DIPLOMARBEIT

Impact of User Behaviour Assumptions on computed Urban Scale Building Energy Use

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I dedicate this work to my grandmother Marlene.

KURZFASSUNG

Mit Hilfe von thermischer Gebäudesimulation können heute verschiedene Key Performance Indikatoren relativ mühelos mit einem hohen Grad an Genauigkeit ermittelt werden. In üblichen Simulationswerkzeugen wird das Nutzer*innenverhalten zumindest rudimentär beschrieben. Nichtsdestotrotz muss festgehalten werden, dass eine genaue Abbildung der Interaktion von Nutzer*innen mit dem Gebäude als Aufenthaltsort und als Aggregat von die Gebäudeperformance beeinflussenden Systemen nach wie vor als eine der größten Herausforderungen in der Domäne Gebäudesimulation gilt. Das hat mitunter mit der sehr diversen Struktur des Nutzer*innenverhaltens betreffend Anwesenheit in zeitlicher und räumlicher Dimension, wie auch mit der Interaktion der Nutzer*innen mit verschiedenen Teilsystemen des Systems Gebäude, wie Heizungssysteme, Verschattung und Lüftung und der damit verbundenen Implikationen auf die verschiedenen Teilaspekte, welche die (thermische) Gebäudeperformance beeinflussen. In verschiedenen wissenschaftlichen Studien wurden historische, durch Beobachtung oder Messung erlangte Werte als geeignet zum Einsatz in den Simulationen verwendet. Dies ist jedoch offensichtlich mit einem großen Aufwand betreffend Datensammlung und entsprechender Bearbeitung (Stukturierung, Skalierung, etc.) verbunden. In dieser Masterthese werden unterschiedliche Szenarien der Nutzer*innen Interaktion („Occupancy“) mit Gebäuden untersucht. Die übergeordnete Zielsetzung ist es, ein besseres Verständnis für den Einfluss des Nutzer*Innenverhaltens auf die Gebäudeperformance zu erlangen. Um dies großmaßstäblich studieren zu können, wurde ein Gebäudesample aus Wien gewählt, welches basierend auf Aspekten wie Volumen, Größe, Nutzung und Alter geeignet ist, die Gebäudestruktur eines Wiener Bezirksteils zu repräsentieren. Da eine genaue simulationsbezogene Analyse des gesamten Gebäudebestands auf Grund des damit verbundenen enormen Aufwands kaum sinnvoll durchführbar ist, dient dieses Sample zur Detailuntersuchung. Auf das Gebäudesample werden unterschiedliche Occupancy-Szenarien angewandt und diese dann mittels thermischer Gebäudesimulation hinsichtlich ihres Einflusses auf KPIs untersucht.

Die Ergebnisse aus dem Gebäudesample werden dann mittels statistischer Methoden auf den Bezirk übertragen („Upscaling“). Damit kann ermittelt werden, mit welchem Einsparungspotentialen hinsichtlich einer Veränderung des Nutzer*innenverhaltens gerechnet werden kann.

Schlagwörter:

Gebäudesimulation, Nutzerverhalten, Nutzerprofile, Hochskalierung

ABSTRACT

Building performance simulation software tools deliver various key performance indicators of different aspects of building performance. To a certain extent such tools integrate occupant behaviour input data. However, an accurate mapping of real user behaviour in form of human interaction with the building and its systems into simulation models can be considered as challenging. This is due to the diverse nature of user behaviour regarding occupancy, time dimension, and impact on the different aspects of the building performance. Several studies suggest the integration of available historical and measured data as input data for simulation. Needless to say, this approach is connected with the strenuous effort of collecting and structuring such data.

In this contribution, reasonable scenarios of occupant's interaction with buildings are studied. Thereby, the major aim is to gain a better understanding of the impact of occupant behaviour onto the building's performance. For this purpose, a sample of buildings, which have been chosen to represent the building stock in the central area of Vienna, Austria, is subjected to building performance simulation with different assumptions regarding the occupancy behaviour. These different assumptions lead to different results in view of building performance KPIs. As such, the impact of different occupancy assumptions onto buildings that vary in size, usage, and thermal envelope quality is extensively studied.

The results obtained for these sample buildings include heating loads, cooling loads, and the temperature conditions including potential occurrences of overheating. An extensive comparison of the different buildings with associated occupant population patterns is undertaken. These interim results are then upscaled to the overall building stock via methods of statistics. As a result, the described efforts allow for a qualified estimation of potential of the behavioural changes in reducing building-related energy use.

Keywords

Building performance simulation, occupant behaviour, user scenarios, urban scale projection

CONTENTS

1 INTRODUCTION

1.1 Overview

In recent years it is common practise to utilise Building Performance Simulation (BPS) tools within the building planning process to pre-assess later building performance in various domains such as energy usage, indoor thermal conditions, or acoustical and lighting performance. Many countries, such as Austria, even demand minimum requirements. In Austria that is the building energy certificate which is calculated with normative methods. An energy certificate is necessary for newly constructed buildings to ensure a required minimum performance standard. Furthermore, existent structures underlie stricter governmental guidelines for performance after refurbishment measures were implemented. It should be noted, however, that these normative methods usually only allow rather rough performance estimations. This derives from the fact that they typically consider one predefined behavioural norm.

