal}$ = time averaged power of the internal heat gains [W] (for ISO 13790 [20], BE EPB/EPC = energy performance calculations in Flanders [80,122], NEN 7120 [78] and PHPP = passive house certification in Belgium [188])

$A_{fl,b}$ = total floor area of the building [m²]

$A_{fl,liv\&k}$ = total floor area of the living room and kitchen [m²]

$A_{fl,other}$ = total floor area of all rooms except the living room and kitchen [m²]

V_b = total building volume [m³]

N_w = number of housing units (1 for a single-family house) [-]

Table 6.5: theoretical internal heating gains for the houses of cs2: standard methods

	Internal heat gains	
	kWh/year	W/m²
ISO 13790	3767	5.38*
Flanders EPB/EPC	3292	4.70
NEN 7120	3274	4.68
PHPP Belgium	2153	3.08

Notes:
*living room and kitchen: 9W/m², other rooms: 3W/m²
Geometry: building volume = 232m³, total floor area = 80m² (floor area living and kitchen = 32m² and floor area other rooms = 48 m²)

During the survey and the measurement campaign, no data was collected with regard to the electrical equipment present in the house or to the activity of people in the house. The only data that was available for estimating the internal heat gains were the reported presence of people in the different rooms. Therefore, only rough estimates about the internal heat gains at room levels could be made based on a series of assumptions. The estimations that were made mainly aimed at making a realistic differentiation between rooms and between households that, when aggregated at building level, could be compared with the values resulting from the standard approaches (Table 6.5). The approach considered heat gains from human metabolism, from cooking and from electric appliances and lighting of which 90% is considered to be released as heat. For the heat gains from human metabolism, no differentiation was made based e.g. on the age of individuals, because the presence in the rooms throughout the day were only reported by numbers of inhabitants, making identification impossible. Those heat gains were considered to be 100W and 75W per person when awake and when asleep, respectively. The bedrooms were almost only used during the night. Therefore, it was considered that only 1.5 hours per day spent by each inhabitant in the bedrooms was while being awake. No data on presence were available for the circulation area and the toilet. For those rooms respectively 12 and 24 minutes of presence per person per day were assumed. No differentiation was made between week-days and weekend-days.

The internal heat gains resulting from cooking activities were defined based on the number of inhabitants. The formula used in Chapter 3 for defining the energy use for cooking (3.2.2) was also used here for calculating the heat gains. For the use of electric appliances, it was assumed that some multimedia devices (television, radio, computer etc.) were used, producing an average of 100W of heat for half the time that at least one person was present in the living room. Fridges and freezers were considered to account on average for 500kWh/year in the kitchen [135,189–191]. Additionally, a 24 hour average of 20W and 5W were considered for the living room and each other room resulting from small electrical equipment (e.g. alarm clocks, chargers) and from standby power consumption.

The heat gains from lighting were estimated based on the presence of people, on the hour of the day and on the room type. Making use of those three parameters, an estimate was made of the number of lighting points consuming 40W of electricity each. The bathroom and the toilet were considered having one lighting point being used whenever someone was present in that room, at any time of the day. One lighting point was considered being used by each person during the 1.5 hours of time spent awake in the bedroom. For the living room and the kitchen three and two lighting points, respectively, were considered to be switched on when at least one person was in the room between 18:00 in the evening and 09:00 in the morning. Outside that night period, only one lighting point was considered to be switched on for half the time when someone was present.

The results from these simplified estimations of the heat gains are summarized in Table 6.6. The median total heat gains at building level is only 14% higher than the value calculated according to ISO 13790. With a median of 9.6W/m² for the living room and kitchen together and a median of 2.5W/m² for the rest of the house, a higher part of the heat gains is attributed to the living area. This was considered realistic based on the high presence of people in the living area throughout the day as a result of the high unemployment and retirement figures on the one hand and, on the other hand, of the low presence profiles in the colder bedrooms caused in part by the median number of inhabitants being only two while these were three bedroom houses (see 3.3.3).

There is a large spread in calculated internal heat gains resulting from the large variation in user profiles. The highest value (7385 kWh/year) was found for a household of 7 people being present at home for a total of 133 man hours per day, for which 59% of the calculated internal heat gains results from their metabolism. The lowest value (2389 kWh/year) was found for a house inhabited by only one person, being at home on average 20 hours per day, and for whom his presence accounts only for 27% of the internal heat gains. The highest percentage attributed to the living room is found for a household of 2 people who use the living room also as their bedroom and who did not report using the bedrooms on the first floor.

Table 6.6: theoretical internal heating gains for the houses of cs2: estimations based on presence profiles

	internal heat gains				% of total		
	Mdn. [kWh/yr]	av. [W/m²]	min. [W/m²]	max. [W/m²]	Mdn. [%]	min. [%]	max. [%]
kitchen	1123	20.12	17.54	25.74	28.7%	17.9%	46.2%
living r.	1578	7.10	3.08	15.57	40.2%	25.6%	63.7%
bedr.1	347	3.53	0.40	14.03	8.4%	1.0%	22.4%
bedr.2	347	3.20	0.36	9.13	10.2%	1.0%	17.8%
bedr.3	39	0.59	0.59	9.83	1.4%	0.6%	13.1%
bathr.	89	2.74	1.21	8.19	3.2%	0.8%	8.5%
toilet	59	4.05	3.38	7.45	1.7%	1.4%	2.1%
circulation	90	0.88	0.63	2.12	2.6%	2.1%	3.6%
TOTAL	3814	5.45	3.41	10.56	100.0%	100.0%	100.0%

Building related parameters

HEATING SYSTEM

Based on the Flemish energy performance assessment method [80], the total efficiency of the heating system (local gas heaters) was estimated to be 65% (using the upper combustion value of natural gas as a reference, 72% if the lower combustion value is used). This results from an emission efficiency of 87%, a heat generation efficiency of 83% and a ratio between lower and upper combustion value of 0.9 for natural gas.

BUILDING ENVELOPE

When available, measured values documented in Chapter 3 were used for modelling the building (see 3.2.2 and 3.3.1). The air permeability of the building envelope was measured for most of the houses (24), allowing to use their respective values in their models. For the cases without measured value, the median value of the measured cases was considered: ACH50 = 10.25. When used for calculating the heat balance of the houses, these measured air change rates at 50Pa pressure difference are multiplied by 0.04 to account for the lower pressure differences under standard use conditions [80]. Based on the results from the few heat-flux measurements, the average U-value of the external cavity walls was considered being 1.35W/(m².K). The other properties of the building components were estimated based on the limited available data from the visit on site, the building plans and the default values used for energy performance assessments in Belgium [111]. U-values of 5.8W/(m².K) and 2.8W/(m².K) and g-values of 0.85 and 0.77 were considered for the existing single glazing and double glazing, respectively. In the absence of detailed data on the window frames, all wooden and PVC frames were considered having a U-value of 2W/(m².K). The windows of the living rooms had external roller shutters increasing the thermal resistance of those windows by 0.22m².K/W when the shutters are closed according to the same national document [111], following the method from EN 13125 [192].. Higher increases of the thermal resistance can be found in literature, both for external blinds and internal curtains, both based on simulations and on laboratory measurements [193–199]. However, the results vary largely depending on numerous parameters: the reflectivity and conductivity of the blinds or curtains, the air gaps, the wind velocity, the temperature difference etc. For this analysis, the official calculation approach is used, considering also a time-weighted average of the U-values with the shutters open (16h/day) and closed (8h/day) [111]. The heat transmittance of the slab on grade was calculated according to EN 13370 [200] resulting for these terraced houses in 0.6W/(m².K). Combining all these parameters results in the characteristics for the transmission heat loss summarized in Table 6.7 at building level and at room level. Those values are values averaged over the external heat loss area of all houses. While the living room accounts for the largest share of the external envelope area and the transmission heat transfer coefficient, the average external heat transmittance of its external boundaries (Um, Eq.(6.19)) is 14% lower than the building average value because of the lower U-value of the slab on grade, while the bedrooms on the first floor have an Um 8% to 18% higher.

The solar heat gains were calculated following the approach of the Flemish EPB-method [80]. For each window, four shading angles define the obstructions from surrounding elements: one vertical, one left sided and one right sided shading angle, and one horizon angle, with default values for the space heating calculation of 25° for the horizon angle and 0° for the other angles. The horizon angle relates to the height of the skyline compared to a horizontal plane through the centre of the glazed area. The lateral and vertical shading angles are defined differently, in relation to the window plane as illustrated in Figure 6.6. The default values were replaced by measured values. The measured horizon angles vary depending mainly on the floor level and on the orientation of the windows, with larger horizon angles at the front façade caused by the houses at the other side of the street compared with the horizon angles at the backyard façade, because of the large depth of the two adjacent gardens (Table 6.8). Because the streets are not exactly parallel to one another, resulting in different garden sizes, and because at some street ends there were houses only on one side of the street, there is a considerable variation in horizontal shading angles amongst the houses. The limited lateral (left and right) and vertical shading angles are caused mainly by the wall edges resulting from the recessed window placement.

Table 6.7: external heat loss area (At),transmission heat transfer coefficient (Ht) and Um=Ht/At at room level and building level: average values over all houses.

	At,av		Ht,av		Um,av	
	[m²]	% of total	[W/K]	% of total	[W/ (m².K)]	% compared to building average
living r.	50	30%	63	26%	1.26	-14%
kitchen	13	8%	19	8%	1.45	-1%
circul.	23	14%	32	13%	1.42	-3%
toilet	7	4%	9	4%	1.27	-13%
bedr.1	23	14%	40	17%	1.74	+18%
bedr.2	24	14%	38	15%	1.59	+8%
bedr.3	15	9%	26	11%	1.71	+16%
bathroom	10	6%	15	6%	1.52	+3%
BUILDING	165	100%	243	100%	1.47	+0%

$$U_m = \frac{H_t}{S_{loss}} \tag{6.19}$$

With

U_m = the average heat transmittance of the external building envelope [W/(m².K)]

$H_{t,xe}$ = the total transmission heat transfer coefficient to the outdoor environment (incl. reduction factors as defined in Eq.(5.5) and (5.6)) [W/K]

S_{loss} = total external heat loss area [m²]

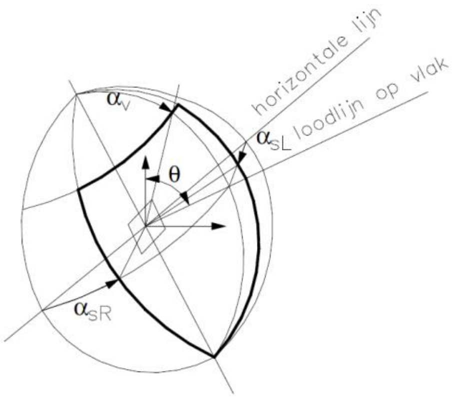

Figure 6.6: vertical (αv),left (αsL) and right (αsR) shading angles, with the centre of the glazed area as the point of reference (source: [80])

Table 6.8: windows and glazed doors: total area (incl. frames) and measured shading angles (reference: centre of the glazed surfaces)

level	façade	window/ glazed door	area (incl. frames)	shading angles				
				horizontal			vertical	lateral
				av.	min.	max.		
			[m²]	[°]	[°]	[°]	[°]	[°]
ground fl.	front	living r.	3.7	23.3	10.7	31.2	3.4	2.5
		front d.	2.2	24.2	11.2	32.4	3.3	5.7
		toilet	0.4	21.8	10.0	29.4	8.7	8.8
	back	living r.	4.2	16.7	13.5	24.6	2.6	2.5
		kitchen w.	0.9	16.0	12.9	23.6	4.8	7.6
		kitchen d.	2.1	17.2	13.9	25.3	2.6	5.8
first fl.	front	bathr.	0.8	12.6	5.5	17.3	8.7	4.6
		bedr.1	3.8	14.4	6.3	19.6	3.5	2.5
	back	bedr.2	2.5	9.8	7.8	14.7	3.7	3.6
		bedr.3	2.5	9.8	7.8	14.7	3.7	3.6

NOTES: 'fl'.=floor, 'r.'=room, 'd.'=door, 'w.'=window

ADJACENT BUILDINGS

For the assessment of the energy performance of a building, the 'protected volume' of that building has to be delimited. This is the volume for which the theoretical energy use has to be calculated. It includes all zones or spaces within a building that are aimed to be protected against heat losses [80]. The thermal insulation envelope usually defines the boundaries of that protected volume and, for residential buildings, it consists at least of all the directly heated rooms as well as indirectly heated rooms used for human activities (e.g. also bedrooms without heating element). For these case-study houses, it is defined as the whole building without the uninhabited attic and the small basement. The heat losses through spaces adjacent to this protected volume are modelled following the approach from the official Flemish assessment method [80]. The thermal resistance offered by the adjacent unheated zones that are part of the house but not of its protected volume are considered using temperature reduction factors (see (5.4)). A detailed value calculated according to Eq.(5.6) is used for the attic while the default value for basements of 0.5 is used for the small basement under the income hall.

No heat transfer between the analysed house and adjacent houses is taken into account in the regulatory assessment method, which considers the party walls as adiabatic boundaries. When building a multi-zone model it is possible modelling also the adjacent buildings with their real heating profiles. Using such an extended model for a comparative analysis with the single-zone models with adiabatic boundaries would result in different assumptions, making it more difficult to analyse these inherent differences of the single-zone and multi-zone models separately. Furthermore, such comparison would be of limited use for supporting the choice between a single-zone and a multi-zone model. Firstly, there is often little information available about the adjacent buildings (geometrical and physical properties, user profiles etc.), cancelling the option of an extended model. Secondly, for the same reasons as why standard user profiles are considered in the official performance assessment methods (see 3.4.1), it is often not wanted to take the real user profiles of the neighbours into account in official performance assessment models. Therefore, the standard assumption of adiabatic boundaries between houses is made in the single-zone and in the multi-zone models when comparing them. However, because this simplified assumption could explain part of the prediction errors while the multi-zone model makes more accurate modelling assumptions possible, the consequences of inaccurate assumptions on the heat exchange with adjacent buildings is investigated separately, in the second analysis described in the following section.

6.2.3 Analyses

The study verifies the hypotheses presented in the introduction (6.1.2) by clustering them in three analyses based on the same case-study neighbourhood. The first analysis compares results from the different single and multi-zone models with real values on energy use and indoor temperatures. The second analysis further focusses on the potential of the multi-zone model for taking zonal differentiation of user profiles into account and on the consequences of wrong or simplified modelling assumptions regarding this zonal differentiation. The third analysis further compares the different single-zone and multi-zone model, but it considers fictive yet realistic renovation scenarios instead of the existing state of the buildings, comparing the models when used for estimating energy savings. The differences between the regulatory modelling approaches and the more detailed models found in this scenario analysis will then be compared with differences reported in literature between regulatory modelling results and real consumption data.

Theoretical versus real energy use and temperatures at building and room level, single-zone versus multi-zone

NET ENERGY USE FOR SPACE HEATING AND INDOOR TEMPERATURES

To evaluate the models, the first analysis compares calculated and measured values of the space heating demand and of the indoor temperatures. The real energy use for space heating was normalized based on a degree-day based analysis of the gas meter readings and the corresponding caloric values of the natural gas, reported by the energy utilities (3.2.2, 3.3.2). Those values were converted to their corresponding net energy demand for space heating considering the theoretical efficiencies reported in the previous section. The degree-day based approach used for normalizing the real energy use for space heating and the estimated efficiencies of the heating system are important sources of uncertainties that can affect the comparison between real and theoretical values (3.3.2). An additional problem for direct comparisons between the real and the theoretical energy use results from the fact that the real energy use is deduced from gas meter readings therefore including only the energy used for heating the living area, while electric heaters were present in the bathrooms and bedrooms. Because those electric heaters were barely used (see previous section) but the gas consumption for heating was high (see 3.3.2), the fact that their electricity consumption is not known is considered to cause only a limited bias to the comparison between real and calculate values. Still, to acknowledge the resulting uncertainty on the real energy use, the real consumption figures are shown in the charts twice: once as calculated in Chapter 3, based solely on the real gas consumption, and once adding to those real consumption values the theoretical values for the bathrooms and for the few heated bedrooms calculated using the multi-zone model.

Because of these uncertainties on the real energy use and because the real energy use gives no information on the real heat balance at room level, the analyses also focus on the indoor temperatures, comparing the measured indoor temperatures with the calculated values. For comparisons with the measured temperatures, separate simulations were run replacing the standard climatic data defined in the Flemish EPB-regulation [80] with the outdoor climatic data from that measurement period (average outdoor temperature and global and diffuse horizontal solar irradiation). The calculated values of the multi-zone model can be compared directly with the measured values at room level. A volume-weighted average of the room temperatures from the measurements and the multi-zone model were calculated, for comparison with the average temperatures from the single-zone models.

Discrepancies between real and theoretical values could result from other parameters than those analysed in this chapter, including e.g. errors resulting from using the default value for the efficiency of the heating systems, from the simplified modelling of ground heat losses etc. Because of the homogeneity within the neighbourhood with regard to the geometry and the technical properties of the buildings, such modelling errors will more likely result in systematic errors on the calculated values. Therefore, the real and theoretical values on energy use and indoor temperatures are compared not only based on the discrepancies at case level, but also based on the correlations between real and theoretical values found when considering the whole set of cases, analysing e.g. to what extent the variations is real energy use and temperatures can be explained using the different modelling approaches, and not only how large the absolute errors are.

ANALYZING THE CAUSES OF DIVERGENCES BETWEEN THE DIFFERENT VALUES

To explain what causes the different measured and calculated values, additional simulations are made using the multi-zone model. These simulations focus on different aspects that the multi-zone model can take into account but that the single-zones model cannot. These aspects regard the differentiation between rooms with regard to their heat gains and to their heat loss coefficients to the outdoor environment and regard the inter-zonal heat exchange, as discussed in the introduction (6.1.2) and modelled according to section 6.2.2. The differentiation of the heat gains and of the air flows through windows at room level is neglected by considering the same total values at building level (thus also the same as in the single-zone models), but allocating those to the different rooms more uniformly, based only on their respective volumes. The real location of the different building envelope components (e.g. glazing, roof, walls) having different thermal transmittance values while some are located around the directly heated areas and other around the indirectly heated areas (see Table 6.7) is neglected by assigning the building average equivalent heat transmittance of the external envelope (Eq.(6.19)) to all the components of the external heat loss area of the house, thus still considering the same total heat transfer coefficient at building level as before in the single and in the multi-zone models. The importance of the inter-zonal heat transfer coefficients is analysed based on the simulation with the different door opening profiles.

Multi-zone modelling and user profiles at building level and beyond

FOCUS AND APPROACH

The second analysis still considers the houses as they were during the measurement and survey campaign. It focusses on the uncertainties caused by standard assumptions on the real, varying user profiles that can be taken into account in the multi-zone model and that, as discussed in the previous chapters, can explain part of the discrepancies between real consumption values and theoretical values from regulatory performance assessment calculations. This analysis extends the multi-zone models by including not only all the rooms of the analysed house, but also those of the adjacent houses. The reference model used for analysing a terraced house thus comprises all coupled zones of three houses and models all rooms to the same level of detail, considering thus also the real user profiles of the neighbours if the adjacent house is inhabited. If the adjacent house is not inhabited it is still modelled in detailed, but without internal heat gains, open windows or heating profiles. To analyse the importance of accurate knowledge on the real user profiles for a correct evaluation of the heat exchange with the outdoor environment and with the adjacent buildings, different modelling scenarios are analysed, each having at least one modelling simplification compared to the reference model. The result of each simplified model is compared with the results from its respective reference, more detailed model. For each separate simplification scenario, the resulting simulation error is expressed as the space heating demand calculated using the simplified model minus the space heating demand from the more detailed, reference model. The relative error is calculated by dividing that absolute error by the space heating demand from the reference model. Thus, a simplification causing an overestimation of the space heating demand will result in positive absolute and relative error values and vice-versa.

SIMPLIFIED MODELLING SCENARIOS

The first modelling scenario regards the user profile of the analysed house. It relates to situations without accurate knowledge on the real user profile by considering a standard ‘median’ profile instead of the real user profile. This standard profiles consists for each room of the median heating hours, set-point temperature, internal heat gains and air flows through windows found across all houses of the neighbourhood.

The following modelling scenarios regard the modelling of the adjacent houses and their user profiles. The strongest simplification to that regard is the one made in the official assessment method, considering all party walls as adiabatic boundaries, as is considered for the models used in the first analysis. In addition to this simplification, this second analysis includes three intermediate modelling scenarios. The first intermediate scenario considers the characteristics of the neighbouring buildings to be known to the same level of detail as for the analysed house, e.g. because they are part of the same building project. This scenario also acknowledges the fact that specific houses are uninhabited and thus not heated. However, in case the adjacent buildings are inhabited, it is considered that there is no knowledge about the real heating profiles of the neighbours. Therefore, a reference ‘median’ profile is attributed to all inhabited neighbouring houses. For the second intermediate approach, uninhabited houses are also simulated as if they were heated according to the median heating profile. This approach resembles a standard design approach, assuming all houses are or will be inhabited. A third intermediate simplification scenario assumes wrong knowledge about the real interior layout of the adjacent buildings. In the real neighbourhood, the houses are mirrored two by two, causing the entry doors to be also grouped two by two (Figure 6.3). As a result, the indirectly heated circulation area of a house is adjacent to the indirectly heated circulation area of the neighbour on that side, while the heated living room is adjacent to the heated living room of the neighbour on the other side. The third intermediate modelling scenario, considering no accurate knowledge of the internal lay-out of the adjacent houses, assumes the opposite: all houses have their doors on the same side of the façade, thus resulting in a continuous alternation of living and circulation areas. For those simulations, the lay-out of both adjacent houses is thus mirrored compared to their real lay-out. The real heating profiles are still considered in order to isolate only the error caused by a wrong assumption regarding the building layout.

Energy savings: scenario analysis on take-back

SCENARIOS

The analysed differences in results between the single-zone and the multi-zone modelling approaches will not only depend on the user profiles, but also on the building performance that also influences the size of the physical temperature take-back. Therefore, the third analysis is a scenario analysis that considers different pragmatic energy renovation strategies that could be applied to the houses: (1) insulating the floor of the unused attic (loft insulation, d=12cm, λ=0.035W/(m.K)), (2) high efficiency double glazing (U=1.1W/(m^2.K), g=0.65) and retrofit cavity wall insulation (7.5cm, λ=0.040W/(m.K)) and (3) the combination of both previous strategies as a pragmatic renovation scenario. While requiring more invasive renovation works, insulating the slab on grade of the ground floor would complete the thermal upgrade of the envelope. Adding floor insulation (6cm, λ=0.040W/(m.K)) is therefore also considered in the analysis, first (4) separately and, subsequently, (5) in combination with all previous renovation measures, resulting in a global envelope upgrade. To compare all houses and all renovation measures based on comparable grounds, the energy savings are calculated in comparison to the status of the houses when they were built, with all windows having single glazing, neglecting occasional window replacement in some houses. Except for this assumptions, the multi-zone models considered ‘before renovation’ are the same as in the first analysis, thus with the party walls considered as adiabatic boundaries to have a more fair comparison between the single and multi-zone models.

DIRECT COMPARISON BETWEEN MODELS

Instead of looking only at the theoretical energy use of the different models, this analysis focusses also on the energy savings, the difference between the energy use before and after renovation. Firstly, the energy savings are more directly linked with financial return on investments and thus on the choice for a specific renovation strategy. Secondly, analysing the energy savings, both in terms of absolute values and of relative values compared to the calculated energy use before renovation, allows correcting for offsets between the models that are already studied in the first analysis. The considered status of the buildings before renovation, for which the potential energy savings are calculated, is not their status during the measurement campaign, but their original status: occasional window replacements over time are neglected and all windows are considered having single glazing. This allows for better comparisons of the different renovation measures and of their respective differences in predicted energy savings depending on the type of model and the real heating profiles rather than depending on what renovation measure already took place. In fact, analysing the combination of renovation measures is already included in the study by the pragmatic and global renovation scenarios.

COMPARISON WITH CORRELATIONS FROM LITERATURE ON THE GAP BETWEEN REAL ENERGY USE AND REGULATORY ENERGY PERFORMANCE CALCULATIONS

The differences between the regulatory modelling approaches and the more detailed models found in this scenario analysis will be compared with differences reported in literature between regulatory modelling results and real consumption data. This makes it possible to estimate to what extent the using the more detailed models can result, on average, in more accurate results. This analysis will be based on the values regarding the final energy use for space heating instead of the net space heating demand, because the correlations those results will be compared to were also defined based on the real and theoretical final energy use. The net energy demands are therefore divided by the efficiencies reported in section 6.2.2.

6.3 Results

6.3.1 Theoretical versus real energy use and temperatures at building and room level, single-zone versus multi-zone

From standard to real user profiles: direct comparison

Figure 6.7 and Figure 6.8 compare the real and theoretical values of the net space heating demand, with each dot representing a different house. The official Flemish calculation method ('FL EPB'), including the standard ventilation flow rates and internal heat gains, overestimates the real energy demand by a factor of two, as was discussed in Chapter 3. Considering the more realistic, calculated air flow rates through windows and internal heat gains lowers the overestimation by 11 percent point, still leaving 39% of overestimation unexplained (Figure 6.7). Furthermore, the real and theoretical values still show no correlations (Figure 6.8). This lack of correlation between the real and the theoretical values is also true when considering the approaches from DIN 18599 ('GE') and from NEN 7120 ('NL') for modelling intermittency and spatial reduction in combination with their respective standard heating profiles, resulting also in large overestimations of on average 44% and 30%, respectively. The higher values given by GE compared to NL (average difference: 38kWh/(m^2.year) or 20%) are mainly caused by the higher set-point temperature and the higher number of heating hours considered in DIN 18599 compared to NEN 7120 (see Figure 6.5 and 5.2.2), and less by the different formulas. This was illustrated by the different equivalent set-point temperatures and average temperatures shown in Figure 5.2 and Figure 5.3 of previous Chapter 5. Also, the lack of correlation can be explained by the difference between the real and the standard heating profiles.

Considering the real heating profiles indeed lowers the difference in calculated net heating demand between GE and NL by 73%, to a still significant difference of 10kWh/(m^2.year) or 7% (Figure 6.7). This also lowers the overestimation of the heating demand by, on average, 12 and 3 percent points to 32% and 27%, respectively (Figure 6.7). On average, the prediction errors remain large when considering the real heating profiles, but there is now a strong correlation between the calculated values and the real values (Figure 6.8 (d) and (f), Table 6.9), showing that the variation in heating profiles explains a large part of the variation of real energy use figures and prediction errors (Figure 6.5). Considering these real heating profiles in the multi-zone model (MZ) results in a lower average overestimation (23%) and an improved correlation (Figure 6.7, Figure 6.8, Table 6.9), but the difference with the GE and NL is not large.