More advanced building performance simulation (BPS) tools allow for the integration of occupancy and behavioural actions in the calculation process. Although this feature opens a lot of possibilities to more precisely study the impact of occupants' behaviour on building energy consumption it is limited due to static definitions of user schedules and actions [Zimmermann 2007]. Therefore, the simulation outcomes tend to be rather generalised and not very realistic. Eventually, the results are regularly not appropriate for further investigation.

Various studies are oriented towards physical building optimisation to reduce the energy consumption of buildings individually but also at an urban scale. The latter was strived for instance by Ghiassi (2017) who developed a model to estimate urban energy consumption. However, the potential of behavioural changes for energy savings at urban scale have not been sufficiently explored. Common methods tend to utilise norm-users without regard to divergences in behaviour. This is because it is challenging to understand occupant's behaviour in terms of energy consumption even at small scale. Needless to say, changes in behaviour might reduce buildings' energy consumption significantly while involving little cost in comparison to refurbishment measures. Additionally, potential occurrences of rebound effect phenomena in certain correlations between user behaviour and building typology can be estimated more clearly.

This work focuses on possible impacts of specified user behaviour scenarios on building's energy consumption. It will be investigated how sample building types that feature specific thermal characteristics are affected by different user behaviour aspects in terms of energy consumption while maintaining decent indoor conditions regarding temperature distribution. Subsequently, the survey conducted at building scale via the mentioned representatives will be upscaled to a larger building portfolio. This will provide not only insights about the main influencing parameters of occupant behaviour on building energy consumption, but also an overview about the energy saving potential connected with a change of occupancy patterns.

1.2 Motivation

During the last decades efforts have been made to more precisely estimate the energy demand of the built environment via building performance simulation (BPS) software. Such tools regularly feature detailed descriptions of the physical properties of the building (e.g. building envelope, heating system) and the geographical situation (climate data, surrounding and orientation of the building). Furthermore, the occupant's influence on energy consumption can be modelled in detail to study the impact of occupants on buildings. Users in buildings in common practice are modelled according to schedules, which can be obtained by specialised organisations that provide the modeller with standard values. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) for instance provides schedules that usually describe typical circumstances in office buildings. The Austrian standard ÖNORM B8110-5 (ASI 2019) offers predefined values for people's behaviour in buildings of different usages. However, detailed schedules of occupant behaviour are not defined and foreseen for use in standardised energy calculation procedures. Generally, it can be observed that only few studies focus on the impact of residents on private households, while it is well known that individual habits and manners vary significantly.

Considering reasonable scenarios of energy related behaviour and the possible subsequent effects on energy consumption based on different behaviour patterns opens a rarely discussed view on the topic.

According to Statistics Austria (2015) more than 149.000 buildings in Vienna are declared as residential, while just over 15.600 account for industry, offices, hotels, cultural or other purposes. These numbers highlight the significance of understanding human interaction in the residential sector. Thus, the core idea of this contribution is to investigate how different characteristics in occupant behaviour in households influence the energy requirements (including the potential of energy/heat dissipation caused by occupant behaviour) of different, commonly found, building typologies in an urban context.

1.3 Background

Numerous studies based on statistics and collected performance data exist and provide a decent overview of building's performances. For instance, within the frame of the EU-project TABULA (Typology Approach for Building Stock Energy Assessment), a transnational concept for classifying building typologies was developed that investigated the building stock of 13 countries in Europe (IWU 2020). It evaluates common building types according to their physical and technical properties and contrasts the status quo with possible refurbishment measures. The EPISCOPE project (IEE 2016) was introduced as its successor to keep track of actual refurbishment measures across Europe. However, the effect of user presence and behaviour on the building energy consumption is rarely considered in these cases. As mentioned earlier, in energy evaluations it is common practise to consider occupant behaviour by implementing normative methods. Reliable information about occupant's impacts on energy demand is usually based on either physical measurements or historical data which are both difficult and arduous to collect, especially if the investigated object is a building of larger scale or even a neighbourhood.

Yu et al. (2011) conducted a data analysis method to investigate user behavioural impacts on energy consumption where buildings in six districts in Japan were grouped via clustering techniques solely according to their physical characteristics. Beforehand the actual end-use energy consumption with human interaction was measured. The building's groupings by similarity in terms of physical properties was the basis to compare as to which amount user behavioural aspects affect energy consumption. Ouyang and Hokao (2009) studied the differences in electricity demand for 124 households. While half of the users were educated in terms of reasonable behaviour towards energy conservation before the experiment, the other residents maintained their usual habits. The "educated" user behaviour group showed an approximately 10% decrease in electricity consumption. The authors suggest a shifting of some effort from technological measures to improving occupant's behaviour. It has to be mentioned though, that the investigated buildings showed different physical characteristics which precluded an accurate comparison. Clevenger and Haymaker (2006) defined plausible ranges of parameter values for simulation to compare the effects of building occupant's behaviour on energy consumption in two schools located in different climate zones. The study concluded that an improvement in occupancy modelling is necessary but also that evaluating alternatives (different scenarios for comparison) is more useful and feasible than reliable predictions of energy performances. Munoz and Peters (2014) developed an urban energy simulation model of the city of Hamburg integrating occupant behaviour on the basis of the

German micro census. Their main idea was to renounce the commonly assumed "average" occupant. They found that introducing socio-demographic attributes of occupants living in specific areas in simulation software is a valuable method. Pont et al. (2019) developed a streamlined GIS-based approach, which was tested on two neighbourhoods in Linz, Austria. The GIS-data was augmented with additional information about the buildings via in-site visits and documentation but also socio-economic aspects of the inhabitants taken from demographical and statistical data. The advantage of this GIS-approach (the project was named "E-Profil") is its fast application and easy to gain results for large building portfolios. The shortcomings are the little level of detail of the results, which widely deny variation amongst important input data aspects such as the user behaviour.

Ghiassi (2017) published broad research on the so-called "hourglass approach". This contribution aimed for three main developments: First, the target area (a city district in Vienna) was modelled using GIS data among others. Second, a clustering method was developed to downscale the built environment of the urban setting to only few representative buildings. Third, a method to then upscale the representative buildings to the neighbourhood was developed, focussing on re-diversification of the original information. Even though it is a powerful technique, a drawback of the "hourglass approach" is that diversity in occupant behaviour is subsidiary since variance is only applied on the building typologies' thermal qualities. To sum up, various research has been conducted in building energy performance identification and energy related occupant behaviour and scientific studies deliver numerous strategies at building scale as well as urban scale. Nevertheless, one key factor that has consistently been identified as problematic and uncertain is the integration of realistic occupant behaviour.

Intensive research pertaining to the general capturing of building occupant behaviour, its' impact onto building performance, and methods for assessing and evaluating occupants' behaviour have been conducted in the IEA EBC Annex 66 (Yan 2018) and the ongoing IEA EBC Annex 79.

1.4 Objective

A neighbourhood in central Vienna is used to conduct a cluster- and simulation-based case-study onto building performance aspects. Thereby, various occupant-behaviour scenarios are applied on different building typologies to examine the impact of these assumptions onto the building energy performance of a larger building portfolio. The simulation efforts focus on whole year runs to clearly identify the influence of behavioural assumptions on key performance indicators.

1.5 Research questions

The application of user behaviour scenarios on sample buildings of diverse physical properties in an urban context delivers a wide range of outcomes concerning energy consumption.

Q1: Is it possible to obtain estimations about the impact of building occupant's behaviour onto building energy performance indicators via the cluster/upscaling method for a whole district or city? If yes, what kind of uncertainties can be monitored?

Q2: Given that Q1 can be answered with a yes, which saving potential for building-related energy consumption would be possible in view of changes in the user behaviour?

2 METHOD

2.1 Overview

This section briefly introduces the processing steps of this work in practical terms: An urban area is selected, including 535 buildings. This entire set of buildings is represented - in terms of building performance - by five buildings which were found through methods of clustering by Ghiassi (2017). These five buildings are simplified to one typical building storey for each instance, three-dimensionally modelled, and imported into simulation software. At this stage three different occupant types are created which are to a variable extent brought together to form three populations, each dominated by one occupant type. Various simulation scenarios are executed and evaluated in spreadsheets. These results are applied to the initial urban area, reverting to the work by Ghiassi (2017). A work-flow diagram in section 2.8 figuratively illustrates the here described steps.

2.2 Investigated urban instance

The foundation of this current work is a sample of representative buildings that were determined by one chapter of the "Hourglass Approach", developed by Ghiassi (2017). This method was developed to represent the building stock of a larger urban instance by clustering buildings that show similarities in their energy related behaviour. With this procedure exactly one typical building evolves from each cluster which makes the urban setting easier to understand. The urban context observed is a neighbourhood close to the very center of the city of Vienna, including parts of the first, fourth and sixth district. In total seven clusters were found to represent the investigated neighbourhood. Ghiassi's work focused on losing as little information as possible to maintain diversification throughout this downscaling process - the "reductive method" - which results in the above-mentioned representatives. Distinct representative buildings provide a solid base for further investigation in urban energy demand. The concluding "re-diversification process" will be discussed in a later section. While the "Hourglass Approach" can be executed on any urban area, Ghiassi applied her work on a neighbourhood, typical for the so-called "inner districts" of Vienna, and located right next to the city center. Regarding the urban area, the same approach is applied within this work. In Figure 1 the concerned area as well as the location of the representative cluster buildings are illustrated.