Before discussing what causes the differences between the values on the net space heating demand (see next section), Figure 6.9 and Figure 6.10 add the average temperatures of the measurement period into the comparison between theoretical and measured values. Good correlations are found between all data-series when analysing the average temperatures at building level (Figure 6.9). With values of on average 15.5°C, 14.9°C and 15.0°C for GE, NL and MZ respectively, the average errors on building level are small compared to the measured average of 15.8°C. However, higher errors (up to 5°C) can be found for a few cases. The higher calculated temperature resulting from GE compared to NL and MZ is in agreement with the higher average theoretical energy use found for GE. The lower theoretical energy use that was found for MZ compared to NL is seemingly in contradiction with the higher average temperature found for MZ, but the differences between these values are small. Before analysing these differences between the models in the next paragraph, Figure 6.10 focuses on the average temperatures at room level, comparing values from the multi-zone model with the measured values. While the fit is good for the living room temperatures, the prediction errors increase and show larger variations when looking at the unconditioned spaces (see also Table 6.9). Two reasons explain this. Firstly, the interior climate in these rooms diverge more from the quasi-steady state assumptions of the models, with e.g. large and fast variations in temperature in the bathrooms due to brief simultaneous or alternating hot showers and airing through windows. Secondly, because those rooms are not or only intermittently heated, their indoor temperature will depend more on parameters that were not documented as thoroughly or not at all by the measurements or surveys: the activities in the rooms defining the internal heat gains (e.g. baths and showers), the door opening profiles, the opening angles of the windows etc. Still, for all room types, the calculated values at room level are strongly correlated with their real values. Moreover, the multi-zone model results in a realistic differentiation between the rooms based on their indoor temperatures (Figure 6.10).

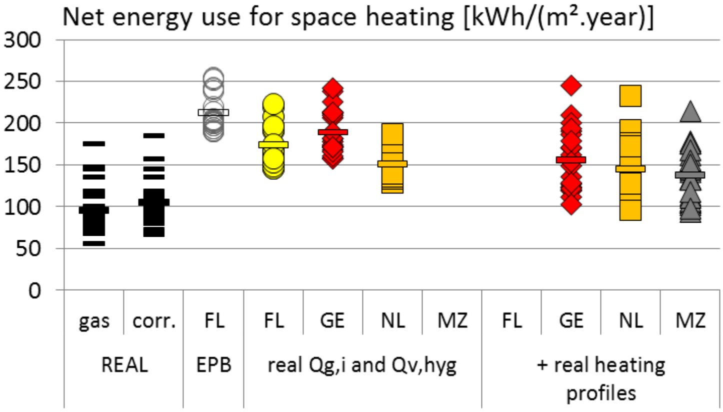

Figure 6.7: net energy use for space heating: real values (from gas consumption and increased with the calculated values for the heated bathrooms and bedrooms ('corr.')) versus theoretical values

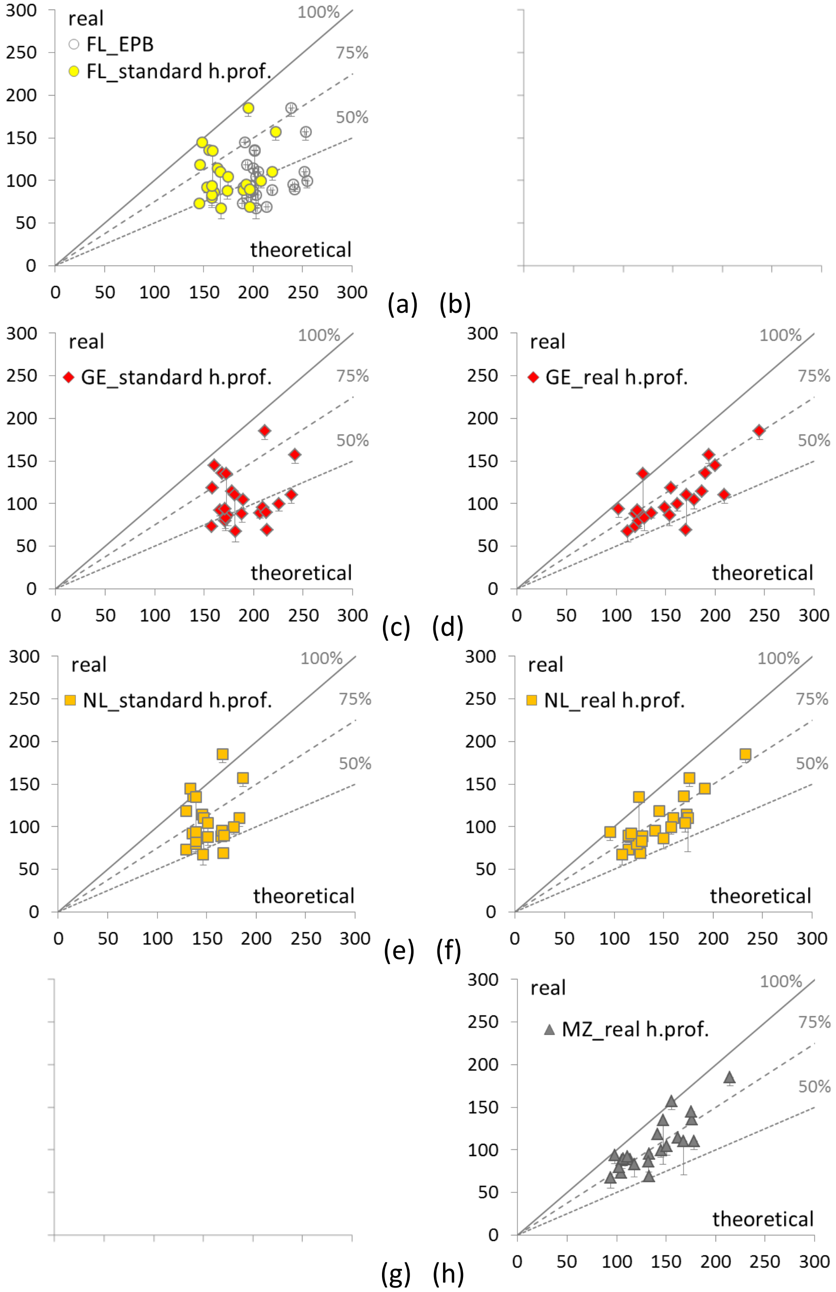

Figure 6.8: total net energy use for space heating [kWh/(m².year)]: 'real' values versus theoretical values (with corrected internal heat gains and window air flows, except for FL_EPB) (standard h.prof. = standard heating profile according to the corresponding official method; real h.prof. = real heating profiles of the households) (error bars on 'real' values = gas-based value without correction for bathrooms and bedrooms)

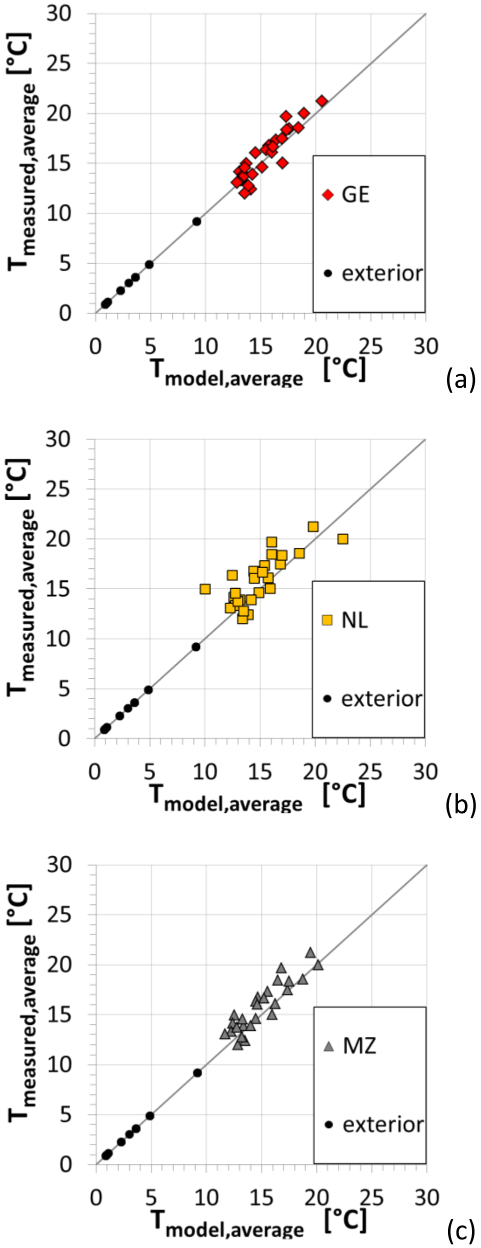

Figure 6.9: Average temperatures in the houses during the measurement period: real versus calculated considering the real user profiles (single zone with correction formulas according to DIN 18599 (GE) and NEN 7120 (NL) and volume-weighted average of the room temperatures from the multi-zone simulation (MZ))

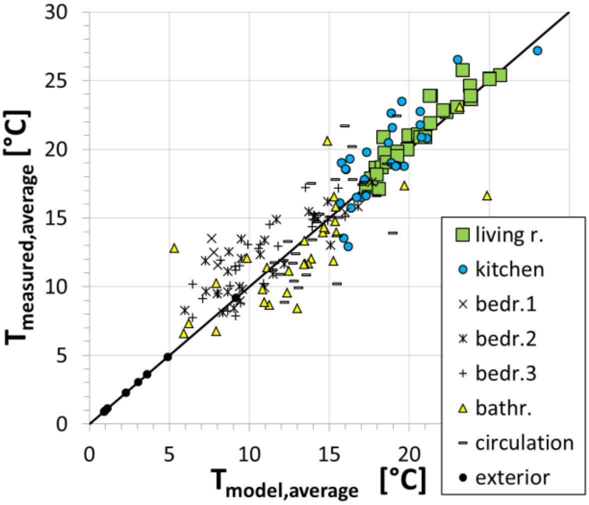

Figure 6.10: Average temperatures in the different rooms of each house during the measurement periods: measured values versus multi-zone simulation results

Table 6.9: correlations between real and theoretical values: energy use for space heating and average temperatures

Theoretical versus real values			
	N	R^2	95% CI
Energy use			
GE	23	.557	[.147, .844]
NL	23	.654	[.256, .873]
MZ	23	.691	[.421, .866]
Average temperatures			
GE	26	.841	[.695, .928]
NL	26	.608	[.378, .797]
MZ	26	.804	[.675, .886]
MZ_living r.	30	.887	[.809, .957]
MZ_kitchen	27	.679	[.443, .816]
MZ_bedr.1	5	(sample too small)	
MZ_bedr.2	26	.692	[.454, .834]
MZ_bedr.3	25	.736	[.584, .857]
MZ_bathr.	30	.590	[.331, .832]
MZ_circul.	30	.551	[.308, .777]

NOTES: all values are significant at $p < .001$

Single-zone versus multi-zone models: zonal differentiation

The fact that the multi-zone model (MZ) uses the intermittency correction formulas from NEN 7120 explains in part why the results of MZ differ more from the results of GE than from the results of NL. Still, additional important modelling aspects differentiate the multi-zone model from the two single-zone models. Firstly, the former enables taking into consideration the unequal allocation of ventilation heat losses, internal heat gains and thermal insulation to the different heated and unheated rooms. Secondly, it enables taking into account in more detail the thermal interaction between the different zones.

RELATIVE LOCATIONS OF GAINS AND LOSSES

The multi-zone model takes into account the fact that only a small portion of the total air flow through windows (Table 6.3) but a large portion of the total heat gains (Table 6.6) apply to the heated living area. This results, relatively, in less heat losses in the area that is actively heated, in more heat gains compensating those heat losses and, by consequence, in a lower calculated heating demand. This is illustrated by the simulation results summarized in Table 6.10 and Table 6.11. Considering a volume weighted distribution of the hygienic ventilation flow rates and of the internal heat gains in MZ results, on average for this specific set of non-insulated case-study houses, in approximately 4.4kWh/(m^2.yr) or 3% and 3.2kWh/(m^2.yr) or 2.5% higher calculated space heating demands, with a difference up to 12kWh/(m^2.year) or 9% regarding the attribution of the air flows through windows. The error caused by not considering the real distribution of the transmission heat losses over the whole building envelope is approximately two times larger: the MZ model that considers all building components having the same, average heat transmittance predicts on average 10kWh/(m^2.year) or 7% higher space heating demands (largest error: 29kWh/(m^2.year) or 18%, Table 6.10 and Table 6.11). Comparing the average temperatures of the different rooms (Figure 6.10) with the average thermal transmittance of the building envelope separating those rooms from the outdoor environment (Table 6.7) explains this large error. Considering a homogeneous building envelope across all rooms neglects the fact that the external envelope of the warmer, heated living room has the lowest (best) average thermal transmittance because it is located on the ground floor. Applying these three simplified modelling assumptions together, making these multi-zone calculations more similar to the single-zone calculations, shows that models not considering these zonal differentiations can erroneously result in predictions that are 7 to 42 kWh/(m^2.year) or 6% to 27% larger while considering, at the building level, the same total internal gains, air flows and external heat transfer coefficient. This can thus explain a significant part of the overestimation made by single-zone models, also by those that take into account the fact that a fraction of the house is not heated.

Table 6.10: single-zone simplifications applied to the multi-zone model: absolute errors. Legend: Allocation of the air flows through windows (Qv,hyg) and of the internal heat gains (Qg,i) based on the volumes of the room, constant average U-value over the whole building envelope (Um) and different door opening profiles ((Ref.)=Reference model=model with all detailed zonal differentiations and with the default door opening profiles)

Absolute simplification errors [kWh/(m².year)]						
	Av.	Min.	0.25	Mdn.	0.75	Max.
Zonal differentiation						
Qv,hyg~V	4.4	-0.4	1.0	3.4	7.9	12.2
Qg,i~V	3.2	0.8	2.4	3.3	3.7	5.6
Um	9.9	3.5	6.5	8.8	11.5	28.6
combined	17.3	6.6	12.9	15.5	20.0	41.6
Interzonal heat exchange: door openings						
no	-24.0	-42.7	-31.7	-22.3	-17.1	-14.5
low	-13.5	-23.6	-18.2	-12.2	-9.1	-6.0
default (ref.)	0.0	0.0	0.0	0.0	0.0	0.0
high	4.1	1.5	3.1	3.6	4.6	8.2

Table 6.11: single-zone simplifications applied to the multi-zone model: relative errors. (legend: see previous Table 6.10)

Relative simplification errors [%]						
	Av.	Min.	25.00%	Mdn.	75.00%	Max.
Zonal differentiation						
Qv,hyg~V	3.2%	-0.4%	0.6%	2.8%	4.9%	9.2%
Qg,i~V	2.4%	0.6%	1.9%	2.5%	3.1%	3.5%
Um	7.1%	3.3%	5.0%	6.8%	8.3%	18.4%
combined	12.6%	6.3%	9.1%	12.4%	15.7%	26.8%
Interzonal heat exchange: door opening profiles						
no	-17.3%	-24.3%	-19.6%	-16.8%	-14.8%	-10.1%
low	-9.8%	-14.1%	-11.8%	-9.1%	-8.5%	-4.1%
default (ref.)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
high	2.9%	1.4%	2.6%	2.9%	3.6%	4.5%

INTER-ZONAL HEAT EXCHANGE

Larger or smaller heat transfers between different zones of a building will level out, respectively accentuate the zonal differentiation discussed in the previous paragraph and illustrated by the different room temperatures in Figure 6.10. Different assumptions regarding these inter-zonal heat transfers will thus result in smaller or larger predictions errors for the different rooms. This is illustrated by Figure 6.11, comparing the prediction errors on the indoor temperatures when considering different door opening profiles in the multi-zone model (see 6.2.2). The calculated temperatures in the indirectly heated rooms can vary by several degrees depending on the considered door opening profiles. The fact that no information was available about the real door opening profiles of the different households can thus explain in part the large differences that were found between the calculated and measured values in these rooms (see also Figure 6.10). The values on building level are less influenced by these assumptions, with an average difference of only 1.8°C between the models considering no open doors and the models considering the highest opening profile. This results from the negligible difference of the living room temperatures calculated by those models (on average 0.1°C, with 0.4°C being the largest difference for an individual case). These smaller differences found in the living rooms are partly explained by the fact that the living rooms are heated to the set-point temperature independently of the heat losses to adjacent spaces. However, considering that most living rooms are heated only intermittently, the effect of the different door opening profiles is lower than expected. This is explained by the Dutch intermittency correction formula that is used in the multi-zone model. The poor insulation quality of the building components separating the living area from the colder surroundings results in a low time constant. At low time constants and large set-back periods the first part of Eq.(5.12) will apply, making the equivalent set-point temperature independent of further increases of the heat losses, e.g. due to the additional air flows through open doors. At the same time, the utilization factor will be high, the unutilized heat gains low and thus the average temperature will remain very close to the stabilized equivalent set-point temperature.

As opposed to their limited influence on the calculated temperature in the living room, the door opening profiles influence the heat loss from the living room to the unheated circulation area and, consequently, the predicted space heating demand. Compared with the simulations without inter-zonal air flows, the low, default and high air flow profiles increase the calculated space heating demand by on average 9%, 21% and 25%, respectively (Figure 6.12, Table 6.11). However, the multi-zone model with the high air flow scenario still predicts a lower net space heating demand than the single-zone models, but the difference is smaller than for the other profiles: it results on average 141kWh/(m^2.year) for MZ with high door opening profile compared to 156kWh/(m^2.year) and 145kWh/(m^2.year) for GE and NL, respectively.

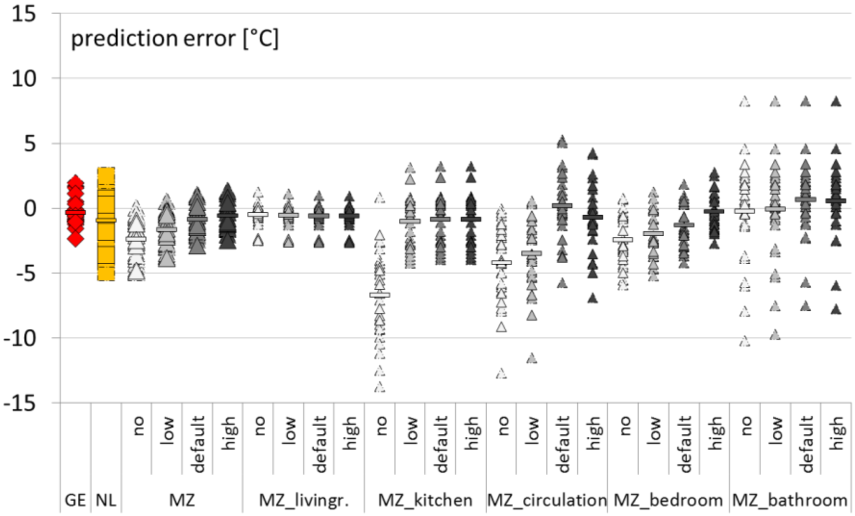

Figure 6.11: difference between calculated and measured temperatures (a positive value indicates an overestimation of the real values by the model)

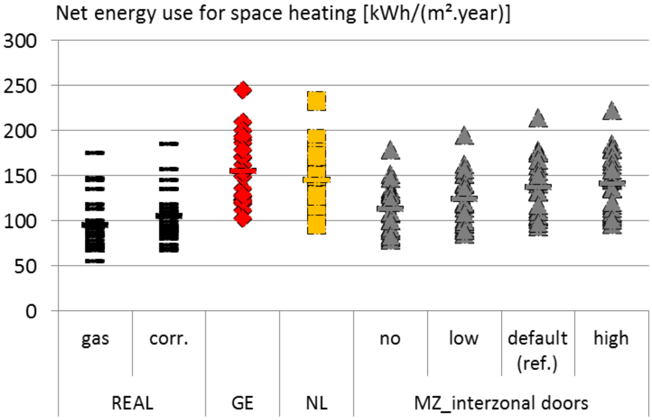

Figure 6.12: net space heating demand: multi-zone models considering the different door opening profiles versus the real values and the values from the single-zone models

6.3.2 Multi-zone modelling and heating profiles at building level and beyond

The errors caused by considering the standard user profiles in the single-zone models cannot be corrected by considering another, unique standard user profile deemed more representative, because the variation in real user profiles is too large, even in the small number of houses of the analysed neighbourhood. This is shown in Figure 6.13 (a), Table 6.12. Considering in the models the 'median profile' of *those* households still causes large errors, positive or negative, compared to considering the real profile. Those errors are between −45% and +48%, creating maximum underestimations and overestimations of −92kWh/(m².year) and +50kWh/(m².year), respectively (with an outlier at −136kWh/(m².year)). This corresponds to the large variations in real and calculated heating demand discussed in the previous section where. Now, the adjacent houses are also modelled and the heating profiles in those adjacent houses also prove to have a large effect on the results. Assuming the median user profile in the adjacent houses can cause an overestimation or an underestimation of the space heating demand, with errors reaching from −4% to +8%. It does not cause a significant positive or negative shift when averaged over all houses (0%), because the average heating profile was based on the real set of heating profiles found in the neighbourhood. However, neglecting the fact that an adjacent house is uninhabited can cause a significant bias, resulting in underestimations as high as −21% or −28kWh/(m².year) for the cases with uninhabited houses on both sides. Because most houses are inhabited, the average error on the whole dataset is not as pronounced, but it is still significant (−3%). Similar errors occur when simplifying the party walls as adiabatic boundaries, neglecting both the real heating profile in the adjacent inhabited houses and the larger heat losses if those houses are not inhabited (average: −4%, [−19%, +5%]).

Compared with the uncertainty on the user profile in the adjacent house, the uncertainty on the user profile in the analysed house thus still largely prevails. When combining the simplifications on both levels in one model, on average, the range of prediction errors remains in the same order of magnitude as if only the latter profile was unknown (Table 6.12). This follows statistical logics: the user profile in the neighbouring houses is considered to be independent on the user profile in the analysed house. Because it is mainly the temperature difference between both houses that affects the uncertainty on the heat losses to the neighbours, it is as likely for both simplifications to compensate for one another as to amplify one another. For cases in the latter, amplifying situation, errors did increase by as much as 7 percent points if both adjacent houses are inhabited and −20 percent points if those houses are not inhabited.

Regarding the neighbouring house, the above analysis focussed on the user profiles. Making a wrong assumption about the design of the adjacent houses, mirroring their lay-out, also proves to alter the results significantly. The errors compared to the reference model with the correct lay-outs reach from small underestimations of −2% to overestimations of +6%. The latter, larger overestimations are caused by the increased heat losses from the heated living area to the neighbour on that side. Considering the unheated circulation area of the neighbour to be located next the living room of the analysed house significantly increases the calculated heat losses through that party wall and thus also the calculated heating demand. The former, smaller underestimation values are found for cases with an uninhabited house on the side of the living room. For those cases, mirroring the lay-out of that uninhabited house does not influence the results. However, mirroring the adjacent house on the other side causes the circulation area to be heated indirectly by the living area of the other neighbour. As a result, the calculated temperature of the circulation area increases, reducing indirectly the calculated heat losses from the living area and thus also the calculated heating demand. This also occurs for the houses with inhabited houses on both sides, but the direct increase in calculated heat losses through the party wall of the living proves to be much higher.

Considering the houses after insulating the external envelope changes these figures (Figure 6.13(b), Table 6.13). Because of the reduced heat losses through the building envelope, the absolute errors linked to the user profile in the analysed house are approximately two times smaller when considering the total renovation scenario, but the relative error remains approximately the same because the energy use is also lower. On the opposite, inaccurately modelling the neighbouring houses causes approximately the same absolute errors because the party was considered to remain non insulated, resulting in relative errors that are approximately two times larger than before renovation. The next section focusses further on different renovation scenarios.

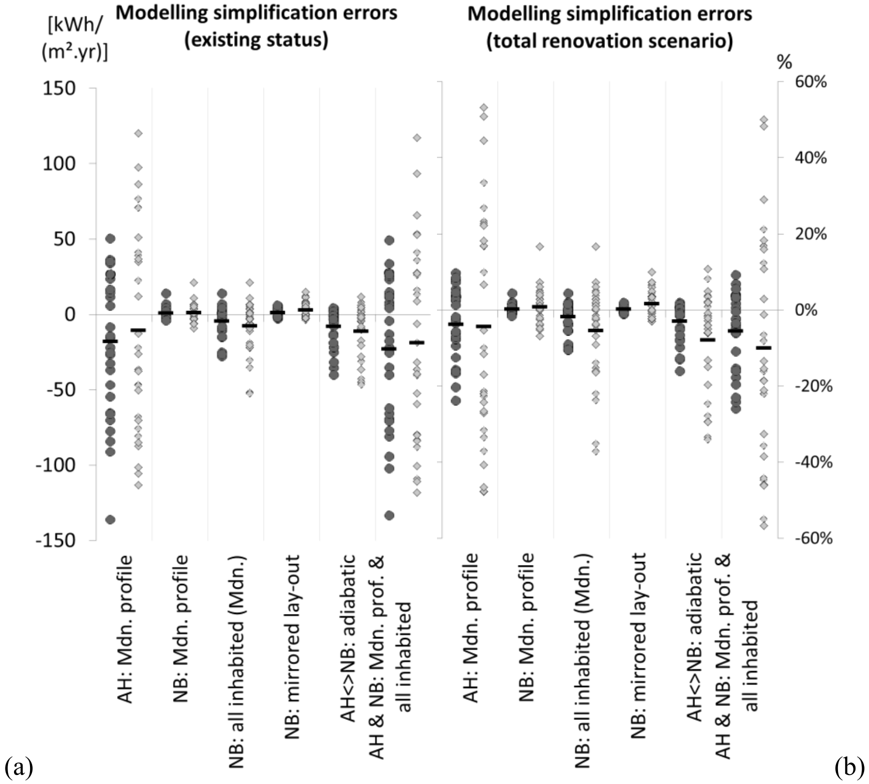

Figure 6.13: modelling errors related to user profiles in the analysed and in the adjacent houses. ('AH'=analysed house, 'NB'=neighbours, 'Mdn. prof.'=median user profile)

Table 6.12: modelling errors related to user profiles in the analysed and adjacent houses, *existing status.* *('AH'=analysed house, 'NB'=neighbours, 'Mdn. prof.'=median profile)*

Modelling simplification errors (existing status)	Av.	Min.	Mdn.	Max.
ABSOLUTE ERRORS [kWh/(m².year)]				
AH: Mdn. profile	-17.8	-136.2	-15.0	50.3
NB: Mdn. profile	1.1	-4.2	0.0	14.0
NB: all inhabited (Mdn.)	-4.3	-27.8	-0.8	14.0
NB: mirrored lay-out	1.3	-2.6	0.7	6.0
AH<>NB: adiabatic	-7.8	-40.2	-2.7	4.2
AH & NB: Mdn. prof. & all inhabited	-22.7	-133.3	-15.3	49.0
RELATIVE ERRORS [%]				
AH: Mdn. profile	-4.1%	-45.3%	-9.7%	48.0%
NB: Mdn. profile	0.5%	-3.7%	0.0%	8.4%
NB: all inhabited (Mdn.)	-3.0%	-21.0%	-0.8%	8.4%
NB: mirrored lay-out	1.2%	-1.5%	0.5%	5.9%
AH<>NB: adiabatic	-4.4%	-18.6%	-1.4%	4.7%
AH & NB: Mdn. prof. & all inhabited	-7.5%	-47.2%	-10.1%	46.8%

Table 6.13: modelling errors related to user profiles in the analysed and adjacent houses, *renovated.* *('AH'=analysed house, 'NB'=neighbours, 'Mdn. prof.'=median profile)*

Modelling simplification errors (total renovation scenario)	Av.	Min.	Mdn.	Max.
ABSOLUTE ERRORS [kWh/(m².year)]				
AH: Mdn. profile	-9.2	-59.5	-7.7	24.3
NB: Mdn. profile	0.9	-4.1	0.0	10.9
NB: all inhabited (Mdn.)	-4.1	-26.2	-0.7	10.9
NB: mirrored lay-out	0.8	-2.6	0.4	4.7
AH<>NB: adiabatic	-6.5	-40.1	-2.3	5.5
AH & NB: Mdn. prof. & all inhabited	-13.5	-64.7	-8.8	23.0
RELATIVE ERRORS [%]				
AH: Mdn. Profile	-4.2%	-47.8%	-10.8%	53.3%
NB: Mdn. Profile	0.9%	-6.8%	0.0%	16.7%
NB: all inhabited (Mdn.)	-5.4%	-37.2%	-1.8%	16.7%
NB: mirrored lay-out	1.8%	-3.0%	0.6%	9.9%
AH<>NB: adiabatic	-7.8%	-34.0%	-4.0%	10.8%
AH & NB: Mdn. prof. & all inhabited	-9.9%	-56.7%	-14.5%	50.0%

6.3.3 Energy renovation scenarios

Absolute and relative energy savings

Figure 6.14, Figure 6.15 and Figure 6.16 compare the theoretical energy savings predicted by the different single-zone and multi-zone models for the different renovation strategies. Before considering the real heating profiles (Figure 6.16), the results of the models considering the standard heating profiles are analysed. As a reference to the official energy performance assessment approach, Figure 6.14 shows the results considering not only the Flemish single-zone approach regarding the heating profiles, but also its standard formulas for defining the hygienic air flow rates and internal heat gains. Figure 6.15 shows the values of the different single-zone approaches, including also GE and NL, with the corrected internal heat gains and ventilation flow rates, but still with their respective standard heating profiles. Because the considered renovation measures are not related to the ventilation or to the heat gains but only to the transmission heat losses, the savings predicted by FL and FL_EPB are nearly identical, with differences that are, on average, smaller than 1kWh/(m^2.year) for separate renovation measures and smaller than 2.5kWh/(m^2.year) for combined measures. These small differences result from the different heat balance in both scenarios, resulting in different utilization factors for the heat gains (see 5.2.1). However, because of the lower calculated demands, the relative savings are much larger when considering the realistic heat gains and air flow rates (on average 6 percent point or 21% larger).