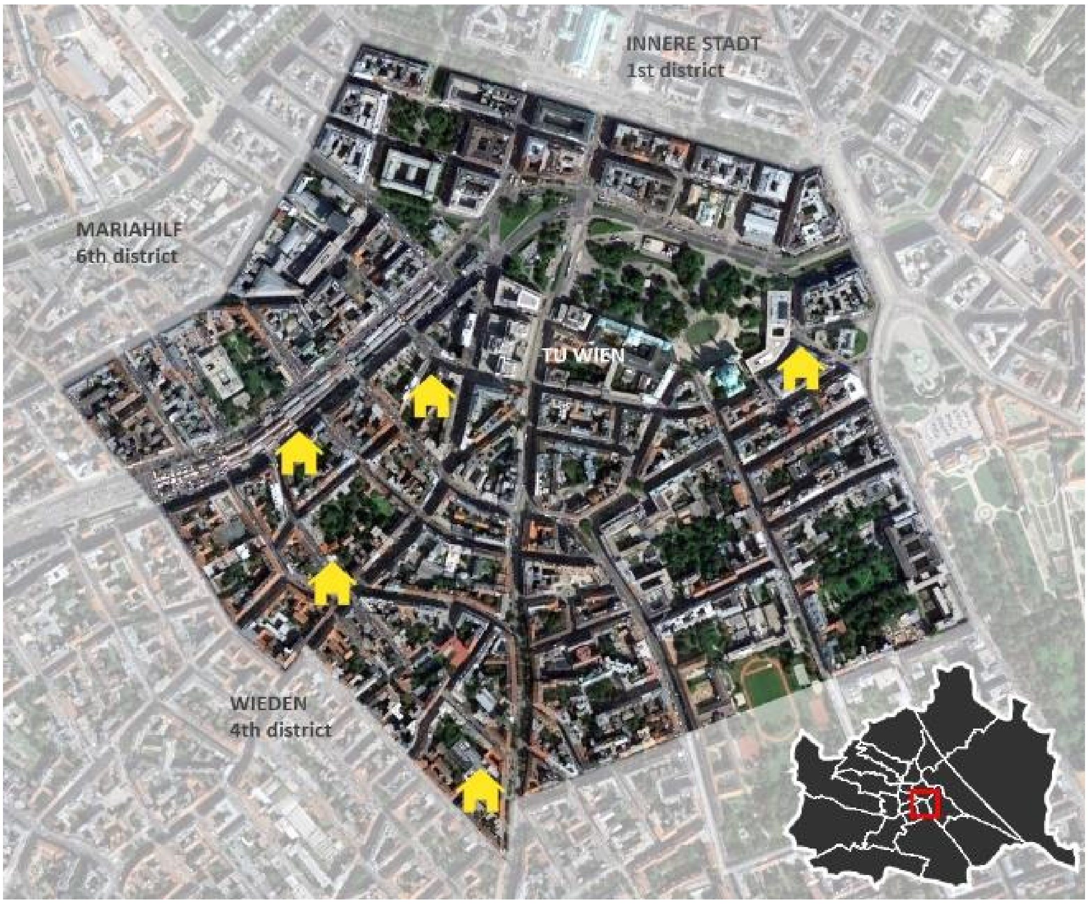

Figure 1: Bird's-eye view of the concerned urban area indicating the locations of the representative buildings. Source: Google Maps, Google 2016, own illustration

2.3 Reference buildings

In the aforementioned, indicated down-scaling process of the investigated urban area, seven clusters have been identified, each represented by one specific building. The clustering algorithms included the k-means method, the hierarchical agglomerative method, as well as model-based clustering (Ghiassi 2017). A comprehensive explanation to the mode of operation of these methods can be found in *"An hourglass Approach to Urban Energy Consumption"*, (Ghiassi 2017.).

Five of the representative cluster buildings are mainly residential (the ground floors are in all cases non-residential), the remaining two are of commercial or mixed usage. Operations within office buildings and commercial activity are excluded from this work due to a number of reasons: First, many studies on commercial buildings have been conducted in the past. As such, there are great quantities of research literature, indicators for energy efficient application, and guidelines for design and refurbishment measures of such buildings available. Second, comparing residential to non-residential building performance can be considered non-trivial, due to different operational schemes, different building envelope specifications, and other differences. Nonetheless, such buildings might become content of future enquiries. Therefore, the two non-residential buildings will not be further investigated in this work. From each of the cluster buildings one typical floor is chosen and modelled. Modelling the entire buildings with all storeys would in the context of this study result in an excessive number of outcomes. This circumstance would complicate the data evaluation due to the vast number of interferences from neighbouring apartments.

Floors and ceilings to other building storeys are considered adiabatic (and thus as non energy/heat transmitting). A further simplification has been applied to neighbouring buildings: Connecting elements to adjacent buildings are considered adiabatic, regardless of these buildings' functionality and usage.

2.3.1 Geometry and geometry input data for simulation.

The geometries of the representative buildings have been derived based on construction permit plans acquired from the responsible authorities (MA37, Magistrat der Stadt Wien). All of the investigated sample buildings date back to a time when architectural plans have been drafted manually. In one case even the dimensioning had to be translated from "Wiener Klafter" to the metric system, since the latter was only officially introduced in Vienna by 1873 (Stadt Wien 2017). To ensure a meticulous reconstruction in the models, the blueprints of the existing buildings have initially been digitalised as two-dimensional floor plans using AutoCAD (Autodesk 2016) and subsequently designed in the OpenStudio Plugin (Version 2.4.0, LLC 2017) for SketchUp (Google 2017) as three-dimensional models. The outlines of neighbouring buildings are integrated as surfaces to determine the urban context and allow cast shadows following the position of the sun over daytime.

All of the rooms and spaces in the concerned storeys in the representative buildings have been created individually and defined as autonomous thermal zones. In more specific terms, this means that each thermal zone (e.g. living room) in itself can be defined, controlled, and monitored independently in the simulation process. Needless to say, this already creates a large number of zones within each building model. These numbers, including conditioned as well as unconditioned zones, can be obtained from Table 1. The wall openings (doors and fenestration) are modelled according to the original blueprints, so that richness in detail and high flexibility are given for various simulation scenarios. In SketchUp the building components have to be assumed and drawn as two-dimensional objects and therefore they do not possess any thickness in geometry. Exterior walls, roofs, and ground floors are geometrically zoned by the inside line of the building component, while interior walls and ceilings separating different thermal zones border in the hypothetical middle axis of the corresponding component. This procedure is crucial for an accurate geometry interpretation for the simulation software EnergyPlus, in which the three-dimensional model is imported and further developed. The modelling progress in EnergyPlus with building-related input data and parameters is discussed in the subsequent section. Table 1 provides basic information about the processed cluster buildings, including construction periods, sizing, and quantity of apartments and zones as well as the buildings' orientation relative to north. For cluster 1 and 2 precise information is available regarding the years of construction while cluster 3, 4, 5 can only be allocated to a construction period, but not to a specific year. The date in Table 1 is provided for the entire buildings as well as for the investigated typical storey.

Table 1: Itemised cluster buildings with basic fundamental data

Cluster denotation	Cluster A	Cluster B	Cluster C	Cluster D	Cluster E
Year(s) of construction / Construction period	1914	1952/53	1781-1848	1848-1918	1996-2000
Main façade orientation [° CCW from North]	58	38	305	131	46
Whole building					
Number of apartments	112	19	15	18	34
Conditioned zones	425	122	66	93	173
Unconditioned zones	39	9	8	8	6
Total number of zones	464	131	74	101	179
Net floor area of conditioned spaces [m²]	5582	983	1311	1401	1893
Investigated typical storey					
Number of apartments	19	3	5	5	5
Conditioned zones	73	20	22	22	25
Unconditioned zones	5	1	1	1	1
Total number of zones	78	21	23	23	26
Net floor area of conditioned spaces [m²]	1055	181	435	318	303

To figuratively illustrate the representative buildings, Figure 2 contains a perspective view of the three-dimensional building model as well as a floor plan of one typical storey for each building. The investigated storey from each building is highlighted in colour. Within these illustrations, the different colours indicate whether the building part is exposed to outside air (blue) or considered adiabatic (pink). In the floor plans the sand-coloured areas indicate conditioned zones while purple designates unconditioned areas inside the building which include staircases, hallways and several sanitary areas from earlier times when integrating toilets inside the flat was not always standard practice.