Figure 6.14 and Figure 6.15 show a larger spread in energy savings associated with retrofit cavity wall insulation compared with attic floor insulation or double glazing. This is caused by the variation in exterior wall areas between houses depending on their typology (terraced or semi-detached) and on the presence of a garage adjacent to their house. This typological variation also explains the variation in relative energy savings associated with any of the retrofitting measures, including the renovation measures on windows and attic floors, which are of equal size for all houses. The German and Dutch approaches predict the largest and smallest theoretical energy savings, respectively, for all the renovation strategies consisting of individual or combined retrofitting measures, with the Flemish predictions laying in between (Figure 6.15). This coincides with the differences in energy demands predicted by the different models (Figure 6.7). Looking at the relative savings, the Flemish and German assumptions yield nearly identical predictions (average difference < 1 percent point) while the Dutch assumptions predict approximately 3 to 5 percent points less savings, except for the already very low estimated savings associated with the floor insulation. These low savings associated with insulating the floor are caused by the already reduced heat losses through that floor before renovation (see 6.2.2).

The difference in predicted savings between GE and NL is reduced when considering the real heating profile, but, for separate renovation measures, only by 30%. The German formulas still consistently predict savings that are more than 8kWh/(m^2.year) or 5 percent point larger compared to those resulting from the Dutch formulation, except again for the floor insulation. For all renovation strategies except for replacing the windows and insulating the floor on ground level, the multi-zone approach predicts both the lowest absolute and relative energy savings. The difference in predicted relative savings between single and multi-zone models is the highest for the insulation of the attic floor (approximately by a factor of two to two and half).

The fact that the prediction difference between single and multi-zone models depends on the renovation strategy is explained by the location of the insulation layers compared to the heated rooms and the indoor temperature distribution (Table 6.7 versus Figure 6.10). As discussed in section 6.3.1, the single-zone models do not take into account the real location of the different building components, having a different heat transmittance, compared to the heated and unheated rooms, having different indoor temperatures. However, the attic floor encloses only the colder bedrooms, circulation area and bathroom on the first floor, while little more than half of the total window area is located in the heated living area on the ground floor. The single-zone model thus overestimates *the temperature difference* between both sides of the attic floor and thus also the reduction of the heat losses and the associated energy savings, while the opposite applies regarding the replacement of the windows and the insulation of the slab on grade. Still, there is an additional reason for this bias of single-zone models in favour of loft insulation, as will be discussed in the next paragraph.

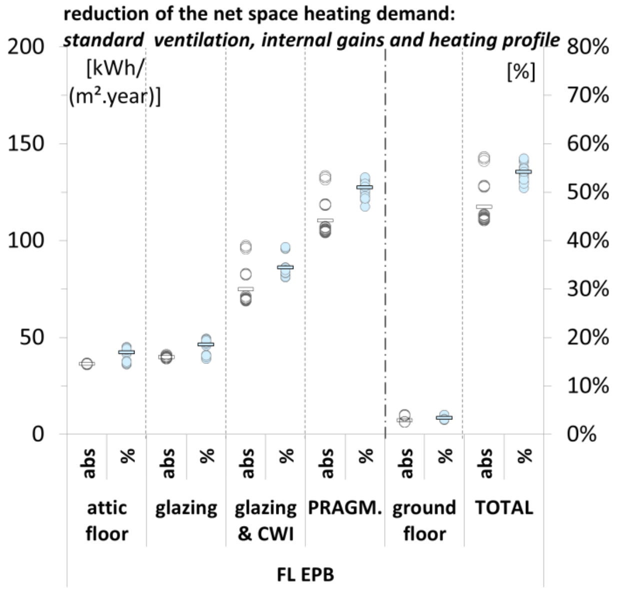

Figure 6.14: reduction of the net space heating demand: official Flemish EPB-method ('FL EPB') (incl. standard internal heat gains and hygienic air flow rates)

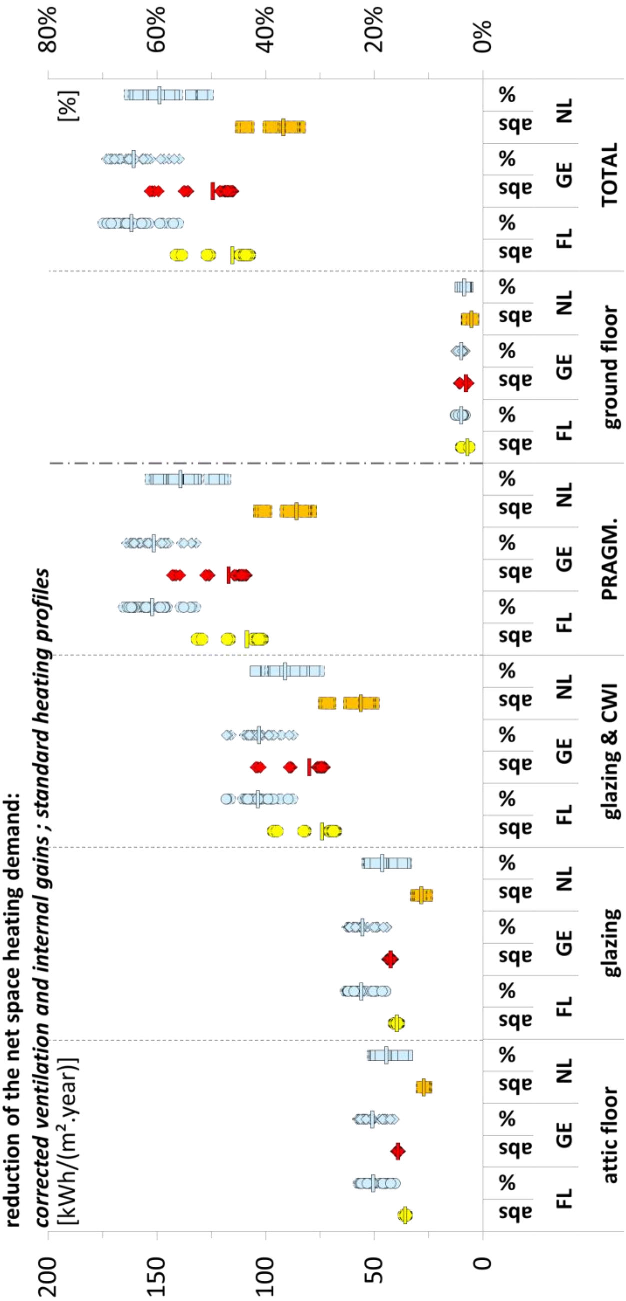

Figure 6.15: reduction of the net space heating demand: corrected ventilation air flows and internal heat gains, but standard heating profiles (approaches: Flanders (FL),DIN 18599 (GE), NEN 7120 (NL))

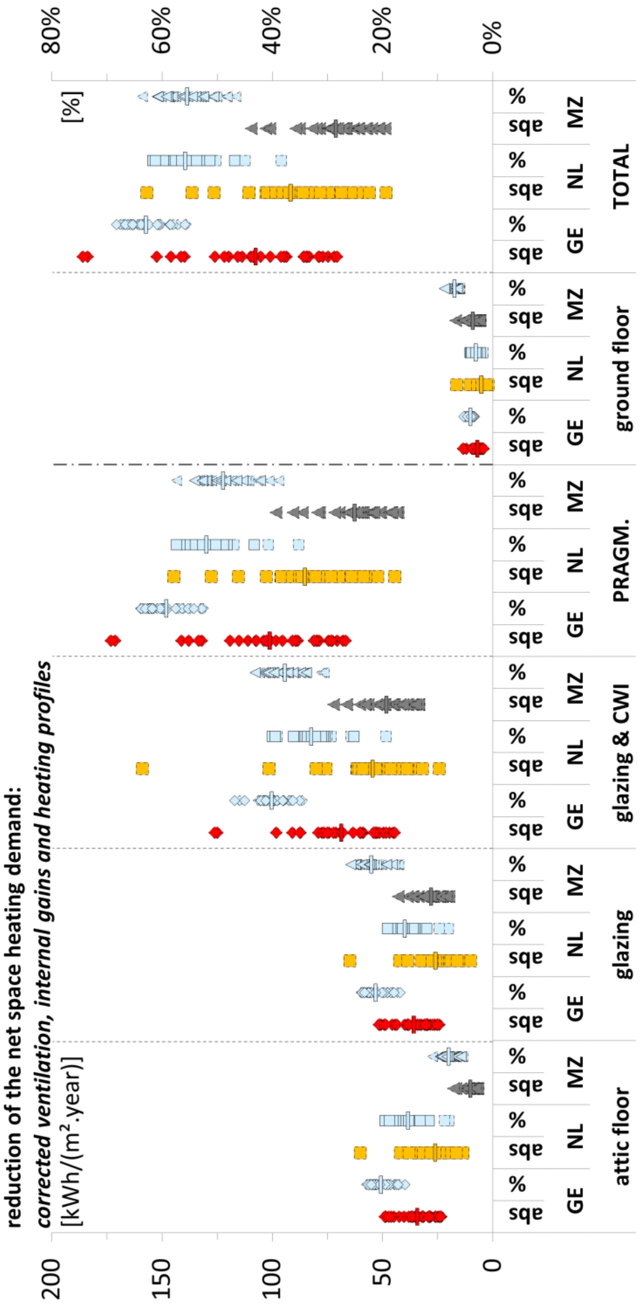

Figure 6.16: reduction of the net space heating demand: corrected ventilation air flows, internal heat gains and heating profiles (approaches: DIN 18599 (GE), NEN 7120 (NL), multi-zone (MZ))

Temperature take back

The differences in energy savings predicted by the different models correspond to differences in calculated temperature increases before and after renovation. Figure 6.17 shows these temperatures when calculated for the coldest month of the standard Flemish EPB-climate: January, with an average outdoor temperature of 3.2°C. Comparing the average temperatures at building level using the German and the Dutch correction formulas explains the lower relative energy savings predicted by the Dutch formulas (Figure 6.16): they predict a larger temperature take-back. In fact, that temperature take-back predicted by the Dutch formulas closely matches the volume-weighted building average temperature set-back calculated using the multi-zone model. The average room temperatures calculated with the multi-zone model illustrate the spatial temperature uniformization caused by improved building envelope. Similarly to the variations in heat exchange due to different door opening profiles, the renovation measures do not result in significantly different calculated average temperatures in the living room. While this can be explained in part by the specific formulas taken from NEN 7120, it is physically correct that the temperature difference between insulated and not insulated houses is larger in the unheated bedrooms (see 3.3.4, 3.4.1). The average bedroom temperatures still do not reach the temperatures of the living rooms, the difference after renovation is approximately two times smaller. By consequence, the temperature increase that has to be considered for the loft insulation, that of the rooms beneath the attic, is higher than the temperature increase at building level, considered by the single-zone models. There are thus two reasons explaining the bias of single-zone models in favour of insulating the top floor. These reasons are illustrated by the simplified Eq.(6.20) expressing the energy savings (based on Eq.(5.8)). Not only do the single-zone models overestimate the temperature *difference* between both sides of the attic floor due to the underestimation of the indoor temperature ($T_{av,x,before}$ and $T_{av,x,after}$ in Eq.(6.20)), as discussed in the previous paragraph, they also underestimate the *increase* of that temperature difference after renovation (the difference between $T_{av,x,after}$ and $T_{av,x,before}$) ‘taking back’ part of the performance improvement.

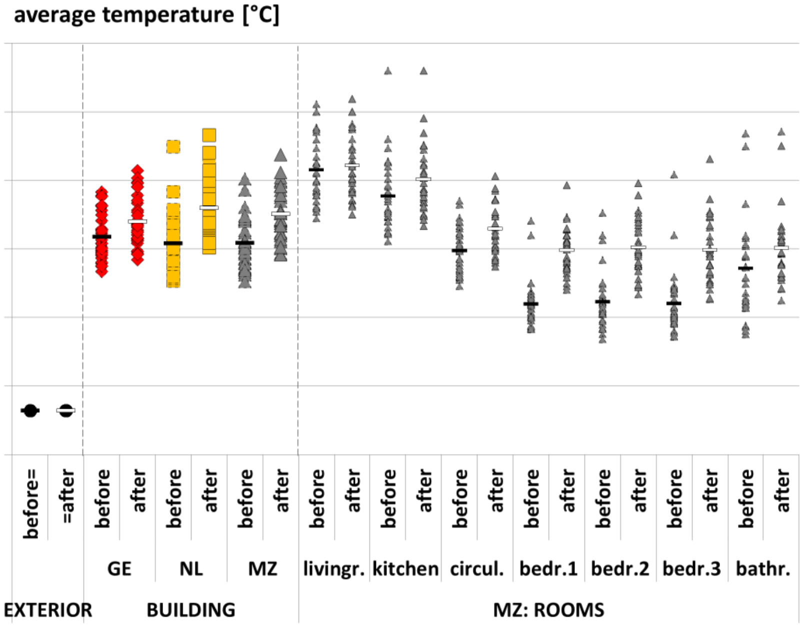

Figure 6.17: average temperatures for the measurement period: before and after the full renovation (attic floor insulation + cavity wall insulation + double glazing + floor insulation) (horizontal lines indicate the average values)

$$
\begin{aligned}
Q_{savings,x} = \; & H_{xe,before} * (T_{av,x,before} - T_{av,e}) * dt \\
& - H_{xe,after} * (T_{av,x,after} - T_{av,e}) * dt
\end{aligned}
\tag{6.20}
$$

With

$Q_{savings,x}$ = the energy savings after renovation

$H_{xe,before}$ = the heat transfer coefficient before renovation

$H_{xe,after}$ = the heat transfer coefficient after renovation

$T_{av,x,before}$ = the average indoor temperature before renovation

$T_{av,x,after}$ = the average indoor temperature after renovation

$T_{av,e}$ = the average outdoor temperature

dt = time duration

REMARK ON THE MODELLING ASSUMPTIONS: INTER-ZONAL HEAT TRANSFER

The different air flow profiles influenced the calculated average temperature and energy demand before renovation (see 6.3.1) and can therefore be expected to also influence the temperature take-back and energy savings after renovation calculated with the multi-zone approach. Figure 6.18 shows the calculated temperature take-back for the different door opening profiles considering the total renovation scenario. The values for the default profile correspond to the temperature increases in Figure 6.17 and the energy savings in Figure 6.16. While the different door opening profiles have a limited impact on the predicted temperature take-back at building level (a maximum difference of 0.5°C), they can have a large impact on the temperature take-back at room level (e.g. in the kitchen and circulation area, with differences up to 2.4°C and 1°C, respectively). Opening more the doors to hotter rooms and less the doors to colder rooms increases the average temperature of unheated rooms (Figure 6.11) and results in a smaller additional temperature increase after renovation (Figure 6.18). This is illustrated the best by the values of the circulation area.

By consequence, the more the doors are left open between the living room and the bedrooms, the larger the absolute and relative savings (Figure 6.20), with an average savings in the highest flow scenario of 12kWh/(m².year), being twice the savings calculated in the scenario without inter-zonal air flows 6kWh/(m².year). Still, even in the scenario with the highest air flows through doors, the multi-zone model predicts low energy savings for loft insulation, lower than according to the single-zone models. On the opposite, in case the doors are kept closed more often than was assumed by the default profile in the previous analysis, the bias from the single-zone model in favour of loft insulation will be even larger than illustrated in Figure 6.16. Because the temperature take-back at building level is influenced less than at room level, different door opening profiles will have a smaller relative impact on predicted savings from global renovation strategies, but the impact can be large in absolute values. As shown in Figure 6.19, the scenario with the largest inter-zonal air flows predicts on average 75kWh/(m².year) of savings compared to 56kWh/(m².year) for the scenario without inter-zonal air flows, a difference of 34%.

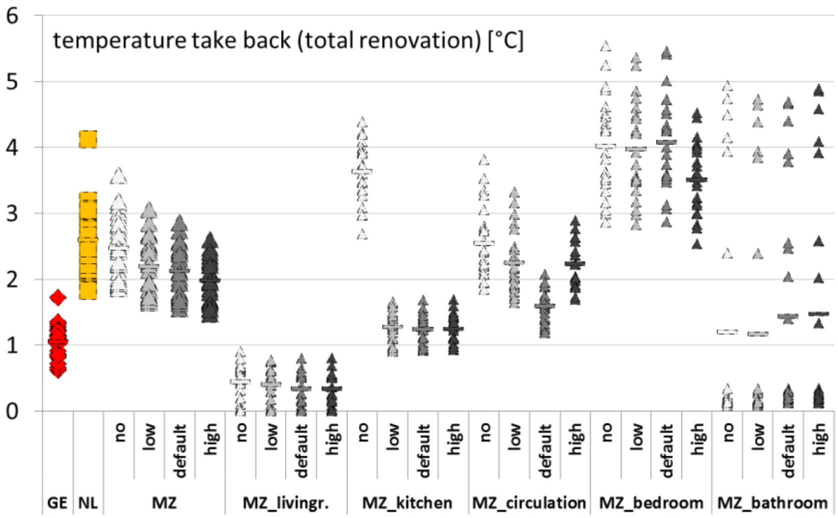

Figure 6.18: temperature take-back resulting from the full renovation (attic floor insulation + cavity wall insulation + double glazing + floor insulation) (horizontal lines indicate the average values)

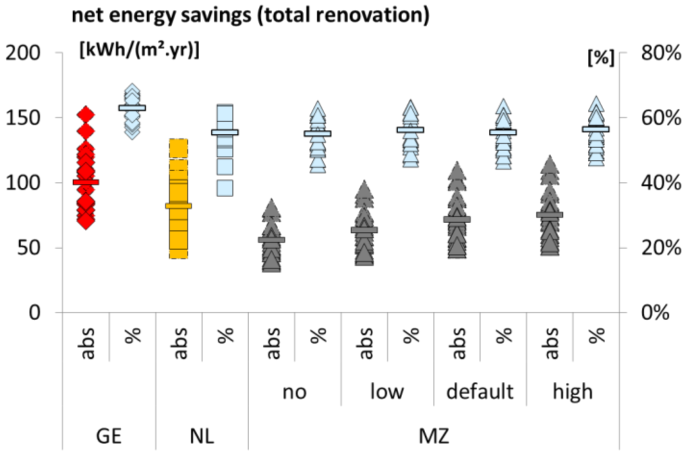

Figure 6.19: predicted energy savings from the full renovation: influence of door opening profiles (attic floor insulation + cavity wall insulation + double glazing + floor insulation) (horizontal lines indicate the average values)

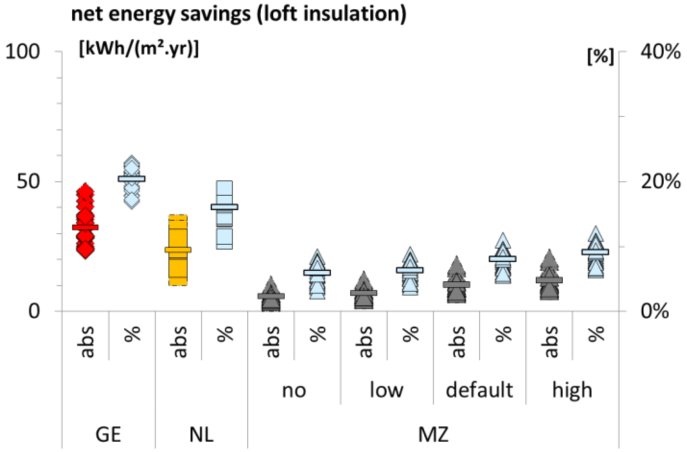

Figure 6.20: predicted energy savings from roof insulation: influence of door opening profiles (attic floor insulation + cavity wall insulation + double glazing + floor insulation) (horizontal lines indicate the average values)

Comparison with correlations from literature

Considering the real heating profiles through the use of correction formulas for intermittency and spatial reduction in the single-zone models and considering additional zonal differentiations in the multi-zone model were shown to result in more accurate theoretical values, with lower overestimations of the energy use and with a strong correlation across houses and households between their real and calculated energy and indoor temperatures. The analysis on the renovation measures was based on fictive scenarios, without the possibility of verifying if the modelling results in those scenarios are indeed more accurate. What can be analysed to that regard is if the relation between the improved models and the theoretical EPB-calculations (which does not consider the real user profiles) is similar to relations between real values and theoretical values from EPB-calculations found in literature. This is analysed considering the final energy use. Compared to the values analysed in the previous paragraphs, the efficiency of the heating system is thus also considered.

Before comparing the difference between real and theoretical values based on Eq.(6.4) and Eq. (6.5) with the difference between results from the more detailed models and the reference EPB-model, the assumptions behind Eq.(6.4) and Eq. (6.5) are verified for this set of EPB-models. Figure 6.21 shows that the EPB-calculations considering the different renovation scenarios (also shown in Figure 6.14 but regarding the net energy demand) confirm the linear relation on the calculated values stated by Hens et al. [31,45]. The linear correlation on the case-study data shows an offset compared to the theoretical linear correlation reported by Hens et. al, but this can be ascribed to the fact that the current set of theoretical values is only based on houses having all the same geometry, window areas, theoretical system efficiencies etc. while the correlation reported by Hens et al. referred to simulations including more variation. In fact, this is also the reason why the linear correlation with the transmission heat transfer coefficient is so strong: the insulation level of the envelope is quasi the only parameter varying between the models, in addition to variations in typology (terraced vs. semi-detached houses). Figure 6.22 shows the same values, but this time expressed in kWh/(m².year) and in function of the theoretical energy demand instead of the transmission heat transfer coefficient, thus making a direct comparison possible between the theoretical energy use and corrected values using the ‘prebound’ factors. Compared to the EPB-values corrected according to Hens et al., for these specific cases, the correlation defined by Loga et al. predicts a lower real energy use (and thus a larger prediction gap) and a larger shortfall at low performance levels, which can be deduced from the flatter slope corresponding to a larger increase of the overestimations for an increase of the theoretical energy use, or vice-versa. This difference between both approaches will of course vary for houses with other geometries, insulation levels and systems. As discussed in section 6.1.2, this difference could also be ascribed to the different reference models those correlations were based on.

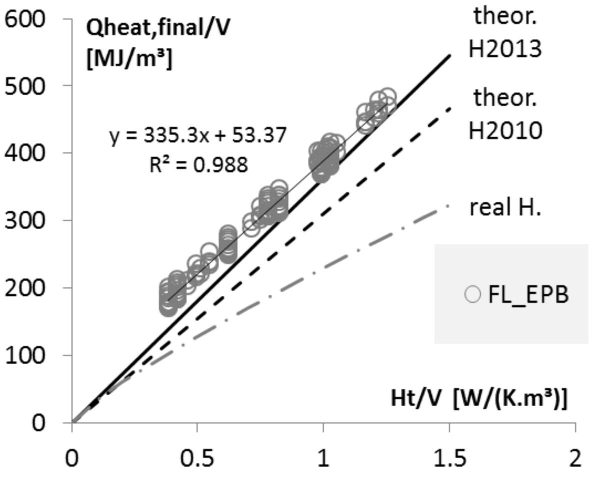

Figure 6.21: the gap between real and theoretical energy use for space heating according to Hens et al.2010 [31] and Hens et al.2013[45]: comparison of the assumption of linear relation with Ht/V for the EPB-calculations on the renovation scenarios

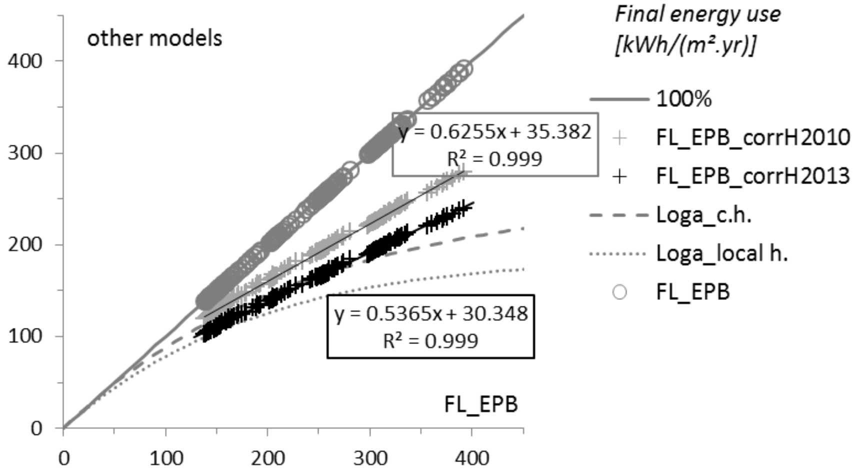

Figure 6.22: The gap between real and theoretical energy use for space heating according to Loga et al. [44] ('c.h.': original correlation based on houses with central heating; 'local h.': correlationcorrection for local heating) and according to Hens et al.2010 [31] and Hens et al.2013[45], considered for the EPB-calculations on the renovation scenarios

Figure 6.23, Figure 6.24, Figure 6.25, Figure 6.26 compare the results from the different models taking the user profiles into account with the results from the original EPB-calculation. Figure 6.23 shows that the only significant effect caused by considering the more realistic internal heat gains and air flows through windows, still in the single-zone model with fixed 18°C equivalent set-point temperature, is a lowering of the theoretical values, uniformly at all performance levels. This is normal considering the changes to the model only consists of a fixed lowering of the heat losses and increasing of the heat gains. Because the physical temperature take-back resulting from intermittent and spatially reduced heating is not taken into account, the model does not result in a more realistic, higher reduction of the calculated values at lower performance levels than at higher performance levels. When taking also the real intermittent and spatially reduced heating profiles into account in the single-zone models, this physical temperature take-back starts to appear in the modelling results, expressed by a lower value of the linear regression coefficient. The formulas from DIN 18599 (Figure 6.24) predict a smaller temperature take-back than those of NEN 7120 (Figure 6.25). This coincides with NEN 7120 considering a larger increase of the equivalent set-point temperature when improving the insulation levels (see also Figure 5.4 in 5.2.2). The take-back considered by NEN 7120 is also in better agreement with the EPB-values corrected using the correlations of Hens et al. (Eq.(6.4) and Eq.(6.5)). Switching further to the multi-zone models, taking also other zonal differentiations into account (e.g. regarding the building envelope, internal heat gains, ventilation flow rates), results in a further decrease of the predicted values and an increase of the considered take-back (flatter slope, Figure 6.26). At high theoretical energy use, the difference between the multi-zone model and the EPB model is very close to the difference between real and theoretical values reported by Hens et al. At better performance levels, the multi-zone model reaches even lower predictions than what is found by applying those empirical correction factors on the EPB-calculations. This can be explained by the scenario analysis simulated with the multi-zone simulations: it considered only refurbishments to the building envelope, and no changes to the systems or the user profiles. Considering a higher probability of central heating systems in the renovated houses with the associated higher number of rooms being heated (see Chapter 4) might have increased the calculated values at the better performance levels.

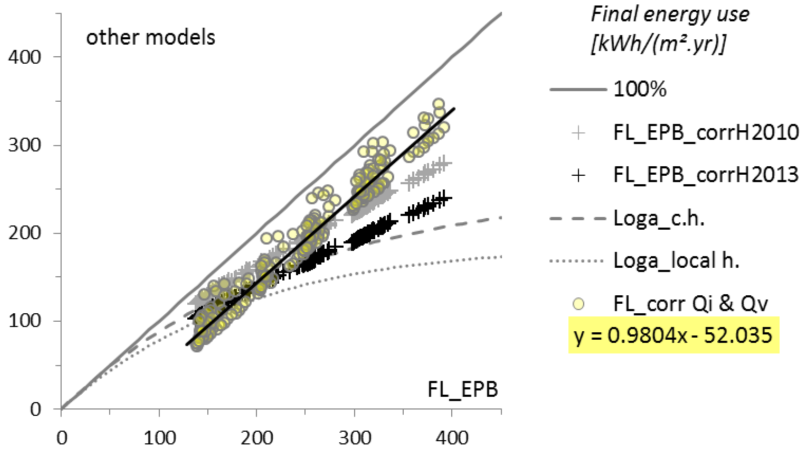

Figure 6.23: the gap between theoretical real and real energy use according to correlations versus the gap between the reference EPB-model and a more realistic model: FL-approach with realistic internal heat gains and ventilation flow rates through windows

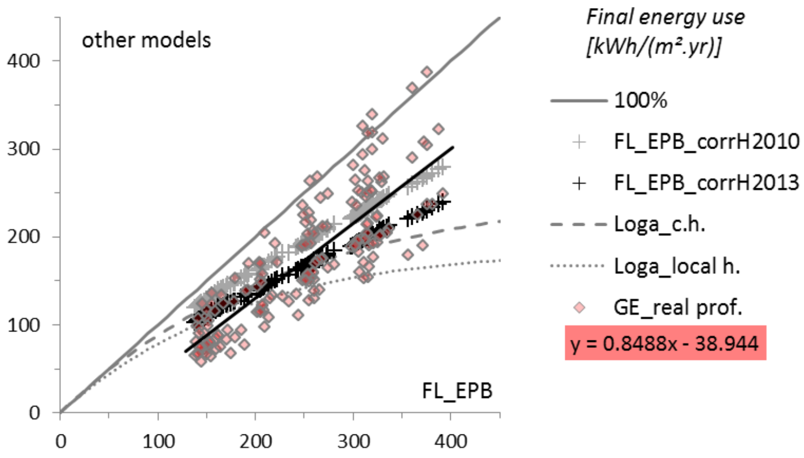

Figure 6.24: the gap between theoretical real and real energy use according to correlations versus the gap between the reference EPB-model and a more realistic model: GE-approach with real user profiles

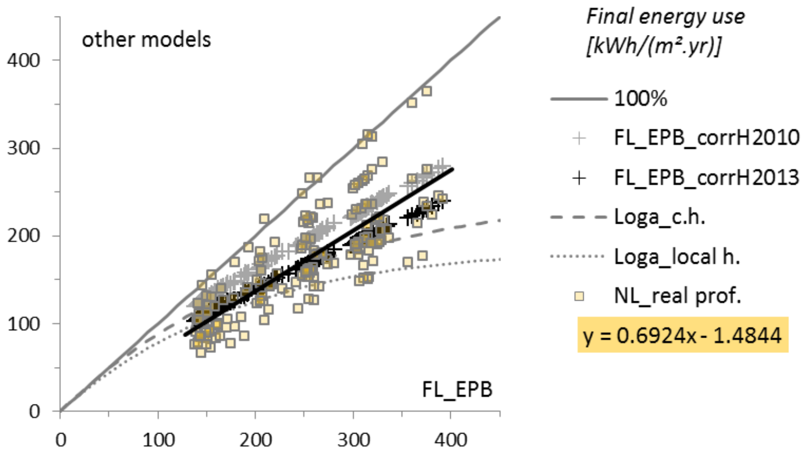

Figure 6.25: the gap between theoretical real and real energy use according to correlations versus the gap between the reference EPB-model and a more realistic model: NL-approach with real user profiles

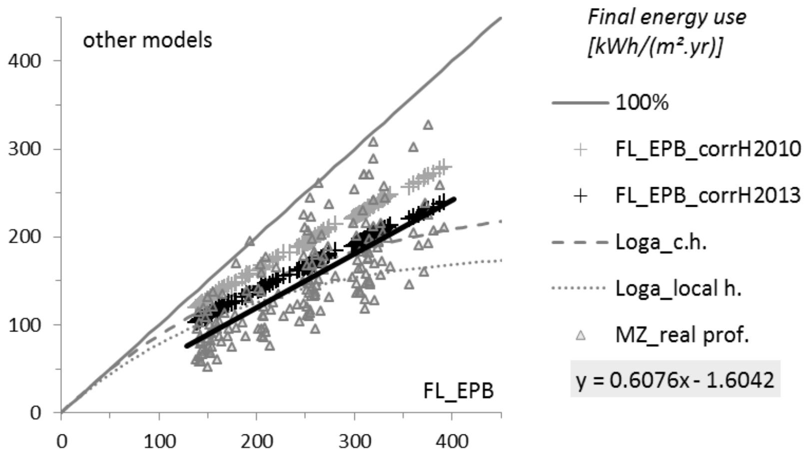

Figure 6.26: the gap between theoretical real and real energy use according to correlations versus the gap between the reference EPB-model and a more realistic model: multi-zone approach with real user profiles

6.4 Discussion & conclusion

6.4.1 Accuracy of the models

A very strong correlation was found between the real energy use and indoor temperatures and the corresponding theoretical values obtained by considering the real user profiles in the single-zone models with correction factors for intermittent and spatially reduced heating and in the multi-zone models. This indicates that, as assumed, a large part of the variation in real energy use can be attributed to differences in heating profiles and also that these models allow taking a large part of this variation into account. The correlations between real and theoretical values at building level were not significantly stronger using the multi-zone model than using the single-zone models with the correction formulas. However, the comparisons between measured and calculated room temperatures illustrated the added value of the multi-zone model, making it possible to consider more realistic input values at room level instead of only at building level. The multi-zone model can reduce the overestimation of the energy use by taking into account additional zonal differentiations like the higher part of the internal heat gains and the lower part of the air flows through windows occurring in the heated living area. It also enables taking into account the variation in thermal transmittance found over the whole building envelope, resulting, in the analysed cases with the heated living area on the ground floor and unheated night zone under a not insulated attic, in a reduced overestimation of the energy use.

Still, the comparisons between measured and calculated temperatures and consumption values also illustrated the remaining inaccuracies of all considered models, including the multi-zone model. The multi-zone variation of the quasi-steady state can take zonal differentiation into account, but not any quasi-steady state approach can take time differentiations into account: the fact that windows that are opened are mainly opened when the heating is off while the opposite is true for a large share of the internal heat gains (e.g. from human activity, cooking, using electric appliances etc.). Remaining errors are caused not only by the simplified heat balance equations, but also by remaining uncertainties about real user profiles (e.g. internal heat gains, position of the open windows), system efficiencies and building properties, furthermore implemented through simplified formulas (e.g. heat transfer coefficients for the slabs on grade, open windows etc.). This type of uncertainty is common when modelling buildings, especially existing ones. In fact, the level of data available for this analysis, based on in-situ measurements and surveys, largely exceeds the common level of data available in standard housing renovation projects. Nevertheless, there was still a lack of data about an important parameter influencing the indoor temperature distribution and heating demand: the opening profiles of the interior doors. While data on window opening profiles in residential buildings can be found in different studies [96,115,201–203], most studies on air flows through doors have focussed on the physical simulation of the air flow, including measurements in test cells and real buildings, however without the real presence of inhabitants

[186,187,204–208]. To further implement those studies in building simulation, additional data on related door opening profiles are needed.

6.4.2 Extrapolating findings

Representativeness versus case-study approach

The specific case-studies that were selected have influenced the findings. Considering long opening hours for the living room door was based on observation on site. The simulations showed that considering different door opening profiles can have a significant impact on the modelling results. Collecting data and performing the same analysis on highly insulated passive houses with mechanical ventilation systems with heat recovery, a central heating system and different inhabitants will probably give different observations regarding the influence of user profiles on the energy use. However, the first aim of the study was to analyse the potential of the multi-zone model for taking zonal differentiated user profiles into account and for explaining the gap between real and theoretical energy use and the variation in energy use between households that was discussed in the previous chapters. For this investigative purpose the selected case-study proved to be adequate. Also, both because of the selected building typology and because of the variation in user profiles considered by simulating about 30 houses with different inhabitants, the case-study analysis is realistic and representative of many old small houses in Belgium. The parameters related to the most important findings in this chapter also apply to many other types of houses and households: having the heated living area on the ground floor and the unheated night zone were windows are opened more often on the first floor beneath the attic etc. For the many old non insulated houses for which these characteristics apply, decision processes regarding future energy performance upgrades can benefit from a more realistic evaluation of different renovation measures as presented in this chapter using the multi-zone model.

Regulatory performance assessment models

Both the considered standard heating profiles and the correction formulas taking these profiles into account vary between countries, notwithstanding their common link with the European EBPD-regulation and the monthly quasi-steady state method from ISO 13790. These different modelling approaches result in different theoretical consumption values and in different predicted savings (both absolute and relative). Considering that only national assumptions about the heating profiles were analysed while national calculation methods differ to many other regards (e.g. regarding the considered internal heat gains, Table 6.5), assessing the energy performance of a house using different regulatory methods will result in even larger differences than those illustrated in Figure 6.7. Therefore, comparing findings on shortfall from different countries should be done with some cautiousness, especially when referring to quantitative evaluations. This difference between regulatory models is not only to be considered by researchers studying the gap between real and theoretical energy use. It should also be considered by authorities evaluating and comparing efforts made by different countries or regions using different assessment methods, e.g. in the framework of regulations by the European Commission for reaching CO2-reduction targets [15,16,39].

6.4.3 Interpreting the zonal temperature take-back and its implications

Temperature take-back: energy use vs. comfort

When interpreting the calculated temperature data, it is important to note that parts of the overestimated energy savings due to temperature take-back should not necessarily be considered as a loss of investments. Indeed, the increase in indoor temperature in the indirectly heated areas can have other benefits related to comfort and to health. The calculated temperatures in Figure 6.17 and the calculated and measured values in Figure 6.10 are average temperatures over both occupied and unoccupied periods and should thus not be compared directly with comfort temperatures. Still, the calculated temperature increase is considerable and would certainly be welcome in these houses, considering the very low temperatures measured in the sleeping areas at all periods of the day, as discussed in Chapter 3 (3.3.4, 3.4.1). Furthermore, local discomfort due to draught or radiation asymmetry is not taken into account in these models. This is important to consider when interpreting the results of e.g. the added floor insulation and the replacement of the glazing. Higher average indoor temperatures also help reducing mould problems.

Temperature take-back: at building vs. at zone level

The balance between energy savings and comfort improvements might shift even further due to additional temperature take-back. Reasons of temperature take-back are extensively discussed in scientific literature. Literature differentiates behavioural rebound from physical causes of temperature increases in houses. When speaking about behavioural rebound, the term is usually used to refer specifically to economic rebound-theory, associating higher (building) energy efficiency levels with less energy conscious behaviour and higher comfort expectations [31,67,75,96,103]. Chapter 4 showed that behavioural changes in heating profiles could be miscategorised under *economic/behavioural* rebound and actually be caused by other reasons, e.g. by different heating systems inducing other heating profiles because of their different control options and not because of their different efficiencies and associated costs. The part that can be physically explained, the physical temperature take-back, is due to the increase in average temperature as higher insulation levels level out heating intermittency and zonal differentiation [68]. This chapter shows that the physical temperature take-back should not be considered only as the increase of the *building average* temperature. A significant overestimation of the energy savings associated with the renovation of the building envelope can be caused by not considering which part of the building envelope is being retrofitted compared to which part of the building is heated. With this in mind, the combination of using single-zone models on the one hand and energy policy and market evolution on the other hand could explain, physically, an additional part of the total shortfall found on large datasets. In Belgium for example, roof insulation has been intensively promoted in the past and still now as the first, easy thing to do, because of the relatively low cost and technical complexity. As a result, strong overestimations of the energy savings can occur if these are calculated based on single-zone models, even if those models include correction factors for intermittency and partial heating (e.g. DIN 18599 and NEN 7120) and thus consider what might be called physical *building average* temperature take-back. This additional mismatch between upgraded building envelope components and the temperature distribution on the inside might explain, in combination with behavioural rebound and physical building average temperature take-back, the smaller difference between real and theoretical energy use found at high energy performance levels than at low energy performance levels, where roof insulation is more likely to occur than e.g. wall insulation [29,31,32,47].

From these perspectives, it is important to take zonal differentiations into account when defining policies and incentives for different renovation strategies, when making calculated prognoses on the resulting energy savings on building stock level and when communicating about potential energy savings to the public, who might have different expectations regarding both comfort and costs. Notwithstanding the simplification of the dynamic heat balances inherent to the monthly quasi-steady-state approach, the simplified and fast multi-zone calculation model that was described in Chapter 5 can help taking those zonal differentiations into account and cancel an important cause of bias present in the official calculation methods. However, compared to the single-zone approach, the multi-zone approach requires additional inputs, e.g. for defining all inter-zonal heat loss coefficients. The resulting extra workload for defining these parameters might create a barrier for using such multi-zone models in small scale building projects. In case of building stock analysis, statistical data on these parameters might also not be available because the commonly most important sources of information on energy related technical aspects of buildings are the databases built in the framework of the energy performance assessments, which are based on single-zone models. In response, the following chapter presents an approach for handling this practical problem by combining single-zone data on the analysed house with multi-zone data from predefined building typologies.

7

Multi-zone simulations based on single-zone data with missing inputs: the use of parametric typologies

Starting from field data, Chapters 2 and 3 showed that simplified assumptions on user behaviour and building parameters, inherent to regulatory performance assessment models or made by the EPB-assessors, can explain large part of the gap between real and theoretical energy use. Chapter 4 discussed the large variations in heating profiles found in different houses and in different rooms of a house. Chapter 6 illustrated the strong prediction biases that can result from simplifying these heating profiles in single-zone models instead of multi-zone models like the one presented in Chapter 5. Using this simplified multi-zone model proved valuable for taking user profiles more realistically into account while keeping computation times low, making it an interesting option for e.g. sensitivity analyses based on statistical building stock data. However, an important obstacle for using such model compared to single-zone EPB-models is the additional inputs it requires (e.g. on the internal partitioning of houses), which might increase the modelling workload or might not be available (e.g. on building stock level). Therefore, this Chapter 7 presents a new approach for filling in the additional inputs required by multi-zone models compared to single-zone models using predefined parametric typologies. The approach was developed in collaboration with Tiemen Strobbe from the research group SmartLab of Ghent University. Part of this work has been reported in two conference-papers that will be presented at the Building Simulation 2015 conference [209,210]. We wish to thank the Flemish Energy Agency (VEA) and Alexis Versele (BAST architects & engineers) for supplying the test data.

7.1 Introduction

7.1.1 Background

Support for policy making: reference buildings and building stock analyses

Bottom-up building stock models are valuable tools for supporting policy making. They allow making scenario analyses on evolutions of the building stock considering different uptakes of the large variation of available energy conservation measures [34,42,211–213]. These scenario analyses could be compared to the renovation scenario analysis discussed in Chapter 6, but they require considering a set of buildings and users that is more representative of the whole building stock. The same is true for studies looking for cost-optimal solutions for the support of policy making, considering not only one specific building project but the variation of buildings found e.g. on national level [16,37,214,215]. For these purposes, a set of reference buildings has to be defined to represent the heterogeneous building stock. Each reference building is considered representative for a specific subset of the whole building stock based e.g. on the type of building (e.g. single-family house, apartment buildings), the age of the building, the construction type (e.g. masonry), the number of floors etc. [36,40,216–218]. There exist different approaches for defining these reference buildings, as summarized by Ballarini et al. [36] 'Real example buildings' are real buildings that are selected by a panel of experts who consider them representative for a specific subset of the building stock. 'Real average buildings' are also real buildings, but they are selected based on statistical data instead of on expertise, comparing their characteristics with e.g. the mean geometrical and physical characteristics of their subset. 'Synthetical average buildings' also require statistical data, but for defining them and not for selecting them. These 'synthetical average buildings' are fictive buildings defined in such way that their characteristics (e.g. volume, floor area) correspond as well as possible to the mean or median of the values of the subset they will represent. Any of these three options results in a finite number of reference buildings that can be used for further simulation studies. The representativeness of the simulation results for the whole building stock will depend on the representativeness of the considered reference buildings. This in turn will depend on the variation that is included in the set of reference buildings, in part defined by the number of different considered reference buildings, and on the knowledge that was available for selecting or defining these reference buildings as accurately as possible. The accuracy of the predictions will also depend on the level of detail to which each individual reference building is defined and modelled after being selected. This level of detail will also be influenced by the availability of statistical data.

Statistical data on the building stock can be collected from different sources, like household surveys, real estate registers or other governmental databases build up in the framework of e.g. energy performance regulations [21,22,27,40,82,217,219–221]. However, the resulting databases usually do not contain enough detailed information for building complex multi-zone dynamic models. A lot of technical information required for these energy simulations can be found in the energy performance databases. By collecting data from the energy performance assessments of buildings, these databases contain geometrical data, physical data, data on the building systems etc. (see Chapter 2, [22,25,27,40,82,220]). However, as the assessment models are single-zone models, the granularity of the collected data does not give enough information to build multi-zone models of each of these documented houses. For example, little data is available about the internal subdivision of the assessed houses. As a result, many studies on building stock level are based on data at the building level and use single-zone models, identical or quasi-identical to the models used in the regulatory framework [34,36,37,40,42]. Using the same calculation method as for the individual regulatory assessments allows better prediction of official performance levels depending on different design or policy strategies. However, this approach will contain the different model simplification biases inherent to the assessment method and revealed by comparisons with real energy consumption figures [25,29,32,220] (see also Chapters 2, 3 and 6). It will thus not allow taking into account those parameters that are severely simplified or not considered in the official models, e.g. the zonal differentiation of heating profiles, of ventilation profiles, of internal heat gains and of the external building envelope. This could result in significant biases when studying reductions in energy use and costs.

While the available statistical data is usually limited to data on the whole building level and while most reference buildings are modelled at the single-zone levels, it is possible to define the reference models to a more detailed level. When using ‘real example’ or ‘real average’ buildings, the necessary data for the multi-zone simulations can be collected because these are existing buildings. For ‘synthetical buildings’, the solution resides in combining statistical data for defining the parameters at building level with knowledge and expertise for defining the internal lay-out of these fictive buildings at room level [214,222,223]. However, because of the lack of available statistical data at room level and the workload required for building each separate multi-zone model manually, it is impossible to follow these approaches for very large numbers of houses while warranting the statistical representativeness of the internal lay-outs. Furthermore, the increased computational load of these dynamic multi-zone models could also limit the number of houses or scenarios that can be simulated. Therefore, the number of geometrical variations is usually limited, limiting also the representativeness of the simulated set of multi-zone models. A balance has thus to be found when making bottom-up models for sensitivity analyses on building stock level: using more simplified calculation models that can be applied on a very large number of houses, directly using statistically representative inputs from the databases, or using more detailed multi-zone models of a more limited number of reference dwellings, with less statistically substantiated inputs regarding the multi-zone characteristics.

Decision support for individual projects

The modelling challenge is different for design teams, wanting to predict the energy use or the associated costs of one specific building or comparing different design variations. Much more detailed information is available for them to build multi-zone models of their unique final building design. However, the workload required to translate that information, e.g. from building plans, into calculation models, containing large amounts of geometrical and technical data, can still be a burden for small housing projects, especially during the design process. It is during that phase that the most important decisions defining the future energy use have to be made, while some parameters needed for performing the simulations are not yet defined and while building multi-zone calculation models of each design variation manually is rarely feasible. In response, different tools exist to automate part of this process, extracting data from the building projects designed in building information modelling (BIM) software and transferring that data to simulation software. While additional work is still required, to clean up the BIM-models or add simulation inputs, this approach takes over large parts of the extra modelling work associated with multi-zone models, e.g. measuring all areas and volumes of rooms, walls, floors etc. Parameterization of those models even allows automated approaches for comparing and improving designs, limiting the need for manual inputs. However, these BIM-based simulation approaches are only applicable for building teams using BIM-models during the building process. Many architects use more low-tech design tools. Furthermore, for small refurbishments of existing houses (e.g. replacing windows, insulating roofs) even detailed 2D-drawings of the house might be missing. In those situations, the lack of data for building multi-zone models is somewhat comparable to that encountered in building stock analyses: the less detailed information about the building (e.g. total gross volumes and areas) can relatively easily be collected, but collecting detailed data (e.g. regarding all internal walls, floors etc.) could outreach the time and budget available for the performance evaluation during the decision phase.

The calculation models used in such situations are usually also identical or quasi-identical to the ones used in the regulatory framework of for building stock analyses. Because the official, simplified tools are well known, available for free and require less inputs than more complex dynamic multi-zone models and because their use is compulsory anyway for new buildings, thorough renovation and when selling a house, using those tools for the additional purpose of a quantitative prediction of the energy use is considered a pragmatic solution. As a result, for most housing projects, only simplified single-zone models are used. Similarly as when using these models for building stock analyses and as shown in Chapter 6, this can result in considerable prediction errors regarding the energy use, leading to suboptimal decisions and thus increasing the running costs and diminishing the return on investments.

7.1.2 Study

This chapter presents and analyses a new approach that helps to create multi-zone models in the absence of detailed multi-zone data. It enables fast evaluations of the energy use in houses in the framework of building stock analyses and small housing projects, taking into account the zonal differentiations mentioned above and discussed in the previous chapter, thus resulting in predictions that will match reality more accurately and reduce the prediction gap. Similar to previous studies on building stock level, the presented approach starts from statistical data available in official EPB-databases in order to define multi-zone models of corresponding typologies. However, the approach starts from reference typologies that are implemented in parametrical BIM-models and that can be transformed to fit the available single-zone data of different real buildings. It thus allows building fictive multi-zone replacement-models in the absence of detailed multi-zone data. This process is automated in order to be applied on large numbers of houses, for building stock analyses. The approach is studied based on two datasets: (1) a large set of 15.000 houses for which only limited EPB-data is available and (2) three houses for which detailed BIM-models are available. The first dataset is used to present the general approach and the quality of the fitting process on a single-zone level. The second dataset is used to analyse the discrepancy on multi-zone level between the replacement models and original models.

7.2 The parametric typology approach

7.2.1 General concept of the parametric typology approach

Reference buildings are meant to be representative of a specific part of a building stock. Therefore, they are often defined based on statistical data on that building stock to correspond to an *average* house of the subset they represent (e.g. terraced houses with three building levels). On the opposite, this study proposes an approach based on parametric typologies that can be transformed to correspond or fit as well as possible to the limited available information on a specific house. For example, that information can be extracted from its official energy performance certificate, as illustrated in Figure 7.1. By automating this fitting process, one fictive parametric typology can be used as starting point to simulate *as many different real houses as possible* within a selected subset of an official database (Figure 7.2), thus considering not only the average of the subset but also the variation within that subset. The geometrical properties of the typologies will thus be altered parametrically to fit the distribution of the statistical data. Therefore, the parametric typologies do not need to have numerical characteristics (e.g. volume, floor area) that match as closely as possible to the average or median of their respective subset. What is more important is the 'elasticity' of the parametric typologies: the extent to which they can be transformed, stretched in different directions, enlarged, and made smaller. This requires mainly simple models, without overly complex yet realistic geometries and with well-defined rules relating the absolute or relative positions of different elements (e.g. walls, floors, windows).

All the rooms of the original parametric typology are defined in a multi-zone geometrical model before transformations are applied. By thoroughly defining fixed relationships between the different internal and external components of the building, the rooms are transformed together with the overall building geometry during the single-zone geometrical fitting process. As a result, all the fitted replacement models will also be multi-zone models and can thus be simulated in more complex ways than the original single-zone models they were fitted to. This enables analysing different heating profiles with different heating durations and set-point temperatures for each room type and asserting for typical, logical relations between different rooms in a house (e.g. regarding their relative sizes and positions). It is thus possible to run different models simultaneously, using e.g. both the official EPB-method and a multi-zone calculation method or assuming different user profiles, in order to compare results on the large variation of houses within the building stock.