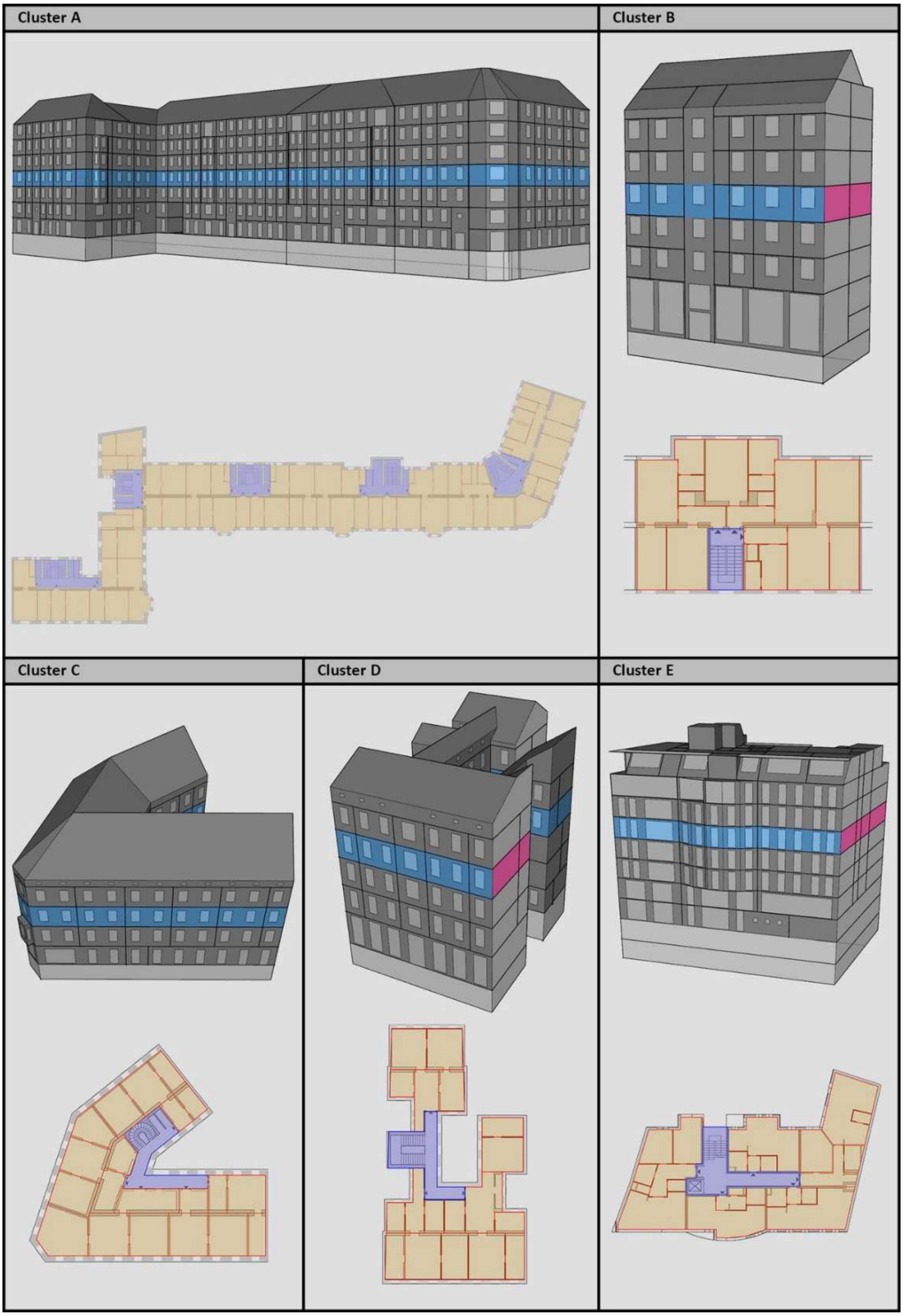

Figure 2: Perspective outside view of each building with floor plan of one typical storey. Source: Own illustration, Top illustration: SketchUp with OpenStudio, bottom illustration: AutoCAD

The room types occurring in the cluster buildings and defined as thermal zones are listed in Table 2. The Occupancy reference, separating the zones in habitable and non-habitable rooms, indicates whether occupants do have a (scheduled) presence in the concerning zone or not. A detailed description on this topic is given in section 2.5.4.

Table 2: Room types with thermal zone assignation and categorisation

Thermal zone	**Occupancy reference**
Living room	habitable
Living room – kitchen, combined	habitable
Living room – kitchen – bedroom, combined	habitable
Bedroom	habitable
Kitchen	non habitable
Bathroom	non habitable
Hall	non habitable
Toilet	non habitable
Storage room	non habitable

2.3.2 Semantic information about buildings and components

The previous section provided an outline on how the five representative buildings' geometry has been considered. This section focuses on the tools and methods used to incorporate semantic information about the buildings' physical and operational properties into the raw geometries. At this stage a description is given on which building related parameters are added or adjusted to lay the necessary foundation for the simulation in EnergyPlus (DOE 2019).

Materials and constructions of the building components have been assigned following a hierarchy: In case, semantic information about the components was available in the building plans this has been used; otherwise, educated approximations have been taken, which were supported by literature, e.g. the handbook for thermal retrofit of historical buildings (WKO 2012).

As mentioned earlier, all building construction elements were created as two-dimensional surfaces in SketchUp. In EnergyPlus, layers with appropriate thickness and physical properties were assigned to these surfaces to generate the corresponding materials. Material layers assembling constructions are arranged vice versa for the adjacent counterpart. To provide an example, Table 3 shows the setup of an interior floor/ceiling construction that connects two thermally conditioned zones (note that for each cluster only one building storey is modelled. Adjacent thermal zones above or below these storeys are only hypothetically conditioned zones. Nevertheless, floor and ceiling constructions are modelled according to the original buildings and considered adiabatic). This construction setup is an excerpt from the configuration of cluster building B, which is a typical residential building from the post-war period of the 1950s in Vienna.