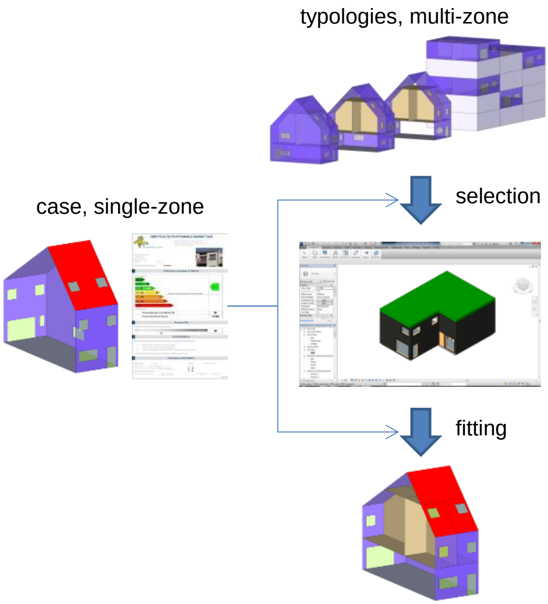

Figure 7.1: parametric typologies approach: individual case level

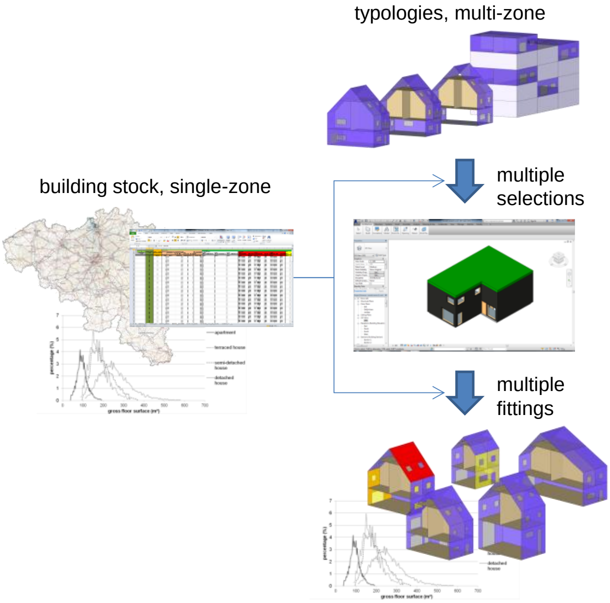

Figure 7.2: parametric typologies approach: building stock level

7.2.2 Fitting procedure

Context

The amount and the quality of the available data on the original house will define the amount of parameters the parametric typology can be fitted to and thus the level of congruency between the fitted replacement model and the original house. The fitting procedure is described in this paragraph starting from the building parameters that are available in the Flemish EPB-database. In that database, the Flemish Energy Agency (VEA) stores administrative and technical information on all houses built in Flanders (Belgium) since 2006. While it does not contain BIM-models nor all the detailed inputs used for building the energy performance assessment models (e.g. data on each wall separately), it does contain some important aggregated variables (e.g. the volume, the floor area and the heat loss area calculated based on exterior dimensions, and the average U-value) as well as important intermediate and final results of the energy performance calculations (e.g. the net, gross, final and primary energy demand for space heating) (see also 2.2.1).

Geometry

Fitting the parametric typologies to the available geometrical data of a specific house is done in different steps. Firstly, the main geometrical parameters of the building, being also important inputs for the heat-balance calculations, are fitted: the volume, the heat loss area and total floor area. For each parametric typology, a set of equations defines these aggregated geometrical parameters as a function of other basic geometrical parameters of the selected parametric typology such as the length, width and height of the building, the distance between floors, etc. As the aggregated geometrical parameters are available for each house in the database, the set of equations can be inversely solved to determine the latter parameters and assign them to the parametric typology. This will result in a transformed parametric typology with the same volume, heat loss area and floor area as the original house. The more simple the shape, the more simple the set of equations. However, a shape that is too close to a primary shape (e.g. a cube) cannot be fitted to the real variations occurring across buildings. Thus, a well-defined, realistic parametric typology is needed to be stretched and squeezed to fit to the required volumes and areas of as many houses documented in the database as possible. Subsequently, the window areas of the transformed typology are scaled to match the total window area documented in the database. Once these geometrical fitting steps have been performed, further physical properties and technical system properties can be fitted.

Physical and technical properties

The considered air permeability of the envelope, being a measured value or a default value, is reported as a function of the heat loss area (v50-value). The construction type, defining the thermal capacity of the building as a function of the volume of the building is also stored in the Flemish EPB-database. For this study it is considered that the air leakages through the building envelope and the thermal capacity of the building are distributed uniformly over the whole heat loss area and the total volume respectively. The latter values have already been fitted and the areas of all envelope components and the volumes of all rooms can be calculated based on the geometrical model of the fitted typology. Therefore, the infiltration heat losses and the thermal capacity of all rooms can be defined directly based on the recorded air permeability value and construction type. The same approach applies for the characteristics of the systems. The efficiencies of the technical systems (e.g. of heating and ventilation systems) are documented and can thus be directly copied. Because the hygienic ventilation flow rates are commonly modelled as a function of the building volumes or floor areas, the geometrical model can supply the remaining information needed for calculating the ventilation heat losses.

Regarding the transmission heat losses, the average U-value of the total building envelope (defined according to Eq.(6.19)) and the average U-value of the windows are also parameters recorded in the official database. However, separate information on the walls, the floors, the roofs etc. are missing while such differentiation can be important in a multi-zone model (see Chapter 5) and often exists in reality, with commonly thicker insulation layers in roofs compared to walls. In Flanders, the government also imposes different maximum U-values depending on the building component, with e.g. lower (better) values for roofs, and updates these requirements regularly to improve the insulation values of houses step by step [224]. In response, the following simplified approach is used. First, each separate part of the building envelope is labelled with the legally defined maximum U-value corresponding to the building period, asserting for the common differentiation between different parts of the envelope. Subsequently, all values are scaled up or down, respecting their mutual order of magnitude, in order for the average U-value of the transformed typology to fit with the average U-value of the house it has to replace

The parameters fitted until now mainly define the ventilation heat losses (infiltration and hygienic ventilation) and transmission heat losses of the building as well as the thermal capacity of the building. Additionally, the parameters influencing the heat gains must be defined. The internal heat gains in energy simulation models are commonly calculated in function of the floor area and the type of rooms. For this study however, they were defined in a simplified way, following the method of the official Flemish EPB-simulations, as a function of the volumes (see Eq.(6.16)). In both cases, the available geometrical data is sufficient to estimate the internal heat gains. However, defining the solar heat gains requires more modelling inputs.

Apart from the already fitted total window area, the orientation of the windows, their glazing fraction, the g-value of the glazing and the external shading angles from the surroundings will influence the solar gains. These characteristics can vary strongly from one window to another and require thus much more data records than the previously fitted parameters, defined on building level. While some data on individual window level is stored in the Flemish EPB-database, that data was not made available for this study. Furthermore, it seems reasonable that many building stock databases will not contain data to this level of granularity. In response, simplifying assumptions are made to define these window parameters in the replacement models. Regarding the glazing fractions and external shading angles, the simplified approach from the Flemish EPB-method is followed (see 6.2.2). In the absence of detailed values, it authorizes the use of default values. The default glazing fraction is 0.7. For the space heating calculation, the default horizontal shading angle is 25°, accounting for shading from the surrounding skyline, and no additional lateral or upper shadings are considered. Similarly as for the U-values, the g-values of the replacement models are defined based on the official requirements from that building period. No requirements exist regarding the g-value, but the maximum U-values that are imposed can, on average, be associated with certain types of glazing and thus with corresponding average g-values. For example, for new houses in Flanders, the maximum U-value for glazing was lowered from 1.6W/(m²․K) since 2006 to 1.3W/(m²․K) in 2012 and 1.1W/(m²․K) in 2014. On that basis, the corresponding average g-values are considered to be 0.65, 0.6 and 0.6, respectively. Regarding the window orientations, no EPB-data and no default EPB-approach is available. Therefore, a good design approach is considered by orienting the most glazed backyard façade of the reference typologies to the South, but without further optimization of the window sizes of the different facades. Apart from the larger glazed sliding doors of the living room, the window sizes of the bedrooms are for example not considered to be smaller on the North facing front façade.

Additional tuning

Following the described procedure, the parametric typology is fitted in an algebraically defined way to as many available parameters as possible. Once the parametric typology is fitted as described to the available single-zone data, resulting in one full replacement model for each individual case in a dataset, all houses can be simulated again using these replacement models. Because the parametric typologies are defined at the multi-zone level, the houses can now be simulated not only using the official single-zone calculation method but also using multi-zone methods. However, assumptions have to be made for some important design parameters. The accuracy of those assumptions thus influences the simulation results. In addition to the presented bottom-up fitting approach, if calculation results of the original single-zone models are available, these can be compared with the single-zone calculation results based on the fitted replacement model. This comparison can then be used to further tune the parameters that are missing in the database and thus cannot be fitted directly (e.g. the window orientations). Bayesian calibration approaches may be used to take stochastic parameters into account, as illustrated in calibration processes on building simulation models [168,173]. However, the results presented in this study were obtained without any additional result-driven, top-down tuning and the analysis will focus on the accuracy of the original bottom-up fitting approach.

7.2.3 Practical implementation

The multi-zone geometrical model of each transformed typology is described in a platform neutral and open data scheme that can be generated by most BIM-software: the green building extensible mark-up language (gbXML). For this project, the BIM-models of the reference typologies were created in Autodesk Revit Architecture. A Revit add-in was developed to collect the parametrical inputs (e.g. parameters the model has to be fitted to), transform the base-models of the parametric typologies and generate the gbXML-files. Subsequently, these gbXML-files are used to build the different single-zone and multi-zone models. These simulation models can be generated and calculated directly using that same add-in or afterwards, using a separate standalone application. To do so, the data is processed and passed on to a calculation kernel. That calculation kernel was already briefly mentioned in Chapter 5 (section 5.4). It contains both the official single-zone quasi-steady state calculation method used in Flanders [80] and based on ISO 13790 [20] (with the option of using the correction formulas and heating profiles from DIN 18599 [176] or NEN 7120 [78], see 5.2.2) as well as the multi-zone quasi-steady state algorithm discussed in Chapter 5 (see 5.3.2). While less detailed than many dynamic simulation algorithms, this multi-zone algorithm allows taking into account different intermittent heating profiles in coupled zones (see Chapter 6) while keeping the calculation times very low (see 5.4) in order to run simulations on very large databases. Furthermore, it requires less data than dynamic models, e.g. regarding the exact layering of walls, thus making it more suited for situations with little available data. The tool, including the calculation kernel, was programmed in .NET (VB.NET and C#) and reads the additional inputs from an Excel-template which is also used to report the outputs of the simulations. It can thus run on any Windows-computer. Creating the geometrically fitted typologies starting from the reference-model takes the most amount of computer time: on average approximately 3 seconds per case on a standard personal computer, depending on the complexity of the geometry. Once the building geometries have been generated, varying the heating profiles, physical properties (e.g. U-values), orientations, and glazing areas, subsequently running the multi-zone simulations and exporting the results takes on average less than 0.3 seconds per case (approximately 5 minutes to run simulations on 1000 cases or variations). These reduced calculation times and the automation of the process enable sensitivity analyses on large sets of buildings.

7.3 Evaluation methodology: from single-zone to multi-zone and from case-study houses to building stock simulation

This parametric typology approach is illustrated and analysed using two datasets. These complementary datasets allow respectively (1) to analyse the accuracy of the fitting on a single-zone building-level and the value of the approach for use on building stock level, and (2) to analyse the errors caused by the use of a fitted replacement multi-zone model instead of an original multi-zone model of the real house. The same three parametric typologies are used for all analyses (left side of Figure 7.3): a detached (Figure 7.4), a semi-detached (Figure 7.5) and a terraced (Figure 7.6) single-family house. All three parametric typologies follow a common internal lay-out principle consisting of the living areas being on the ground floor and three bedrooms and a bathroom on the first floor.

7.3.1 EPB-database: single-zone data on building stock level

The first dataset is extracted from the Flemish EPB-database (see section 2.2 and 7.2.2). Because it is impossible to start from one single reference building and fit it to all houses within the database, the available dataset was subdivided in clusters based firstly on the building type (apartment, detached, semi-detached and terraced houses). Several options exist for further subdivision, with e.g. the number of floors being an obvious option [36]. However, the number of floors of a house is not reported in the EPB-assessments and thus not available as selection criterion in the Flemish EPB-database. As an alternative, the dataset was further subdivided based on the number of bedrooms of each house (Table 7.1). The approach is illustrated based on the three largest clusters amongst the single-family houses, representing together 63% of them: the detached, semi-detached and terraced single family houses with three bedrooms. For each of these typological clusters, a set of 5000 cases was randomly selected from the full population of the database. Herewith, it can be analysed to what extent one single parametric typology can be used to fit a dataset of 5000 real houses, all part of the same cluster, however all having different shapes, sizes and technical characteristics. The most important characteristics of these 15.000 three-bedroom houses are summarized in Table 7.2 (detached), Table 7.3 (semi-detached) and Table 7.4 (terraced). Distributions of these parameters will be compared n the results section with the values of the fitted typologies.

Because there are no precise multi-zone models available for these houses, the accuracy of the fit can only be tested at the level of the single-zone model. Before analysing the results from the multi-zone calculations on the fitted replacement-models, the accuracy of this fitting procedure towards the single-zone EPB-data has to be assessed. Therefore, the first target of the presented approach, is to come as close as possible to the calculated parameters of each house stored in this database. The geometrical fit (e.g. volumes and areas) and the fit regarding intermediate technical properties (e.g. average U-values) is analysed before comparing the results of the single-zone simulations. The latter will be affected by missing inputs (e.g. regarding the variation in window orientation) and by using a limited number of parametric typologies, possibly resulting in some bias regarding those missing values.

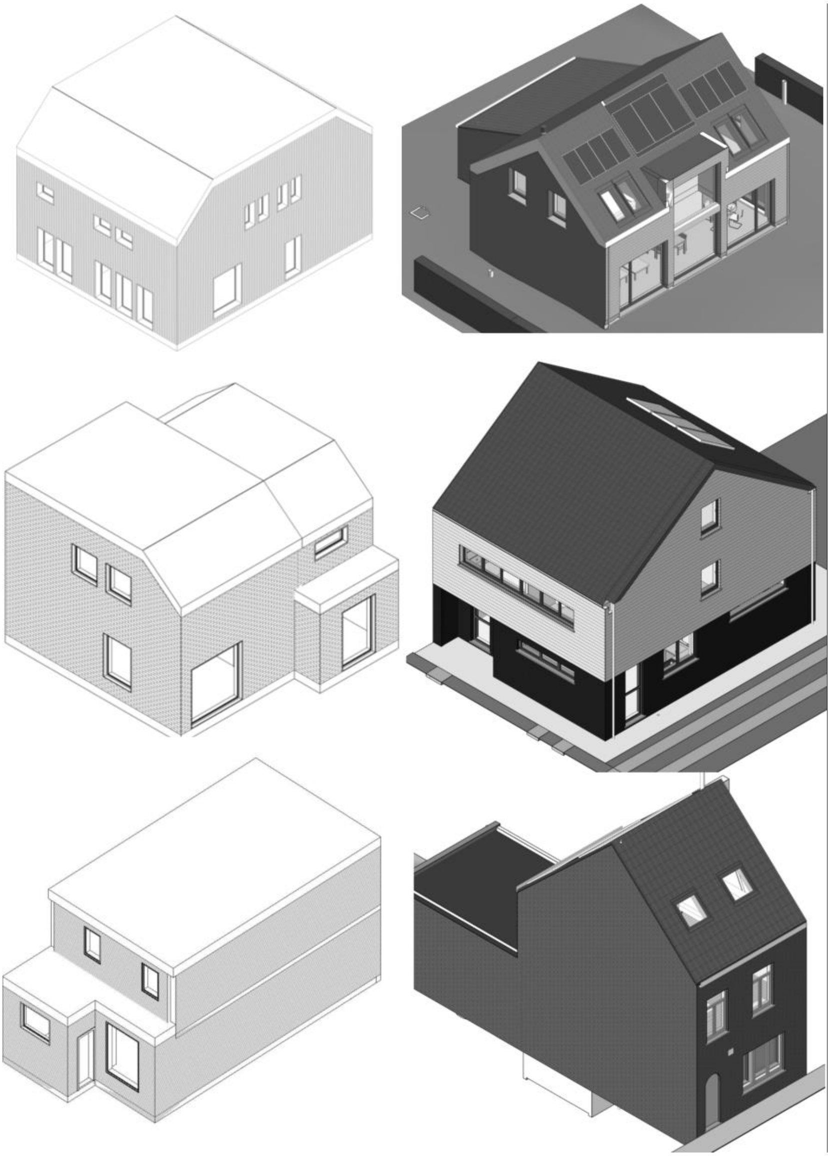

Figure 7.3: parametric typologies (left) and case-studies (right, copyright: BAST-architects & engineers), from top to bottom: detached, semi-detached and terraced

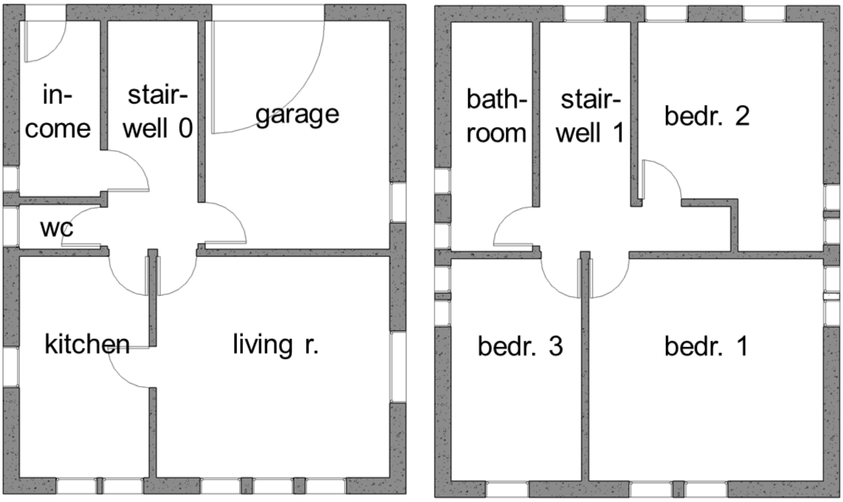

Figure 7.4: detached parametric typology

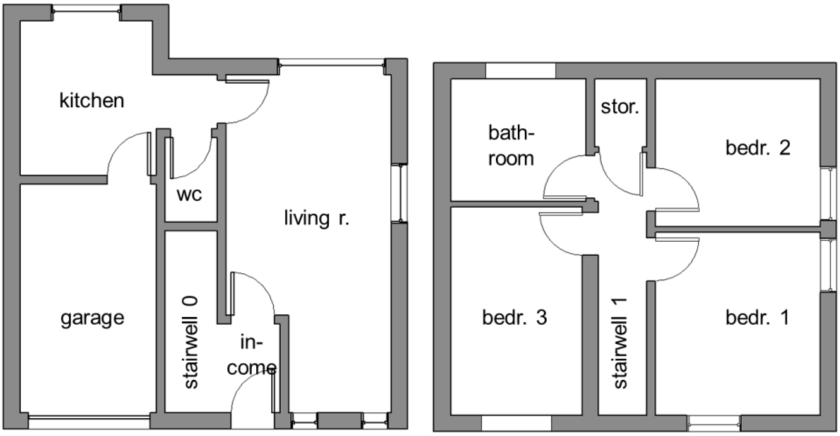

Figure 7.5: semi-detached parametric typology (left: ground floor, right: 1st floor)

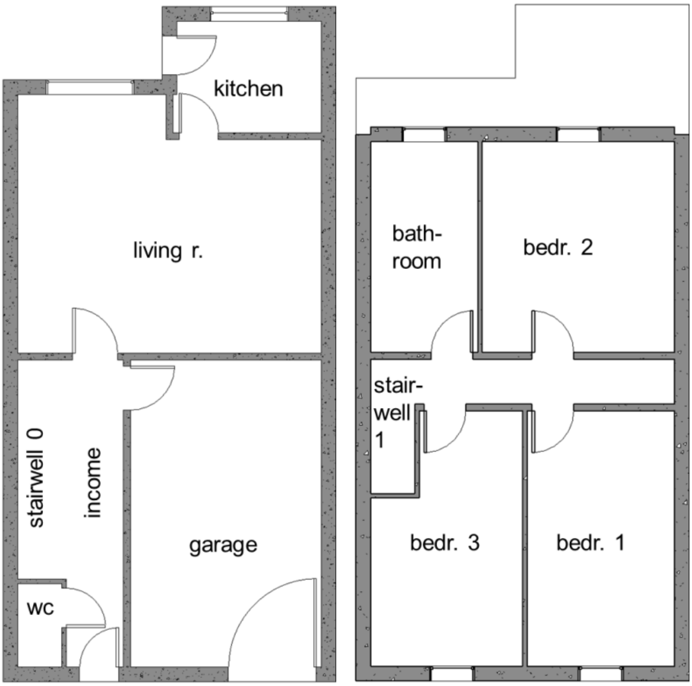

Figure 7.6: terraced parametric typology (left: ground floor, right: 1st floor)

Table 7.1: Clustering of the available EPB-dataset: new single-family houses

	number of bedrooms (N=53408)				
	1	2	3	4	5
detached	1.3%	4.9%	24.7%	11.9%	2.0%
semi-detached	0.7%	4.8%	27.5%	5.2%	0.7%
terraced	0.4%	2.5%	10.9%	2.4%	0.2%

Table 7.2: Characteristics of the sample of 5000 detached houses with 3 bedrooms

		Av.	1%	Mdn.	99%
floor area	[m²]	245	104	235	470
volume	[m³]	787	375	760	1519
heat loss area	[m²]	565	316	552	957
window area	[m²]	44	17	40	107
compactness	[m]	1.38	0.99	1.37	1.85
Um	[W/(m².K)]	0.42	0.23	0.42	0.54
net sp. heating	[kWh/(m².yr)]	79	17	76	175
final sp. heating	[kWh/(m².yr)]	96	19	92	215

Table 7.3: Characteristics of the sample of 5000 semi-detached houses with 3 bedrooms

		Av.	1%	Mdn.	99%
floor area	[m²]	193	83	178	349
volume	[m³]	596	330	570	1115
heat loss area	[m²]	382	239	365	668
window area	[m²]	30	15	28	67
compactness	[m]	1.56	1.10	1.54	2.11
Um	[W/(m².K)]	0.44	0.28	0.45	0.55
net sp. heating	[kWh/(m².yr)]	79	24	78	179
final sp. heating	[kWh/(m².yr)]	97	25	97	225

Table 7.4: Characteristics of the sample of 5000 terraced houses with 3 bedrooms

		Av.	1%	Mdn.	99%
floor area	[m²]	170	81	162	310
volume	[m³]	542	302	517	967
heat loss area	[m²]	293	159	279	545
window area	[m²]	24	12	22	58
compactness	[m]	1.87	1.25	1.86	2.68
Um	[W/(m².K)]	0.45	0.31	0.45	0.59
net sp. heating	[kWh/(m².yr)]	67	25	66	156
final sp. heating	[kWh/(m².yr)]	84	29	82	222

7.3.2 Detailed case-studies: as built multi-zone data

Real, original building designs

Because a good fit on single-zone level does not guarantee a good fit on multi-zone level, the approach is further tested on three real case-study houses. Again, a detached house (Figure 7.7), a semi-detached house (Figure 7.8) and a terraced house (Figure 7.9) are analysed (right side of Figure 7.3). The as built BIM-models (Revit-files) were supplied by the architects, to whom it was asked to select some houses, without further specifications. However, limited changes to the Revit files were needed for the simulation tool to process the models. Firstly, some complex joints between walls or between walls and roofs were cleaned up in the Revit-model or simplified to avoid junction-errors when generating the gbXML-model. Secondly, large openings between e.g. an open kitchen and the living room or stair well were closed using partition walls and doors, to have distinct room types and because, in its current development stage, the tool does not yet process large air openings defined in the gbXML-models and it thus cannot yet feed the data required for modelling these large air openings to the calculation kernel. No other changes were applied to the shape or the internal lay-out of the building. Still, two important modelling assumptions were made. The real semi-detached case-study house had a large attic. For this study, that attic was defined as an adjacent unheated attic outside the building envelope. The real detached house had only two bedrooms, but it had a workspace on the first floor that is connected with the living room. Therefore, one of the three bedrooms of the detached typology (bedroom 3, Figure 7.4) was considered to be used as an office room, with the same heating profile as the living room. This way, considering still also the differences in shape and size between the original houses and their respective unfitted typologies, they are appropriate for performing initial tests on the approach that are presented in the following paragraphs and that focus on errors caused by different geometries and internal lay-outs when considering the same user profiles.

Figure 7.7: detached case-study, adapted for simulation (with added partition walls and doors between the living area and the originally open kitchen) (copyright: BAST-architects & engineers)

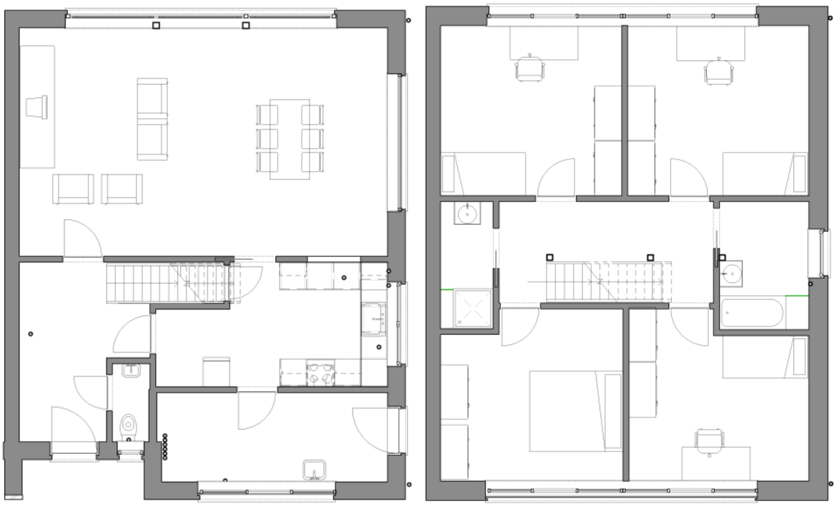

Figure 7.8: semi-detached case-study (left: ground floor, right: 1st floor) (copyright: BAST-architects & engineers)

Figure 7.9: terraced case-study , adapted for simulation (with added partition walls and doors between the originally open kitchen and the living area and stair well) (top: ground floor and 1st floor, bottom: 2nd floor) (copyright: BAST-architects & engineers)

Scenario-analysis on the original building designs

The importance of using multi-zone instead of single-zone data and models depends on the heating profiles and on the thermal performance of the house. Indeed, a better insulation level of the exterior envelope and a higher thermal time constant will result in lower temperature differences between rooms and in reduced temperature drops during night-time heating set-back (see section 6.3). The simulation error caused by using a fitted replacement model showing geometrical differences compared to the original multi-zone model will thus also depend on the considered thermal characteristics and user profiles. Therefore, different levels of insulation and different ventilation systems are considered as well as two different construction types: light weight timber frame construction and semi-heavy masonry construction. Following the Flemish EPB-assessment framework, these construction classes correspond to 27 kJ/K and 117 kJ/K per cubic meter of building volume, respectively. The simulated insulation levels (Table 7.5) range from that of old, uninsulated houses, via houses with only added roof insulation and via the different minimal insulation levels that have been imposed in Flanders since 2006, ending up with the minimal insulation levels recommended for passive houses in Belgium. Table 7.5 and Figure 7.10 summarize for the three different case-study houses the average U-values that result from the U-values that were defined at the level of the envelope component. Together with the U-values, the air permeability of the exterior envelope is also considered to have improved during the years (see 2.3.2, 3.3.1, and [25,90]), starting from the default air permeability defined in the Flemish EPB-framework (v50=12 $m^3/(h.m^2)$) and ending with a value below 1 for the passive house scenario (Table 7.5). Apart from varying the properties of the external building envelope, two different levels of insulation are considered for the interior walls, the interior floors and the interior doors: 2W/(m^2.K), 1.75W/(m^2.K) and 2.5W/(m^2.K) in the worst case and 0.9W/(m^2.K), 0.5W/(m^2.K) and 2W/(m^2.K) in the best case, respectively. Additionally, the performance of the considered ventilation system is considered to evolve together with the envelope performance levels from the most basic ventilation system without demand control or heat recovery, via a demand-controlled exhaust ventilation system to a balanced system with heat recovery (Table 7.5).

As opposed to the simulations from Chapter 6, the ventilation flow rates and the internal heat gains are calculated according to the Flemish EPB-method (see 6.2.2, Eq.(6.7) and Eq.(6.16)) and the calculated values are distributed over all rooms based on their volume, thus without more realistic assumptions regarding these user related parameters. However, the heating set-point temperatures and daily heating hours were varied depending on the type of room (Table 7.6). Making different combinations between these heating profiles at room level, 8 different heating profiles at building level were included in the scenario analysis (Table 7.7). This set of clearly different but realistic heating profiles at building level was defined based on the findings from Chapter 4 (clustering of room types, heating hours and relative differences in set-point temperatures between room types). These heating profiles cannot be considered to be statistically representative for some specific types of households or for an entire building stock and its inhabitants. Statistical representativeness would be a major concern for building stock analysis, aiming at simulating realistic scenarios e.g. for policy support. However, the three case-study houses were selected for a first exploratory analysis on both the possible biases caused by the parametric typology approach and the causes of those biases. Making all possible combinations between the exterior insulation levels, the two construction types, the internal insulation levels and the heating profiles, 320 different scenarios were thus defined and simulated for each case-study and its respective fitted typology. The resulting net space heating demands lay within the ranges of 24 to 492 kWh/(m^2.yr), 17 to 378 kWh/(m^2.yr) and 18 to 394 kWh/(m^2.yr) for the detached, semi-detached and terraced cases, respectively (Figure 7.11). The higher space heating demand of the terraced house compared to the semi-detached house, notwithstanding the former's lower average U-value, are caused by its protruding living area at the back of the house compared to the more compact shape of the semi-detached house.

Differences with the default fitting procedure

Because of this scenario approach, the fitting procedure on these three case-studies differs from the fitting procedure on the 15.000 houses from the EPB-databases. For those 15.000 houses, the fitting procedure was performed exactly as described in section 7.2.2. The first difference for these three case-study houses, is the initial assumption regarding the U-values, the g-values, the glazing fractions of the windows and the external shading angles. For both the original model and the replacement model, the same g-values were used and the default glazing fractions and shading angles were considered. Before scaling up or down all U-values of the geometrically fitted typology to match the average U-value of the original house, exactly the same U-values were considered on component level for both the original house and the fitted typology. The last difference regards the window orientation. The replacement model was put to the same orientation as the original building. This does not mean all glazing areas are spread correctly to the different orientations, but the orientation of the most glazed backyard façade was the same for both the original and the replacement model.

These differences to the original fitting procedure will improve the fit on the calculated results. These choices were motivated by two reasons. First, while the analysis on the 15.000 houses from the EPB-database focusses on the errors on single-zone level resulting from the standard fitting procedure and the data missing in the EPB-database, the additional study on the three case-study houses aims at analysing foremost the *additional* errors on multi-zone level caused by using the internal building lay-out and the building shape of a parametric typology that differs from the original house. Secondly, these additional assumptions are very realistic for the application of the parametric approach in the framework of small scale housing projects as opposed to building stock analyses. In such context, it would require negligible effort from the design team to supply this additional information (e.g. the main building orientation). In fact, it would probably be easier to supply the average U-values per type of components (e.g. walls, roofs, windows) than the building average U-value.

These assumptions regarding the U-values of the components would need to be made for any calculation model anyway, also for a simple single-zone model thus for the official energy performance assessment.

Table 7.5: Sets of insulation measures and resulting average U-values for the three case-study houses. (Ventilation systems: A=natural exhaust & supply, C=mechanical exhaust & natural supply, D+HR=balanced with heat recovery unit with a test effectivity of 0.8, dem.1 and dem.2=demand controlled with correction factors of 0.75 and 0.5 respectively)

		1950*	**+ roof insu-lation***	**pragmatic reno-vation***	**2006**	**2010**	**2012**	**2014**	**2015**	**2016**	**PH***
INPUT											
roof	U [W/(m^2.K)]	2.00	0.35	0.35	0.40	0.30	0.27	0.24	0.24	0.24	0.15
wall	U [W/(m^2.K)]	1.30	1.30	0.50	0.60	0.40	0.32	0.24	0.24	0.24	0.15
floor	U [W/(m^2.K)]	0.67	0.67	0.67	0.40	0.40	0.35	0.30	0.30	0.24	0.15
door/gate/ window	U [W/(m^2.K)]	5.00	5.00	1.80	2.50	2.50	2.20	1.80	1.80	1.50	0.80
glazing	U [W/(m^2.K)]	(5.6)	(5.6)	(1.10)	(1.60)	(1.60)	(1.30)	(1.10)	(1.10)	(1.10)	(0.80)
	g [-] *	0.85	0.85	0.60	0.65	0.65	0.6	0.6	0.6	0.6	0.55
air permeability	v50 [m/h]*	12.00	10.50	9.00	9	9	6	6	6	3	(n50= 0.6/h)
ventilation system	(type)*	A	A	C	C	C	C dem.1	C dem.1	C dem.2	D+HR	D+HR
OUTPUT											
detached case	Uav. [W/(m^2.K)]	2.00	1.58	0.73	0.84	0.75	0.65	0.53	0.53	0.46	0.26
semi-detached	Uav. [W/(m^2.K)]	1.85	1.41	0.69	0.76	0.67	0.58	0.48	0.48	0.42	0.24
terraced case	Uav. [W/(m^2.K)]	1.59	1.19	0.59	0.64	0.52	0.44	0.36	0.36	0.33	0.19

*No compulsory values. Values selected for this study.

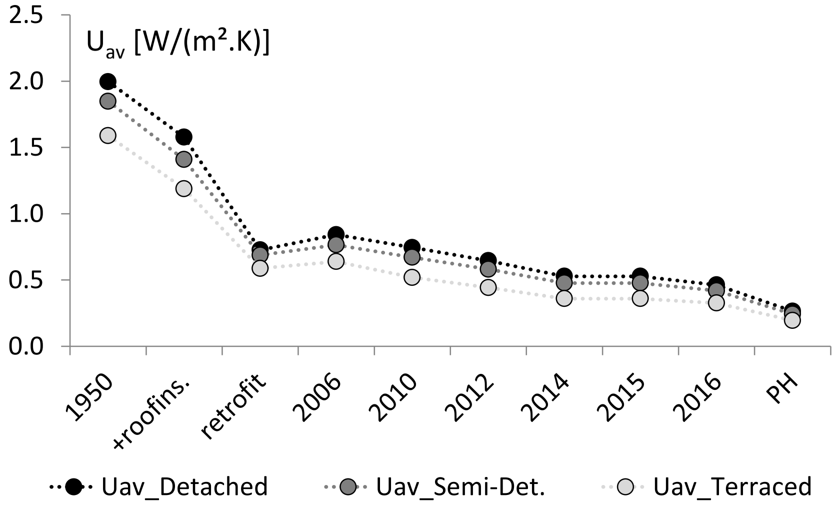

Figure 7.10: average U-values: scenario-analysis on the multi-zone models of the three original houses

Table 7.6: Ranges of heating set points and heating times included in the heating profiles (in addition to the two fixed heating profiles of 21°C and 18°C for 24h/day for all rooms)

	Tset,heat [°C]	theat [h]	Tsetback [°C]
living & kitchen	21/19	24/14/5	12/14
bedroom	15/12/(-)	24/5/2/(-)	0
bathroom	22/21	24/24/5/2/1	0
circulation & toilet	17/12/(-)	=living/(-)	0
garage & storage	8/(-)	24/(-)	0

NOTE: possible settings other than all for 24h/day at 18°C or 21°C

Table 7.7: heating profiles used for the analysis on the three case-study houses (fixed low protective set-point temperatures, below comfort levels, are indicated as set back temperatures)

	0			**1**		
	Tset,heat [°C]	theat [h]	Tsetback [°C]	Tset,heat [°C]	theat [h]	Tsetback [°C]
living & kitchen	21	24	(-)	21	24	(-)
bedroom	21	24	(-)	17	24	(-)
bathroom	21	24	(-)	22	2	20
circulation & toilet	21	24	(-)	17	24	(-)
garage	21	24	(-)	(-)	(-)	8

	2			**3**		
	Tset,heat [°C]	theat [h]	Tsetback [°C]	Tset,heat [°C]	theat [h]	Tsetback [°C]
living & kitchen	21	14.5	14	21	5	14
bedroom	17	2	14	17	5	14
bathroom	22	14.5	14	22	5	14
circulation & toilet	17	14.5	14	17	5	14
garage	(-)	(-)	8	(-)	(-)	(-)

	4			**5**		
	Tset,heat [°C]	theat [h]	Tsetback [°C]	Tset,heat [°C]	theat [h]	Tsetback [°C]
living & kitchen	19	5	12	21	14.5	14
bedroom	15	5	12	(-)	(-)	12
bathroom	20	5	12	22	1	12
circulation & toilet	15	5	12	(-)	(-)	12
garage	(-)	(-)	(-)	(-)	(-)	(-)

	6			**7**		
	Tset,heat [°C]	theat [h]	Tsetback [°C]	Tset,heat [°C]	theat [h]	Tsetback [°C]
living & kitchen	21	5	14	18	24	(-)
bedroom	(-)	(-)	12	18	24	(-)
bathroom	22	1	12	18	24	(-)
circulation & toilet	(-)	(-)	12	18	24	(-)
garage	(-)	(-)	(-)	18	24	(-)

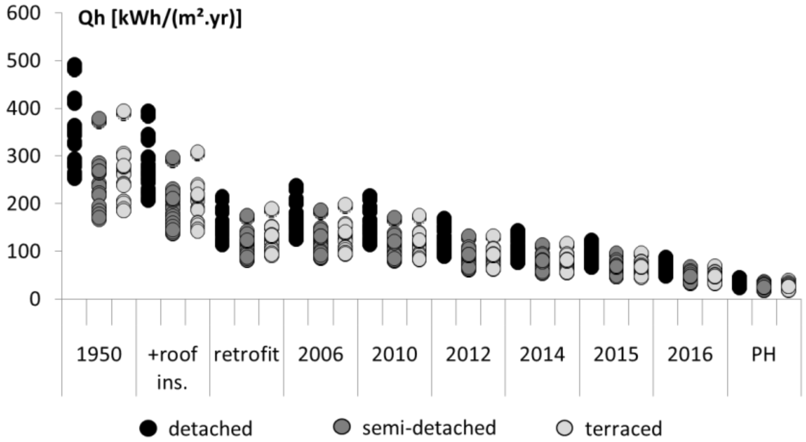

Figure 7.11: net space heating demand per floor area: scenario-analysis on the multi-zone models of the three original houses

7.3.3 Using multi-zone models for building stock analyses

Building further on both previous described analyses, one last analysis illustrates the additional value of the multi-zone replacement models for building stock analyses. The set of 5000 detached houses from the EPB-database are selected as a test-set, however this time in combination with the multi-zone calculation model used previously on the three case-study houses. The analysis compares the predicted energy savings according to the single-zone models with the more nuanced estimates that can be made using the multi-zone models. The evaluated energy savings are those resulting from roof insulation, the current standard set of building measures ('2015') and the passive house set of measures ('PH') from Table 7.5 compared to the situation with no insulation ('1950'). All other characteristics of the buildings are defined in the same way as for the single-zone analysis described in 7.3.1, thus following the fitting procedure explained in 7.2.2. The calculated energy savings are expressed in absolute and in relative values to account for offsets between the models that were discussed separately in Chapter 6.

First, the reduction of the net space heating demand is analysed without considering any changes in heating profiles and thus considering only the additional physical temperature take-back that is taken into account in the multi-zone model and the non-uniform distribution of thermal insulation and heating profiles across the houses (see Chapter 6). For this analysis the living areas are heated to 21°C for 14.5 hours per day and the bathrooms to 22°C, while the other rooms are only kept from cooling down below 12°C (heating profile '5', Table 7.7). Subsequently, the reduction of the final space heating demand is analysed, including a shift in user behaviour. For this analysis, the heating system is considered to be improved together with the thermal performance of the building envelope (Table 7.8). For the base scenario ('1950'), a gas furnace is considered, similarly to the old neighbourhood analysed in Chapters 3 and 6. It is replaced in the improved building scenarios with a centralized heating system with a central thermostat and a condensing gas boiler, similarly to the new neighbourhood analysed in Chapter 3 and the high performance houses analysed in detail in section 2.3.2. Following the reduction of the net space heating demand, the return water temperature is also considered to be lower when shifting to better insulation levels, resulting in higher system efficiencies calculated following the Flemish EPB-method [80] (Table 7.8). Thus considerable improvements of the building and system performance are considered. However, following these improvements and based on the findings discussed in Chapters 2, 3 and 4, realistic shifts in heating profiles (heating more rooms and for longer hours) are also considered as a result of behavioural rebound associated with the better building performance levels (referring to economic rebound-theory), with the centralized control system and with shifts to lower temperature systems. For the scenario without insulation, the same heating profile is used as in the previous analysis that did not consider changes in user profiles (heating profile '5', Table 7.7), being with 14.5 hours of heating in the living room and only 1 hour in the bathroom similar to the heating profiles found in the old neighbourhood discussed in Chapter 3 ('cs1') where someone was present during the day. For the renovated scenario and the current standard performance scenario ('2015'), both with a central heating system, the radiators in the bedrooms are used two hours a day to heat these rooms to 17°C while the valves of the radiators in the bathroom and in the circulation areas are left open all the time, thus following the schedule of the central thermostat (14.5 hours per day), however with a lower set point temperature of 17°C for the circulation area (heating profile '2',

Table 7.7). This is a realistic scenario for new houses with a central heating system and someone at home during the day (see Chapters 3 and 4, Figure 4.19). For the passive house scenario with a very low temperature heating system, the same set point temperatures are considered, however without set back periods (heating profile '1', Table 7.7, see also Figure 4.20).

Table 7.8: scenario analysis: total system efficiencies compared to the lower (LCV) and upper (UCV) combustion values (detailed information on insulation levels and heating profiles: Table 7.5 and Table 7.7)

insulation level	space heating system				heating profile
	type	return water temperature	efficiency		
			LCV	UCV	
1950	gas stove	(-)	83%	75%	6
roof ins.	(condensing) boiler	70°C	94%	84%	3
2015	condensing boiler	45°C	99%	89%	3
PH	condensing boiler	32°C	100%	90%	1

7.4 Results

7.4.1 EPB-database: single-zone verification

Fitting parameters: volume, heat loss area, floor area, average U-value

For each separate case in the database, the geometrical fitting procedure is based on solving a set of equations describing the geometry of the parametric typology and using exact input values from the original case. For some cases however, because of the limited elasticity of the parametric models, the set of equations has no realistic solution. Indeed, the elasticity of the model is limited to avoid e.g. overlaps between different building components or unrealistic floor heights when making the building smaller. As a result, the detached, semidetached and terraced typologies proved to be useable only on 73%, 66% and 74% of their respective dataset of 5000 houses, resulting in a total of 10626 replacement models.

Illustratively for the detached houses, the following figures in this section compare the cumulative distributions of different parameters between firstly the total original dataset (5000 cases, *'stat, total'*), secondly the selection from the same original dataset of only those cases for which the parametric typologies were useable (thus 73% of the 5000 cases, *'stat, filtered'*) and thirdly the parametric typologies after being fitted to those cases (thus also 73% of the 5000, but including possible fitting errors, *'fitted'*). Errors on the level of the individual cases could be hidden in the cumulative distribution of the parameters if these errors occur to the same extent both in positive and negative way. Therefore, the figures also include the cumulative distribution of the fitting errors ('fitted' compared to 'stat, filtered'), showing both the errors in their original unit (e.g. m^2 of floor area, *'Δ_abs'*) and the relative errors compared to the values of corresponding original EPB-models (*'Δ_%'*). The match between the values from the fitted typologies and their respective original cases is nearly perfect regarding the floor area (*Figure* 7.12), the external volume (Figure 7.13), the heat loss area (*Figure* 7.14), the resulting compactness (i.e. the heat loss area divided by the volume, Figure 7.15), the window area (Figure 7.16) and the building average U-value (Figure 7.17). 98% of the fitted cases had a relative error in the range [-2%, +2%] for all these parameters and, except for the building volume and the derived compactness, all cases had a relative error in the range [-1%, +1%]. Similar values were obtained for the semi-detached and terraced houses. These small residual errors occur notwithstanding the algebraic fitting procedure. They are caused by rounding errors and the difficulty of taking into account the exact location of the reference planes of the different Revit components (e.g. walls, roofs, floors) defining the dimensions of the exported gbXML-model.

The large ranges of areas and volumes that were obtained starting from a single parametric typology illustrate the large scalability of the typology compared to the real variations found in the database. However, the compactness values shown in Figure 7.15 also illustrate that the initial shape of the typology limits the number of *combinations* of volume, floor area and heat loss area it can achieve, thus failing in matching the most extreme cases.

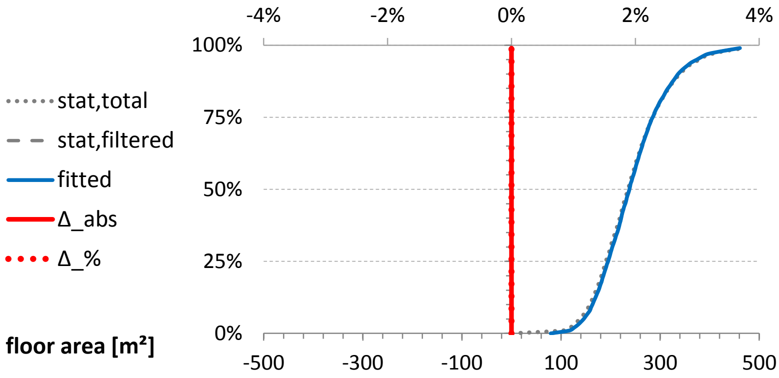

Figure 7.12: accuracy of the geometrical fitting, detached house, gross floor area

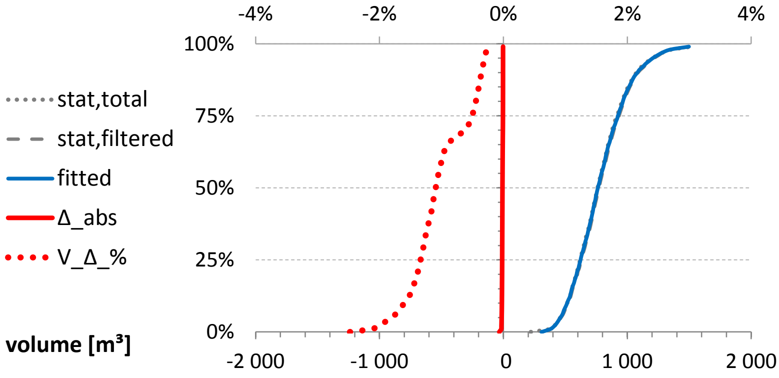

Figure 7.13: accuracy of the geometrical fitting, detached house, external volume

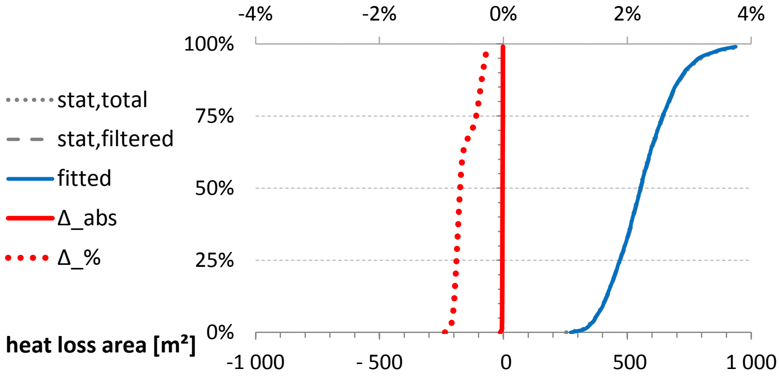

Figure 7.14: accuracy of the geometrical fitting, detached house, heat loss area

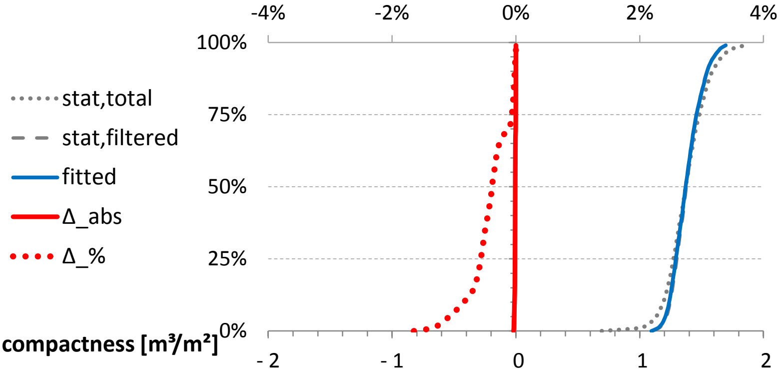

Figure 7.15: accuracy of the geometrical fitting, detached house, compactness

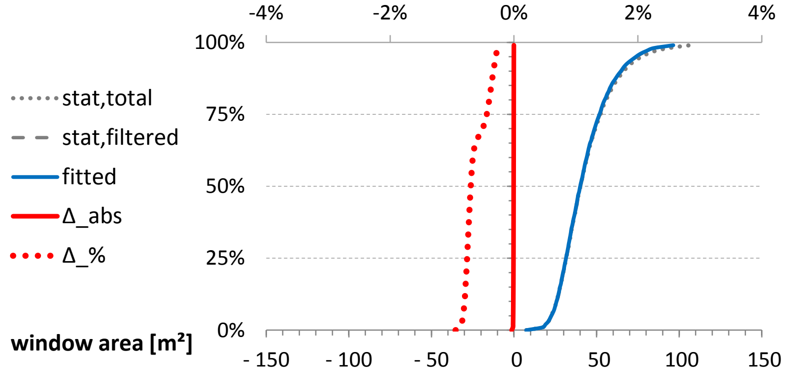

Figure 7.16: accuracy of the geometrical fitting, detached house, window area

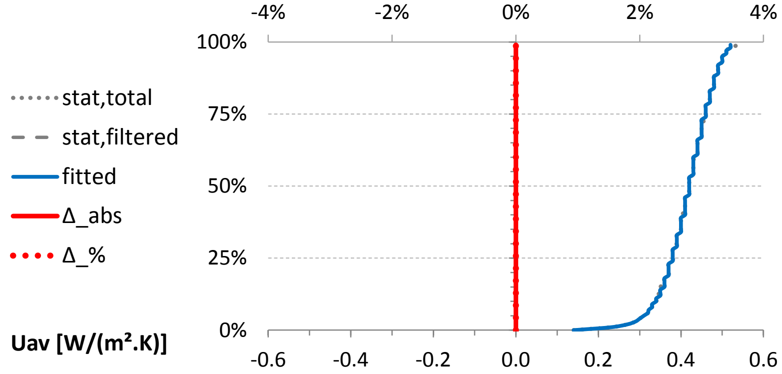

Figure 7.17: accuracy of the geometrical fitting, detached house, average U-value

Single-zone simulation results: verification

Comparing the distributions of the calculated net space heating demand, there is again a very good match between the results from the set of fitted models (*'fitted'*) and the results from the set of cases they were fitted to *('stat, filtered'*). In fact, both cumulative distribution lines cannot be distinguished in the charts of the detached (Figure 7.18), the semi-detached (Figure 7.19) and the terraced houses (Figure 7.20). Because not all the houses could be fitted geometrically, only a small difference exists, at the extremes of the distributions, with the distributions of the officially reported space heating demands of all 15.000 houses (*'stat,total'*). However, comparing the calculated space heating demand from each fitted model individually with the result from the corresponding original EPB-model reveals larger relative errors at case level (*'Δ_%'*) compared to the errors at case level found on the geometrical parameters. Still, compared to their respective original models, 95% of all replacement models differed by less than 6.7 kWh/(m².year) compared to their space heating demand recorded in the database and 75% differed by less than 2.6 kWh/(m².year). Expressed as relative errors, 95% of the replacement models had an error smaller than 11% and for 75% of the cases the relative error was below 4%.

These errors on the individual case level are not caused by the lack of fit for the geometrical parameters, as shown in Figure 7.21, Figure 7.22 and Figure 7.23 for the detached, the semi-detached and the terraced houses. The errors are also not caused by inaccuracies regarding the ventilation systems, because the exact performance values of the ventilation systems were available in the database (effectivities of heat recovery systems and reduction factors for demand controlled systems and the air tightness of the system components). The lack of fit can be explained by the only data that was missing for defining the single-zone heat balance equations, namely data required for calculating the solar gains: the real glazing fractions, window orientations, g-values and considered external shading angles. This is illustrated for the detached houses by Figure 7.24, showing the error of the calculated space heating demands according to the replacement models as a function of the U-value of the windows divided by the window fraction (U_w/f_w). These are the only two window-related parameters that were available in the studied dataset from the EPB-database. It shows that, the larger the window fraction and the better the thermal performance of the windows, the larger the possible error of the replacement model. Larger window fractions result in larger solar heat gains and thus in larger errors on the heating demand caused by wrong assumptions regarding the glazing fraction, the g-value, the orientation and the shading angles. Furthermore, the larger window fractions and better U-values indicate larger investments and efforts for reaching better performance levels. This was found to be associated with a higher use by the EPB-assessor of detailed input values instead of default values (Chapter 2, [25]) and can thus further explain the uncertainty caused by the replacement model. Because large and high performance windows are associated with lower heating demands (e.g. passive houses), U_w/f_w is even more associated with the extreme *relative* errors of the replacement model (Figure 7.25).