For cluster buildings A, B, C, and D, materials and construction arrangements were chosen according to the handbook for thermal retrofit of historical buildings (WKO 2012). The fenestration objects in these cases are defined as casement windows, commonly known in Viennese buildings from earlier construction periods. Cluster E descends from a later building construction era, in which it was already obligatory to list detailed information about the construction components on the blueprints. Therefore, detailed data about the corresponding constructions for all building parts is available. In contrast to the other buildings, double-glazed insulation windows can be found in cluster E; as a result, the U-Value of the windows of this building are significantly lower than those of the other cluster buildings.

Table 3: Exemplary construction setup of an interior floor/ceiling in cluster building B

Material	Roughness	Thickness [m]	Conductivity [W/(m*K)]	Density [kg/m³]	Specific heat [J/kg*K]	Thermal absorptance
Internal plaster	Medium smooth	0.01	0.7	1600	1000	0.9
Reinforced concrete	Medium rough	0.2	2.1	2400	1000	0.9
Levelling granule	Very rough	0.03	0.7	1600	800	0.9
Footstep insulation	Medium smooth	0.005	0.04	11	1450	0.9
Cement screed	Medium rough	0.05	1.4	2000	1080	0.9
Parquet flooring	Smooth	0.015	0.15	740	1600	0.9

The simulation settings for the windows of each of the representative buildings have been determined based on the window type that can be found at the corresponding building: Both glass and frame/divider settings have been set accordingly. Exterior and interior doors are assumed to be timber constructions. Such constructions are the prevailing door typology in older buildings (wooden doors are also assumed for cluster E since no definite information is available). Natural ventilation aspects (opening of windows) are key factors of this work and will be discussed later on. Ventilation and infiltration (hereby understood as “unintended” air change through gaps and leakages) both in reality and in the context of simulation need to be considered in conjunction (Sherman 2008). Given the age of cluster buildings A-D, the infiltration in these buildings was assumed to be remarkable, resulting in corresponding air leakages settings.

Several studies investigated the air tightness of the building stock by for instance using the Blower-Door procedure with tracer gas. Weithaas (2003) investigated natural air changes in existing building stock. Muenzenberg (2003), in this context, analysed the outcomes of 80 buildings from different qualities and construction periods and found typical infiltration values ranging from 0.1 to 0.5 h^{-1}.

In this work, a permanent infiltration rate of 0.3 h^{-1} (air change rate per hour) has been assumed and defined as input data for the simulation of the building storeys in buildings A-D. In contrast, for cluster E, which is from a more recent building period and thus assumed to feature a higher level of air tightness, a constant infiltration rate of 0.15 h^{-1} has been set. Ventilation via Windows (and specific ventilation systems) are not considered to be an aspect connected with the building envelope and its technical features, but rather a part of the human interaction with the envelope and thus considered as occupancy. These will be described in section 2.5. of this thesis.

2.4 Microclimatic context and observation periods

Vienna's climate can be described as a transition between oceanic and continental climate (Stadt Wien, 2020), showing significant distinctions in temperature between winter and summer months. For the simulations the EnergyPlus weather data file for Vienna (Schwechat airport) is used as provided from IWEC/ASHRAE (EnergyPlus 2021). The core idea of this work is on obtaining ranges in energy demand as a result of occupant behaviour scenarios. In this sense simulation events run through one whole year are investigated, starting with the 1st of January at 00:00 and ending with December 31st at 24:00. Figure 3 shows the average monthly temperature curve of the whole year for Vienna as provided from ASHRAE (2020).

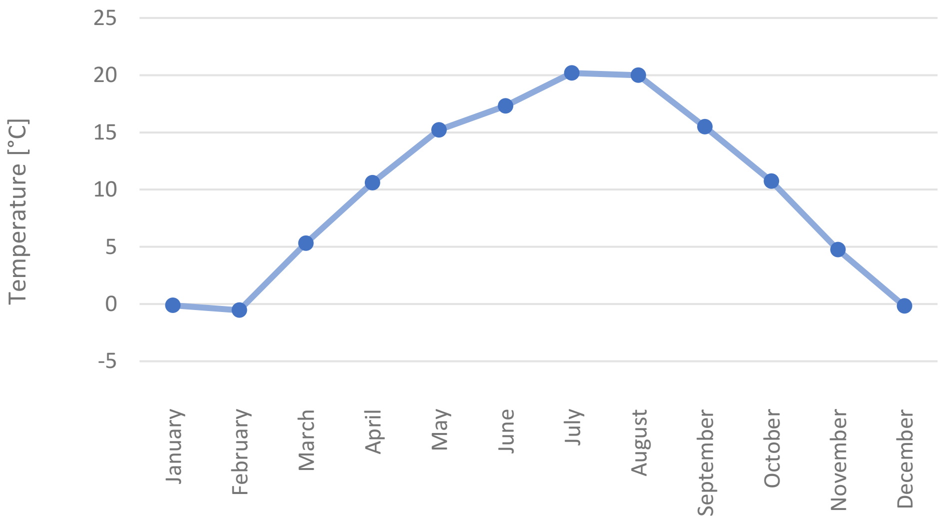

Figure 3: Monthly average temperatures for Vienna (ASHRAE 2020)

The simulation setup was configured to deliver hourly results throughout the investigated time periods. Furthermore, it has to be noted that the actual calculation steps were set at an interval of five minutes, resulting in a total of 12 time steps per hour. This fragmentation allows for a precise and at the same time more flexible integration and calculation of occupant behaviour interaction. Hence, it is possible to introduce behavioural actions in the simulation that occur at any time and last for any fragment of an hour, given that the five minutes interval is satisfied.