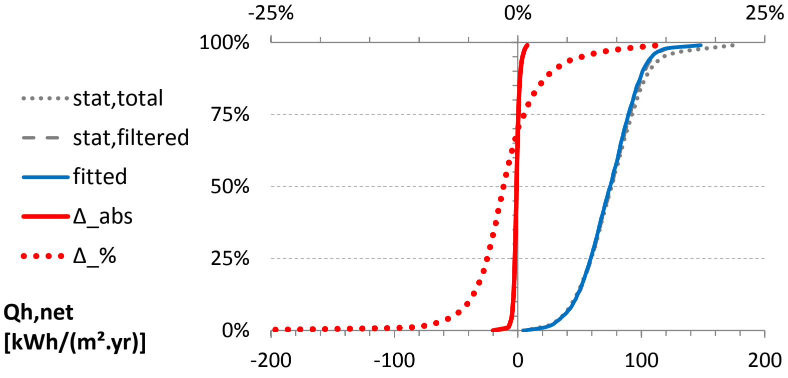

Figure 7.18: accuracy of the fitting, <u>detached</u> house, net space heating demand

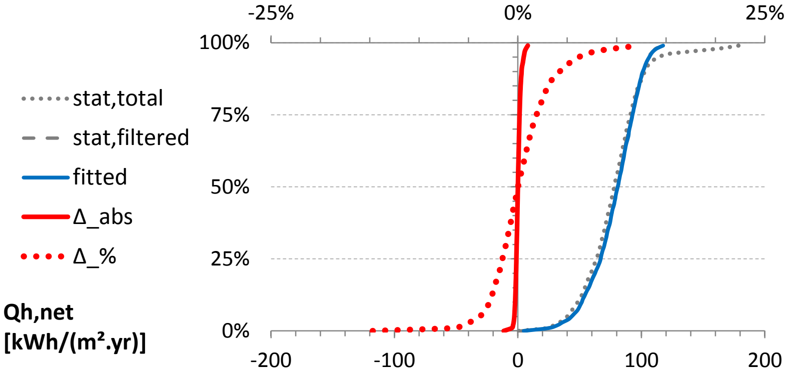

Figure 7.19: accuracy of the fitting, <u>semi-detached</u> house, net space heating demand

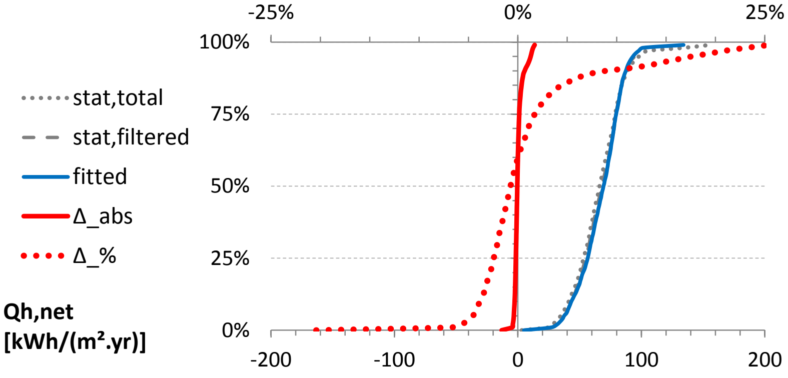

Figure 7.20: accuracy of the fitting, <u>terraced</u> house, net space heating demand

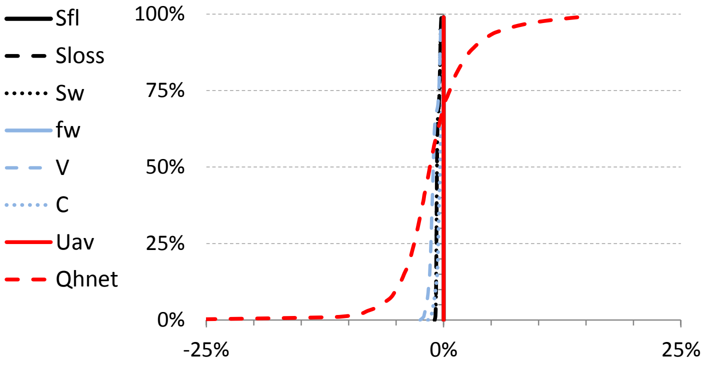

Figure 7.21: relative fitting errors, detached house

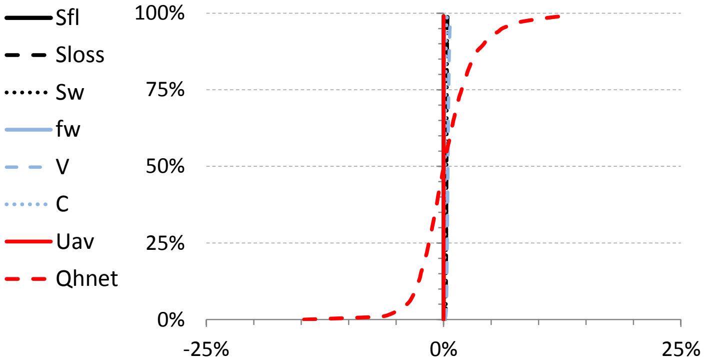

Figure 7.22: relative fitting errors, semi-detached house

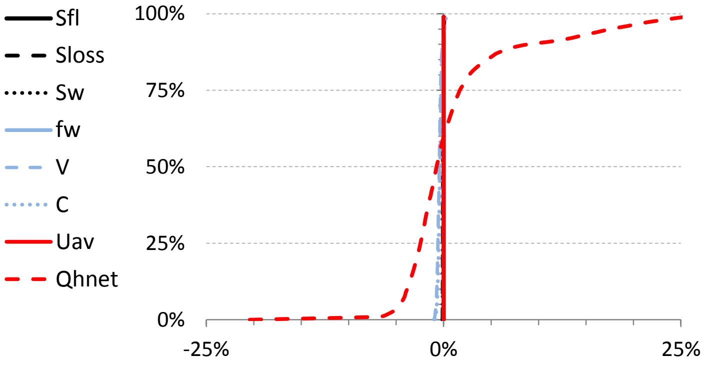

Figure 7.23: relative fitting errors, terraced house

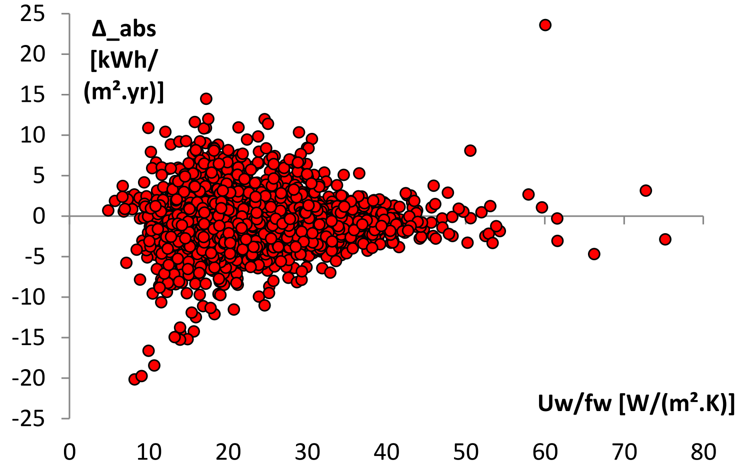

Figure 7.24: absolute fitting error, detached house, space heating demand

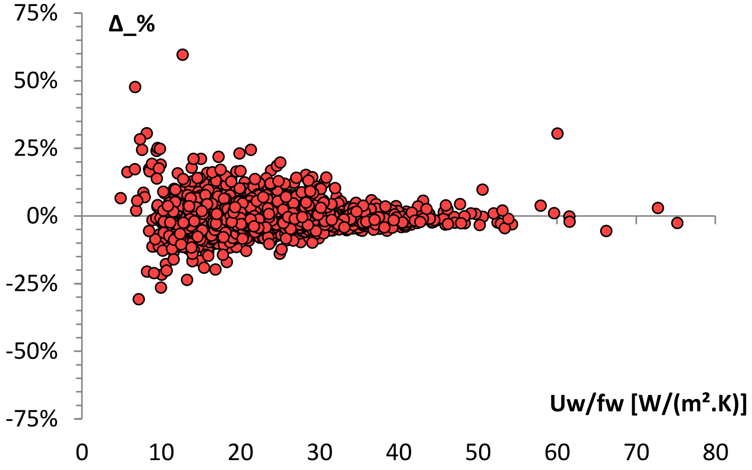

Figure 7.25: relative fitting error, detached house, space heating demand

7.4.2 Detailed case-studies: multi-zone verification based on as-built BIM-models

The importance of an appropriate typology

Reaching a good match for the official, single-zone EPB-calculations does not mean that the simultaneously calculated multi-zone models are a good replacement for the lack of original multi-zone models. First, an appropriate typology must be selected to start from. Figure 7.26 illustrates the biases that can occur from using an inappropriate typology. It compares the simulation results from the detached case-study house with the results from the fitted detached typology. The plotted results include the simulations of all combinations of different heating profiles and technical building properties described in the materials section (7.4.2). They are divided in three clusters, which are discussed later in this paragraph. The figures show a growing mismatch for the cases with the higher heating demands. This is caused by an important typological difference between the original house and the parametric typology. While both houses have a garage, the garage of the case-study house is located outside the insulated building envelope, attached to the building and is thus not included in the building volume considered in the official EPB-calculation. On the opposite, the garage of the parametric typology lies within the protected volume of the house and is thus included in the volume that was fitted. As a result, while the protected volume, heat loss area and corresponding floor area fitted well, a large part of the floor area of the fitted typology was assigned to the garage, thus resulting in smaller remaining living areas, bedrooms etc. When lesser insulation levels are considered together with more energy conscious inhabitants, heating mainly the living areas, the temperature differences between the rooms will increase. Because of its smaller living room area and thus its smaller heated building fraction, the simulations on the fitted typology will predict lower heating demands. Indeed, Figure 7.26 shows three distinct clusters. One cluster shows a very good agreement between both modelling approaches (*'profile-cluster 1'*). This cluster contains the heating profiles where all the rooms are heated to the same temperature (profiles 0 and 7, Table 7.7). On the opposite, the replacement models show the largest relative underestimations of the space heating demands for the scenarios where, apart from the bathroom for 1 hour per day, only the living area (living room and kitchen) is heated (*'profile-cluster 3'*, profiles 5 and 6, Table 7.7). The intermediate cluster (*'profile-cluster 2'*) contains the heating profiles with bedrooms, circulation areas and toilets that are heated, however to lower temperatures or for fewer hours per day than the living room (profiles 1, 2, 3 and 4, Table 7.7). The error is much smaller when comparing the results of the official EPB-calculation on the original BIM-models to those on the fitted typology, with the absolute and relative errors over all building performance scenarios remaining below 4 kWh/(m².year) and 4%, respectively. This results from the official EPB-calculation method being a single-zone method, making no distinction between different parts within the protected envelope of the building. However, in the multi-zone model with different heating profiles, the error can reach up to 26% or 61kWh/(m².year) of net space heating demand in old, barely insulated scenarios. Figure 7.27 makes the same comparison as Figure 7.26, however starting from an altered parametric typology: the space of the former garage has been attributed to the formerly adjacent living and circulation areas on the ground floor. As a result, the outcomes of both approaches fit much better. The largest absolute and relative errors are found when considering the heating profile with the largest zonal differentiation (profile 5, Table 7.7).The maximum absolute error (18kWh/(m².year)) is reached in case of the worst insulation level (1950, Table 7.5). The maximum relative error (10%) is reached in case of the best insulation level (PH, Table 7.5).

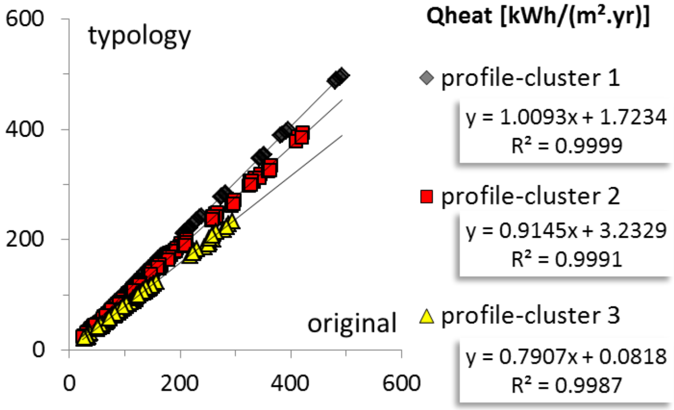

Figure 7.26: detached case-study: comparison between original model and fitted, however inappropriate typology with garage

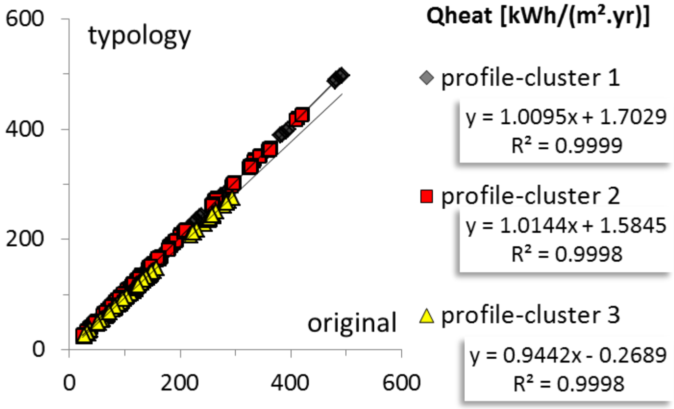

Figure 7.27: detached case-study: comparison between original model and fitted typology (without any garage in the protected volume)

Accuracy of the replacement model with fitted, appropriate typologies

Figure 7.28, Figure 7.29 and Figure 7.30 analyse the three case-studies together. They compare the calculated space heating demands of the original BIM-models of all three case-study houses with the values from their respective fitted typology, using in both cases a multi-zone calculation. For all three case-studies, Figure 7.28 shows a very strong correlation between the original models and their replacement models, over all variations of technical properties and heating profiles. The absolute errors decrease with better building performance levels (Figure 7.29). The relative errors remain in the same range but show a slightly larger variation at better building performance levels (Figure 7.30). Importantly, the values of the errors can be more on the positive or on the negative side depending on the analysed case-study. These biases are explained by the typological differences between the analysed case-studies and their respective parametric typology. Depending on e.g. their different ratios in heated living area versus unheated sleeping area, replacing the original model with the typologically generated model can cause a bias.

This is illustrated in Table 7.9 and Table 7.10, comparing the characteristic areas and volumes of the different case-studies with the values of their respective fitted typologies. Looking first at the total values on building level, the fitted gross heat loss areas, volumes and total floor areas reach an error of less than 0.6%. However, the errors increase up to 10% and 4% when looking at the total net volume and net floor area, respectively. A first cause for this increased error resides in the different thicknesses of the exterior and interior walls, floors and roofs of the parametric typologies compared to the original model. The net volumes and floor areas are calculated based on the internal dimensions of all the individual rooms. Because the real houses had large insulation thicknesses, accurately modelled in their original BIM-model, they have smaller internal dimensions. A second cause of the increased error is the different shape and internal lay-out of the typologies compared to the original model, resulting e.g. in different total lengths of internal walls. Resulting from those different lay-outs, the sizes of the different rooms will also differ. The living area (living room and kitchen) take 42%, 35% and 32% of the net floor area of the original detached, semi-detached and terraced house, respectively. However, these values are 6 percent point lower, 4 percent point higher and 4 percent point lower in the corresponding fitted detached, semi-detached and terraced typologies respectively. This partly explains why the slope of the regression line in Figure 7.28 is higher than 1 for the semi-detached house but lower than 1 for the other two fitted cases. Indeed, the living area is the most heated area of the houses (see Table 7.7) and therefore the larger the size of the living area within the building, the larger the calculated space heating demand.

Further analyses showed that the thermal resistance of the interior walls, floors and doors and of the thermal capacity had a very limited effect on the accuracy of the replacement model compared to the original model with the same assumption. The difference between the two considered insulation levels of the internal components mainly influenced the accuracy for the scenarios with low exterior insulation levels and large differences in heating profiles between the zones, however by no more than a maximum of three percent points.

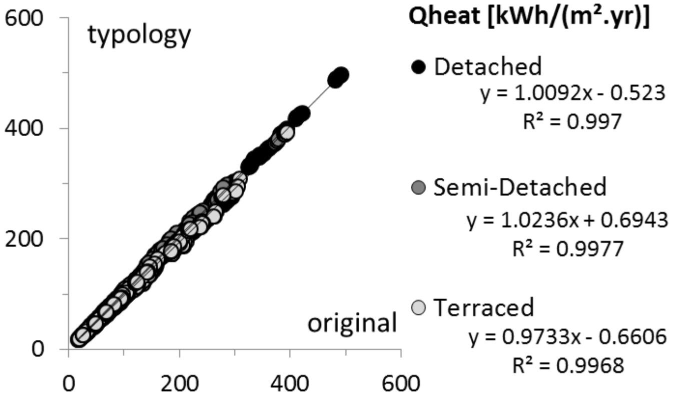

Figure 7.28: comparison between original model and fitted typology (three casestudies)

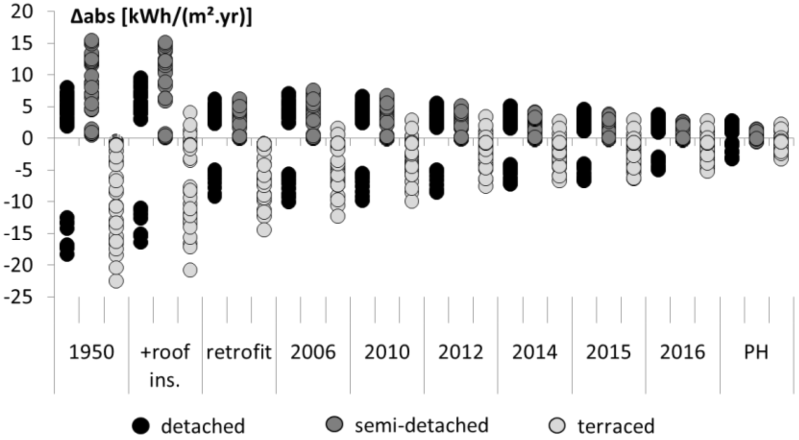

Figure 7.29: absolute error of the parametric typology approach for all scenarios (different insulation levels and heating profiles) (three case-studies)

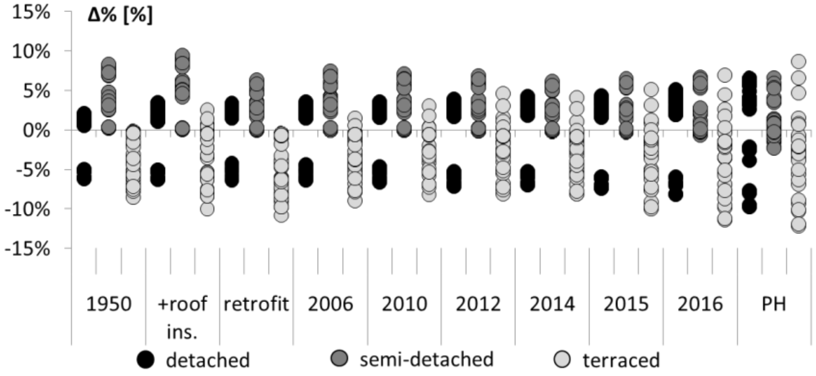

Figure 7.30: relative error of the parametric typology approach for all scenarios (different insulation levels and heating profiles) (three case-studies)

Table 7.9: main geometrical properties of the three original case-study houses and their respective parametric typologies at the end of the fitting process (V=volume, S=surface, living=living room+kitchen, sleep=bedrooms)

		Sloss	Vgross*	Vnet	V: net/gross	Sfloor, gross*	Sfloor,net				Sfloor: net/gross
		[m^2]	[m^3]	[m^3]	[%]	[m^2]	[m^2]	[m^2]	[m^2]	fraction	[m^3]
						total	total	living+ kitchen	sleep	living+ kitchen	
Detached	Original	405.4	551.6	390.0	71%	167.6	140.9	59.9	38.5	42%	84%
	Fitted	403.4	548.6	425.8	78%	167.6	144.6	51.9	32.7	36%	86%
Semi-detached	Original	345.4	463.4	408.5	88%	180.8	159.3	55.4	60.4	35%	88%
	Fitted	346.6	466.1	370.3	79%	180.8	161.8	62.6	67.3	39%	89%
Terraced	Original	357.5	465.9	404.3	87%	164.4	149.6	47.8	57.6	32%	91%
	Fitted	357.5	466.3	362.6	78%	164.4	144.2	40.3	42.5	28%	88%

*the gross dimensions are based on the external dimensions of the gbXML-models. However, those are defined by Revit, depending on the type of component, based on the external boundary or on the central axes of those components

Table 7.10: absolute and relative errors of main geometrical properties of the fitted parametrc typologies (V=volume, S=surface, living=living room+kitchen, sleep=bedrooms)

		Sloss	Vgross*	Vnet	V: net/gross	Sfloor, gross*	Sfloor,net				Sfloor: net/gross
		[m^2]	[m^3]	[m^3]	[%]	[m^2]	[m^2]	[m^2]	[m^2]	fraction	[m^3]
						total	total	living+ kitchen	sleep	living+ kitchen	
Detached	Δabs	-1.9	-3.0	35.8	7%	0.0	3.7	-8.0	-5.8	-7%	2%
	Δ%	-0.48%	-0.54%	9.17%	9.76%	0.00%	2.62%	-13.39%	-15.11%	-15.60%	2.62%
Semi-detached	Δabs	1.3	2.7	-38.2	-9%	0.0	2.6	7.3	6.9	4%	1%
	Δ%	0.36%	0.59%	-9.35%	-9.88%	0.00%	1.62%	13.12%	11.37%	11.32%	1.62%
Terraced	Δabs	0.0	0.5	-41.7	-9%	0.0	-5.4	-7.5	-15.2	-4%	-3%
	Δ%	0.01%	0.10%	-10.32%	-10.41%	0.00%	-3.62%	-15.60%	-26.32%	-12.43%	-3.62%

*the gross dimensions are based on the external dimensions of the gbXML-models. However, those are defined by Revit, depending on the type of component, based on the external boundary or on the central axes of those components

Unknown average U-value

The above analysis on the three case-studies showed a very good correlation between the original models and their replacement models. However, in case less data is available, the size and spread of the errors can further increase and more biased results can be obtained. In an early building design or assessment stage, the overall geometry of the house can be reported very quickly and an estimate can be made of the U-values of the different types of envelope components (e.g. roofs versus walls). At that stage, the design or assessment team might want to have a first rough and quick estimation of the building performance, without having to measure the areas of all envelope components separately and thus without supplying an accurate value for the total transmission heat loss coefficient or the average U-value. In that situation, the last fitting step, tuning up or down the different U-values to reach the correct building average U-value, cannot be performed. The error on the resulting average U-value is presented in Figure 7.31. It shows the building average U-values of all three case-study houses at the different performance levels. Additionally, the figure also shows the absolute and relative errors of the average U-value of the replacement model before the last fitting step. The errors prove to vary to great extent depending on both the analysed house and the analysed set of U-values. Firstly, the error depends on the different ratios between floor, wall and roof areas found in the replacement model as opposed to the original model. Secondly, the difference between the U-values of the floors, walls and roofs varies from one set of U-value to the other, thus accentuating or hiding the different envelope component ratios in the fitted model compared with the original model.

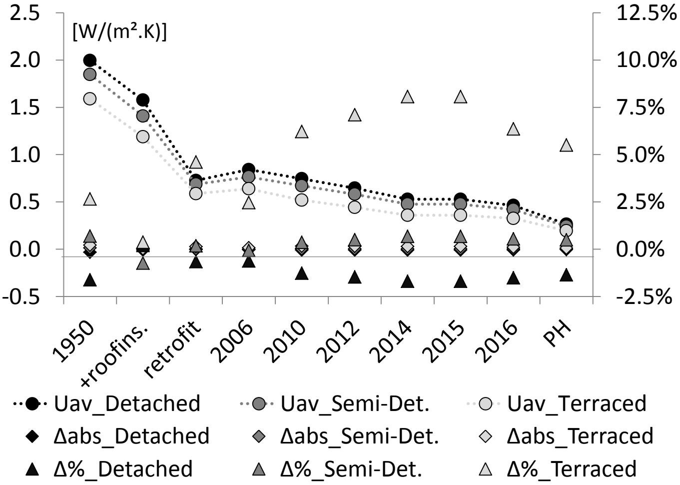

Figure 7.31: Average U-values of the three case-study houses: values of the original model and absolute and relative error of the replacement model if the same U-values per envelope component type are used without further fitting

The resulting error on the average U-value can affect the accuracy of calculated space heating demand. Figure 7.32 and Figure 7.33 compare the calculated space heating demand based on the original BIM-model with the values resulting from the replacement model without the last fitting step. Comparing the former figure with Figure 7.28 does not show any significant improvements from the additional tuning up or down of the U-values. Comparing the latter figure with Figure 7.30 shows that the last fitting step mainly results in a shift of the prediction errors that can accentuate or compensate for other biases from the replacement model (e.g. caused by the difference in window orientation). However, the limited improvement or small increase of the error is caused not only by the compensating effects of different biases. Fitting the average U-value can result in a bias regarding directly the transmission losses. The lower average U-value of the replacement model can result from its larger roof area compared to the real house and the fact that the U-value of roofs is lower than the U-value of the other components. Tuning up the U-values to reach the same average U-value will result in higher U-values for the walls of the replacement model and thus in larger heat losses for the living area on the ground floor. As a result, if only the living area is heated, the last fitting step will cause an overestimation of the space heating demand.

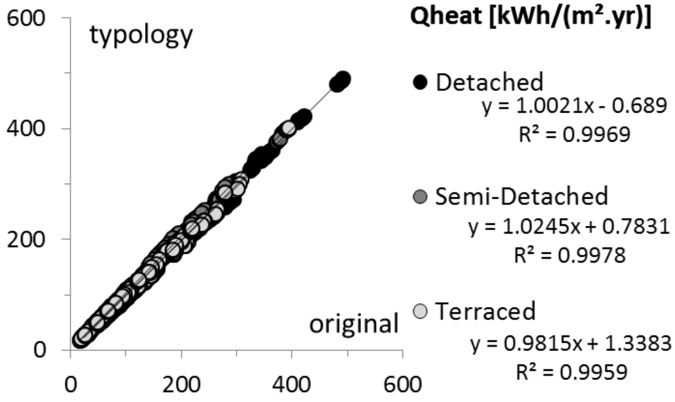

Figure 7.32: comparison between original model and fitted typology, without fitting the average U-values (three casestudies)

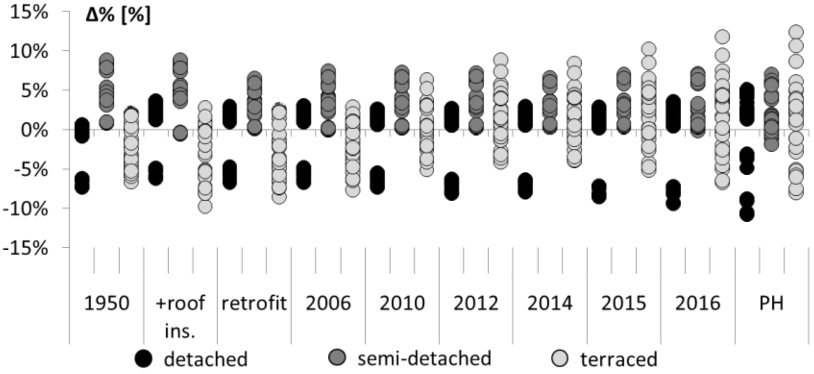

Figure 7.33: relative error of the parametric typology approach for all scenarios (different insulation levels and heating profiles), without fitting the average U-values (three case-studies)

7.4.3 Multi-zone sensitivity analyses on building stock level

Section 7.4.1 tested the parametric typology approach for building stock analyses based on single-zone calculations, following the calculation method from the Flemish energy performance framework. Section 7.4.2 focussed on the accuracy of the multi-zone replacement models through an analysis on three case-study houses. Building further on those two sections, this section illustrates the additional potential from using the multi-zone replacement models for building stock analyses. It is based on a scenario-analysis on the set of detached houses from the EPB-database (73% of 5000 cases). First, the reduction of the net space heating demand is analysed considering no changes in heating profiles and, subsequently, the reduction of the final space heating demand is analysed, including a shift in heating profiles (see 7.3.3).

Physical temperature take-back and mismatches between added insulation and heated zones

Figure 7.34 and Figure 7.35 show, compared to the scenario without any insulation, the absolute and relative reductions of the net space heating demands associated with roof insulation, the current envelope performance requirements and the passive house building envelope guidelines. Figure 7.34 shows the calculated reductions following the single-zone calculation method from the Flemish EPB-assessment framework. Figure 7.35 shows the results from the multi-zone method considering an intermittent heating profile in the living area and no direct heating in the bedrooms (see 7.3.3, heating profile ‘5’, Table 7.7). Comparing the predicted savings for the different scenarios, their relative order of magnitude are similar for both modelling approaches. However, looking in more detail at the results, starting with the predicted savings resulting from roof insulation, the EPB-method predicts on average savings of 25% or 69 kWh/(m^2.year), while the multi-zone method predicts considerably lower savings of on average 16% or 30 kWh/(m^2.year). As discussed in 6.3, the different relative savings result from two aspects that are not taken into account in the regulatory single-zone method. The first is the building average physical temperature take-back. The second is the sub-optimal positioning of the added insulation (in the roof) compared to the spaces that are heated and have the highest heat losses (the living area on the ground floor). Furthermore, the very high difference in absolute saving values expressed in kWh/(m^2.year) (by a factor of 2.3) is further explained by the overestimated equivalent set-point temperature in the single zone model causing large absolute overestimations in buildings with poor energy performance (see 3.4.1, Chapter 6 and [29,68]). The same findings apply to the predicted savings associated with the better building performance levels.

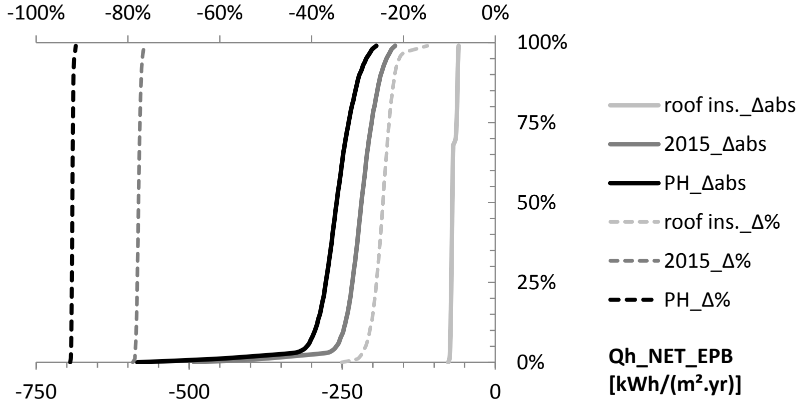

Figure 7.34: absolute and relative reduction of the <u>net</u> space heating demand compared to the uninsulated scenario '1950': EPB-dataset, detached houses; <u>EPB-calculation</u>

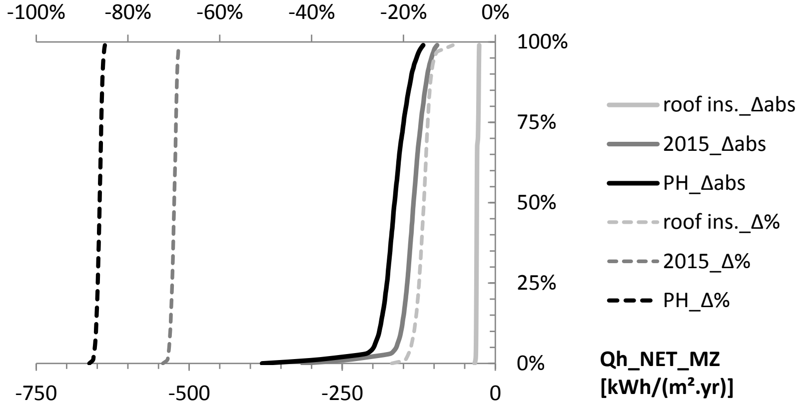

Figure 7.35: absolute and relative reduction of the <u>net</u> space heating demand compared to the uninsulated scenario '1950': EPB-dataset, detached houses; <u>multi-zone calculation with fixed heating profile '5'</u>

Changing user profiles

Figure 7.36and Figure 7.37 make the same comparisons as Figure 7.34 and Figure 7.35 respectively, however looking at the final energy demand (including changes to the heating system) and considering altered heating profiles. The EPB-method now predicts higher relative savings thanks to the additional improvements of the heating systems. However, when looking at the results from the multi-zone calculations, large parts of the savings are cancelled by the scenario that considers more demanding heating profiles at the higher building performance levels with central heating systems. For some cases, the analysed scenario even results in a higher energy use in the case of added roof insulation and the placement of a central heating system, because the heat losses through the roof are limited before renovation because the bedrooms are considered unheated while some limited heating of the bedrooms is considered after insulating the roof and installing the central heating system (see 7.3.3). The difference is less visible in the high performance scenarios. This is explained by the highly insulated envelopes levelling out the zonal differentiation and reducing the temperature drops during night-time set-back, thus showing smaller differences when considering fewer or more rooms being heated for fewer or for more hours. However, comparing the results from the EPB- models with the results from the multi-zone models, the differences are larger for all scenarios than when no changes in user profiles were considered.

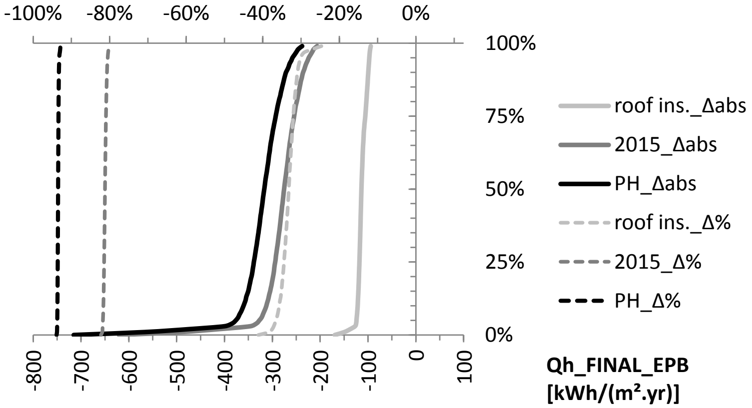

Figure 7.36: absolute and relative reduction of the final space heating demand compared to the uninsulated scenario '1950': EPB-dataset, detached houses EPB-calculation

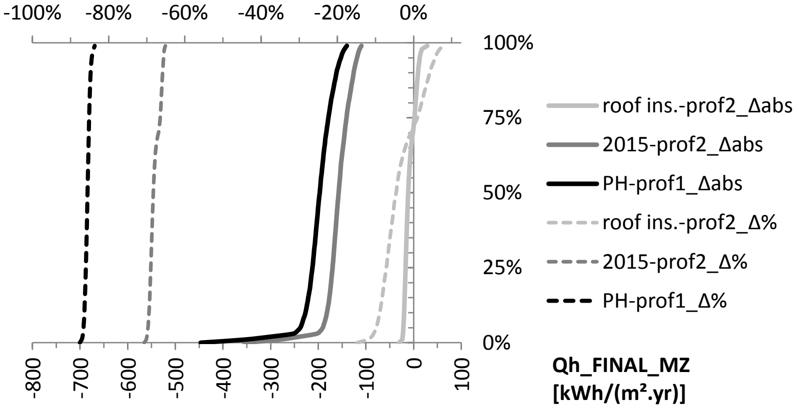

Figure 7.37: absolute and relative reduction of the final space heating demand compared to the uninsulated scenario '1950': EPB-dataset, detached houses; multi-zone calculation

7.5 Discussion

7.5.1 Single zone

The parametric typology approach proves to reach very good results on the single-zone level. The fit between original cases from the official EPB-database and the fitted typologies is quasi perfect with regards to the main geometrical properties, the building volume, floor area, heat loss area and its glazed area, and also with regards to the average U-value. The errors on the calculated space heating demand are limited. Furthermore, these errors are not systematic. They originate mainly from uncertainties regarding the original buildings (e.g. regarding the window orientations), resulting sometimes in an overestimation and sometimes in an underestimation for an individual cases. To a large extent, these small errors could easily be tackled by some minor tuning of e.g. the building orientations. However, on the level of the whole analysed dataset, the current approach already gives a nearly exact distribution of the space heating demand. This gives the approach a great potential for sensitivity analyses on building stock level. It enables making new calculations based on large numbers of real house, assuming e.g. different insulation levels, glazing types etc. This is possible notwithstanding important modelling data is often missing in official databases, e.g. regarding window orientations or the area fractions of the total building envelope that are made out of walls versus roofs versus floors. Related assumptions made on the parametric typology will be projected on the results. Therefore, it is important for the parametric typologies to follow realistic assumptions, but variations can easily be included in the process, like e.g. changing the orientation of the fitted typologies. In the end, compared to the common use of fixed, non-parametric typologies, the new approach will still enable simulating larger realistic variations present in the building stock with fewer, though ‘elastic’ typologies. This approach can thus support governments in defining what future official performance levels (e.g. regarding space heating) can be reached with specific sets of measures (e.g. insulation thicknesses and glazing types) if applied to their diverse building stock.

The building characteristics are not the only parameters evolving over the years and changing the official building performance levels. The calculation methods are also regularly updated. With each change to the calculation method, the question rises to what extent the change in the method will change the result and for what type of houses. This is an important question, because some continuity within the regulation framework is needed to enable stakeholders, professionals and buyers, to anticipate on future evolutions and to compare the performance levels of buildings. I.e. not only comparing houses built during the same year and evaluated using the same version of the calculation software. The presented simulation approach could also prove useful in those situations, allowing recalculating a very large number of houses from the database using a new calculation method and subsequently comparing results, before officially launching the new calculation method.

In fact, the developed approach and tool presented in this chapter have already been used for a project commissioned by the Flemish Energy Agency (VEA) [225]. The aims of that project were (1) to develop a new way of labelling the performance of the building envelope (without e.g. HVAC-systems), (2) to propose what the tightening requirements will be for the following years for that new building envelope label and (3) to improve the normalization of the calculated total primary energy demand into an abstract primary energy performance indicator (the E-level, see Chapter 2). Having solid theoretical grounds is not enough to support such changes to an energy regulation framework. The study had also to take into account the building realm, with large variations in types of buildings resulting not only from the varying ambitions of different design teams, but also from different building requirements (e.g. for different sizes of households) and different building sites. Indeed, it was important to know in advance not only what type of houses would face more or less difficult challenges for reaching the newly developed criteria, but also how large a percentage of typically built houses would face those changes. Answering these questions required testing the proposed evaluation methods and the imposed performance values on a representative set of houses instead of on a limited number of test cases. Furthermore, scenario analyses on those houses had to consider future evolutions regarding the technical performance levels of the different envelope components and services, linked e.g. to new performance criteria that were already defined for the upcoming years. Therefore, the method presented in this chapter was used for that project. It was applied on similar statistical data from the same database used for the building stock analyses in this chapter: the official Flemish EPB-database, containing data on all the new houses that have been built since 2006 and thus guaranteeing a large representativeness of the calculated results. Because the studied building performance levels were not limited to the net space heating demand, the tool was further extended to include the full EPB-assessment method for residential buildings, including the calculation of the primary energy demands for space heating, space cooling, domestic hot water, auxiliary energy and the electricity production from PV-panels.

7.5.2 Multi-zone

While only tested on a limited number of geometries, the comparison of the results from the replacement models with the results from the original models support the potential of the approach for using more accurate multi-zone models quasi without increasing the workload compared to building single-zone models for each individual building project or case within a larger dataset, at least if appropriate parametric typologies are available. Running the multi-zone simulation through the automated approach proved possible, however to lesser relative accuracy than when aiming only at a single-zone replacement model. Furthermore, on multi-zone level the results of the parametric typology approach are more sensitive to the selection of an appropriate typology and to additional parameters such as the distribution of the insulation across the building envelope and different heating profiles in different rooms.

A sound selection procedure for the typology is thus a condition for reaching good results. Important typology selection criteria should include asking for the presence of large unheated areas (e.g. garages and attics) or other non-standard rooms that could influence the internal ratio of heated and unheated rooms and thus cause a lesser fit at multi-zone level. For individual housing projects, architects, energy performance assessors or even inhabitants could easily indicate the presence of such spaces and thus help selecting an appropriate typology. For building stock analyses, the quality of the typology selection will depend on the available information stored in the database for each individual case. The Flemish EPB-database stores the names of each room within the context of their hygienic ventilation requirements. Automated room type identification based on those names allows identifying the presence of specific room types and, to some extent, deduce knowledge about their respective size [82]. This could allow a more appropriate typology selection and even to verify to some extent the geometrical fit on the level of the interior spaces.

Errors resulting from inappropriate typologies or differences in internal lay-out will decrease with increasing homogeneity of the insulating envelope and of the heating profiles across rooms, approximating further the single-zone assumptions of the official assessment methods. However, the relative error associated with a replacement model compared to the original model could increase when using dynamic simulation algorithms, because they depend on more detailed information on building characteristics and user profiles than the quasi-steady-state algorithms used in this study. Dynamic models can e.g. account for time shifts between the heating profiles and fluctuating temperatures in coupled zones. The potential of coupling dynamic multi-zone models with the presented parametric typology approach will also depend of the application that is aimed, because the step towards dynamic models could increase the number of inputs and the calculation time.

7.5.3 Further applications

Real energy use on building stock level

The first analysis of the parametric typology approach focussed on its use for building stock analyses based solely on single-zone models. Subsequently, this chapter analysed the validity of the replacement models on multi-zone level based on a limited number of case-studies of small housing projects. Finally, the last result section illustrated the value of the multi-zone enrichment of the single-zone data, allowing for building stock analyses that could take into account physical temperature take-back, zonal differentiations, behavioural rebound effects and other aspects influencing user profiles. Comparing the savings on the net space heating demand predicted by the multi-zone replacement models with the values predicted by the single-zone replacement models gives similar findings as those discussed in Chapter 6, e.g. with regard to the single-zone models overestimating the savings associated with roof insulation. As illustrated with a fictive yet realistic scenario of changes to the user profiles, including multi-zone algorithms in the parametric typology approach enables taking more complex residential heating profiles into account in simulations on building stock level. This allows considering shifts in heating profiles associated with user behaviour and changes to the building performance levels or to the type of systems (e.g. centralized thermostats, low temperature heat emission systems). However, the accuracy of the predictions will depend on the accuracy of the assumptions. While realistic in the light of the findings from Chapters 2, 3 and 4, the analysed scenario was exemplary. It was mainly aimed to be illustrative and was not based on large statistical data regarding shifts in heating patterns as a function of e.g. different building performance levels and types of system controls. As opposed to technical characteristics and theoretical performance levels, heating profiles in houses are not documented as systematically in official databases. Different statistical studies have analysed data on heating profiles [47,52–54,107,226]. However they are often based on smaller datasets, containing often less accurate self-reported values. Furthermore, studies based on measured internal temperatures in houses seldom focus on set-point temperatures or on heating profiles in other rooms than the living room (see 4.1). Further statistically robust and extensive data on heating profiles and the behaviour of inhabitants should be collected and studied further in order to gain the necessary knowledge for defining statistically and scientifically sound inputs for more accurate bottom-up building stock models, taking e.g. behavioural rebound into account. This would limit the need for tuning the models based on comparisons between outputs and real consumption data and thus limit the associated risk of overseeing important causal relationships.

Application in online advice tools

This chapter presented the approach through its application for building stock analyses and for the energy simulation of individual housing projects, using the current offline version of the tool. An additional sound application of the approach would be its implementation in the background of online home energy efficiency advice tools. Such tools give advice about energy renovation measures and sometimes about behavioural measures [227]. They can be differentiated based on their underlying simulation approach [219]. The first approach consists of running a very simplified simulation in real time. That simulation can be as simple as a heating degree-day based method [228] or it can be based on methods similar to official EPB-calculation methods, taking variations in user profiles not or only limitedly into account in models that are based on a limited number of predefined reference typologies. The second approach consists of selecting the results from a large number of simulations that have been run before setting up the website and that are stored in a database [222,229]. While sometimes used in combination with results from simplified calculation methods [229], this approach allows using more complex, e.g. dynamic simulations requiring more computing power and longer calculation times [222,230]. Thanks to the parametric approach regarding the building geometry, the new approach presented in this chapter could significantly increase the number of possible variations, allowing for a better match between the real house that one seeks advice for and the model the advice is based on. In case of real-time simulations, the combination of this parametric typology approach with the simplified model it is currently linked with, presented in Chapter 5 an analysed in Chapter 6, would also reach results that are more tailor-made for a specific household and the corresponding heating profile. However, apart from a different software implementation, this implementation in online advice tools would require a larger number of parametric typologies. Furthermore, it would benefit from further studying the accuracy of the fitted replacement models based on a larger number of case-studies, as opposed to the proof of concept on three case-studies made in this chapter.

7.5.4 Further research

In fact, further research should focus on improving the fitting procedure by taking not only the external geometry into account but also basic information about the internal geometry (e.g. the approximate size of the living room and kitchen) and the thicknesses of the construction elements defining the differences between internal and external dimensions. Further research should also focus on additional model calibration based not only on inputs, but also on outputs, comparing e.g. the results from the single-zone simulation on both the original and the replacement model for tuning the replacement model before performing the multi-zone simulation. Real consumption figures could also be used for this top-down calibration. For that aim, Bayesian calibration methods might result in interesting approaches, because they enable taking uncertainties stochastically into account in simulation studies [168]. Combining the parametrical typology approach with stochastic approaches would be a sound research path in order to handle the uncertainty of the modelling approach in a probabilistic rather than discrete way [231]. In combination with fast calculation algorithms similar to the simplified multi-zone model discussed in Chapters 5 and 6 and used in the tool discussed in this chapter, uncertainty analyses could also become more accessible for small building projects.

7.6 Conclusion

This chapter showed the potential of using parametric typologies for replacing missing data on houses and performing more detailed energy simulations. The approach proves to be applicable for building stock analyses based on official databases documenting very large numbers of houses. It enables scenario analyses with a higher degree of representativeness than by using a smaller number of fixed typologies. However, additional statistical research is needed on the inputs regarding the inhabitants' behaviour in order to ascertain the validity of the analysed scenarios and of the resulting predictions. Furthermore, a word of caution is needed when using results not only from the single-zone models, but also from the multi-zone models. While very high correlations were found between the original multi-zone models and the multi-zone replacement model, large errors can result from the selection of an inappropriate typology. To reach sufficient accuracy, more data is needed than purely about the building shape and size. Additional parameters should be considered like the presence or absence of garages, attics and other large and non-heated or differently heated rooms that are not present in every house but that can account for a large fraction of the building. While the availability of such information on building stock level will vary from one country to another, depending on their databases, collecting that information on a specific house requires only few questions to the designer, the performance assessor or the inhabitant. Therefore, the approach also has potential for use in fast decision support tools, useable in early design stages or giving tailored energy renovation advice to house owners, e.g. through a web platform, taking both the building and the users better into account than by using single-zone models on fixed typologies.

8

Conclusions and perspectives

8.1 Conclusions

The energy performance of houses is intensively discussed in the scientific community, in the private building sector and in the press because it concerns everyone for financial and ecological reasons and because governments impose more demanding performance levels every year. However, the simplified assessment models used in the regulatory frameworks, in building stock analyses to support policy making and by architects to support their design process prove to be inaccurate predictors of the real energy use in houses. The prediction errors vary to a large extent from one house and household to the other, but the predictions are not accurate on average either. Predicted energy savings are rarely achieved because higher overestimations of the energy use for space heating are found at lower energy performance levels. This study contributed to the research on the causes of these discrepancies between real and theoretical values and to the development of simplified modelling approaches that allow making more accurate predictions.

Economic rebound and physical temperature take-back are often cited as the important causes of the shortfall, the fact that predicted energy savings are not achieved. Literature also reports that installations of central heating systems are associated with more demanding heating profiles (e.g. heating also the bedrooms), which explains part of the temperature take-back and thus of the shortfall. The findings from this dissertation cannot confirm nor refute the importance of economic rebound, but the analysis based on field-data and simulation results corroborate the importance of physical temperature take-back (see Chapters 3 and 6: 3.3.4, 3.4.1, 6.3.3) and the changes in heating profiles associated with the shift from local to central heating systems (see Chapter 3 and 4: 3.3.3, 3.4.1, 4.3.1). In addition, four additional reasons explaining parts of the prediction errors were identified:

- Official energy performance assessment methods consider the same heating profile for all houses. However, focussing only on houses with a central heating system, more demanding heating profiles (especially more hours of heating per day) were found in houses with low-temperature heating systems, which have higher efficiencies and are found mainly in high performance houses. (see Chapter 4: 4.3.3, 4.4.3)
- Inhabitants barely open the windows in houses with no ventilation systems and high air leakage rates, which are mainly houses with low performance levels. Considering the same total hygienic ventilation air flow rate in all houses in addition to the air leakages results in an overestimation of the total ventilation heat losses and thus also of the space heating demand in these low performance houses. (see Chapters 3 and 6: 3.3.3, 3.4.1, 6.2.2, 6.3.1)
- Single-zone models do not take into account the zonal differentiations of the indoor temperatures, of the ventilation flow rates, of the internal heat gains and of the thermal transmittance of the external envelope. In old non-insulated houses with no ventilation system, showing the largest temperature differences between the heating living area and the other rooms, hygienic ventilation flow rates result mainly from windows being opened in the barely heated night-zone (see Chapter 3: 3.3.3, 3.4.1). On the opposite, the internal heat gains mainly occur in the heated living area. Being commonly located on ground, those living areas also have an external building envelope with a lower average thermal transmittance than the average at building level when considering non insulated single-family houses. Not taking these zonal differentiations into account further increases the overestimation of the energy use for space heating, especially in these old houses with large differences in heating profiles and temperatures between the living area and the other rooms (see Chapter 6: 6.2.2, 6.3.2).
- An additional overestimation of the energy savings associated with high official performance levels results from reporting biases. Building teams making investments and efforts to reach high building performance levels are shown to put also more effort in detailed energy performance assessments, using more accurate input values that give more accurate but also better calculation results than the conservative default values. (see Chapter 2: 2.3.2, 2.4.2)

In general, the different causes of prediction errors mentioned above will mostly result in higher overestimations of the energy use in non-insulated houses and they therefore explain part of the shortfall.

A multi-zone simulation model was developed to take into account the variation of zonally differentiated user profiles, which is necessary not only for reaching more accurate predictions on average, but also for reaching more accurate predictions at the level of the individual house and household (see Chapter 5: 5.3.2). A simplified, quasi-steady state approach was chosen and embedded in BIM-software. This allows making more accurate predictions with no significant increase in calculation time or modelling time compared to using regulatory single-zone models, provided that a BIM-model of the house exists. In addition, a replacement modelling approach was developed (see Chapter 7). It enables to use the multi-zone calculation approach in situations where no BIM-models of the houses are available, e.g. for architects using more standard 2D software, small renovation projects of houses for which no building plans are available or for building stock analyses based on single-zone EPB-data. The approach is based on predefined parametric building typologies for which BIM-models are available and that can be transformed to fit to the more limited available data on the real building, thus resulting in replacement models that can be evaluated using multi-zone simulation algorithms. The approach was illustrated by simulations on 15.000 houses documented in the Flemish EPB-database, showing the potential and added value for more representative and more realistic bottom-up building stock models.

8.2 Perspectives

While the proposed modelling approach was shown to be valuable for future building stock analyses, more detailed and quantitative data is required to get the most out of it. This is true both for technical input parameters and for behavioural input parameters. More knowledge is required on user profiles, focussing not only on heating and ventilation, but also on the opening of doors. Research on heating profiles should consider not only the living room, but all rooms of the house, the associations between their heating profiles and the link between their heating profiles and the characteristics of the construction (e.g. the insulation level), the systems (e.g. the type of emission system and temperature regime), their controls (e.g. manual or automatic, local or central) and the socio-demographics of the households.

Increased availability of accurate data is needed not only for this aim of more accurate and statistically representative modelling inputs, but also for more detailed validation of the simulation results and improvements to the model. There was still a significant gap between the real energy use and the energy use calculated using the multi-zone model. While the modelling research of this study focussed on the calculation of the net space heating demand using quasi-steady state models, further research on the gap between real and theoretical energy use should also focus on how system efficiencies and time-related aspects are taken into account in the simplified models.

System efficiencies were taken into account following the approach from the Flemish EPB-method, where inefficiencies of the systems (e.g. heat losses of storage tanks and distribution systems, overshoot etc.) are taken into account only by a reduction of the considered system efficiencies, while these inefficiencies can result in increased heat gains, as considered e.g. in DIN 18599 (Germany, [176]) or SAP (UK, [76]).

Using dynamic models would also allow taking into account the significant simultaneity between internal heat gains and space heating requirements, mostly during presence in the rooms, and the asynchrony that was reported by the inhabitants between opening the windows and switching on the heating system.

While these research perspectives regard the modelling equations and their inputs, further investigations should also focus on the practical implementation of more detailed models. On the back-end, the presented replacement modelling approach would benefit from further research into the selection and fitting of parametric typologies. On the front-end, the approach can be made more user-friendly for researchers and engineers and accessible for designers and house-owners, seeking tailored but accessible decision support. A valuable implementation of the approach would be in the background of energy advice tools allowing non-professional, private individuals to receive more customized advice on how to lower their energy use by renovation measures or behavioural changes, without the need for them to supply extensive and detailed inputs on their house and their behaviour. Following these different research paths will help reduce the prediction gap and support policy makers, designers and inhabitants to make sound decision for reducing the residential energy use.

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