The buildings' orientations are a relevant component in the context of sunlight and shading and associated radiative solar heat gains. Figure 4 illustrates the orientation of the buildings with reference to their main façade.

Figure 4: Orientation of the cluster buildings (north arrow): The main façades are indicated by the arrows

2.5 User Behaviour Scenarios

2.5.1 Primary influencing factors

Defining reasonable scenarios in behaviour of human interaction in the residential building sector is the main focus of this work, and thus the essential parameter for the simulation procedures. Residents in their homes behave in many different ways when it comes to energy consumption, thus determining occupant behaviour is a complex procedure influenced by numerous circumstances (Mahdavi 2015). Important influencing factors of user behaviour for zone energy consumption are thermostat set points for both heating and cooling, applied ventilation regimes, and the use of shades in the summer months. Electrical equipment is a relevant energy consuming factor as well, however, it is subsidiary for thermal sensation and therefore kept constant for all occupant types in this study.

Regular opening of windows is necessary in homes without mechanical (semi-automated) ventilation systems to maintain acceptable indoor air quality levels. In this context minimum required ventilation rates are given by standards (e.g. DIN 4108-2 defines a minimum all time ventilation rate of 0.5 h^{-1} for residential homes). However, inappropriate ventilation regimes might result in increased heating loads in cold seasons or might negatively influence summer overheating mitigation in summer season.

Direct sunlight transmitted through windows increases indoor temperatures all year round. This circumstance makes it one relevant component for all seasons throughout the year. However, the effect during warm days needs to be separated from cold days. Sunny days during the winter time can increase indoor temperatures and, therefore, reduce heating energy consumption. At the same time, given the assumption that a cooling system is installed and in use, direct sunlight increases cooling loads on warm and sunny days. Therefore, a deliberate use of shading devices, blinds or curtains is useful to reduce solar gains on warm to hot summer days.

All of the mentioned parameters significantly influence the indoor climate conditions. The critical issue is to determine and create combinations of different influencing factors and provide realistic values. Obviously, it is quite challenging to describe and categorise people based on their building performance influencing behaviour. The following two key indicators were found to understand and describe occupant behaviour: First, the occupant's awareness or interest in possible energy saving potential and, second, the occupant's individual perception and request regarding indoor climate conditions. The question arising is how to determine and categorise individuals by their behavioural actions in domestic homes. The upcoming section is introducing a derivation on how building occupants can be grouped by their behaviour.

2.5.2 Categorisation of occupant types

Van Raaij and Verhallen (1983) developed a model focusing on how to categorise typical behaviour of building occupants in terms of heating energy consumption. The study descends from an economical and sociological background and dates back to the early 1980s. Nevertheless, it is based on extensive research and precisely explains reasonable methods on how to describe typical human behaviour in residential buildings. Figure 5 shows a graph originating from Van Raaij and Verhallen's publication conceptionally representing their determined user behaviour categories. Inspired from the mentioned study's straightforward approach, but not 1:1 building up on it, user behaviour scenarios of similar distinction are created for this work.

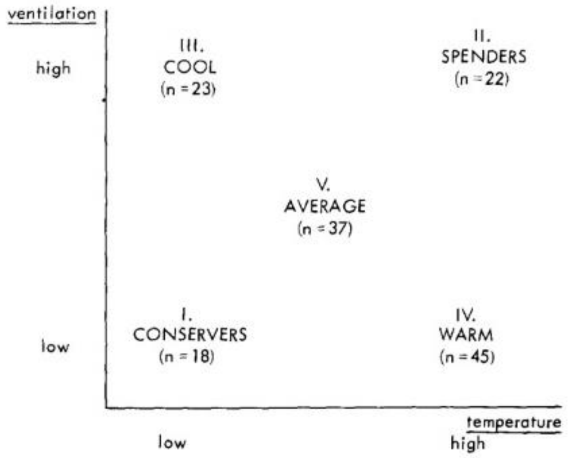

Figure 5: A way of representing user behaviour in residential buildings, Van Raaij & Verhallen 1983

The category designations basically remain the same in their denotation and mode of action except for the “average” user scenario. The latter is in this study not representing a building occupant that consumes the actual average energy in relation to other user scenarios but rather behaves very close to default values from previous research and suggested by norms. This circumstance prevents it from resulting in actual average outcomes from the simulations. To avoid confusion between the statistical meanings of average, the “average” occupant is refereed to as “default user” (or simply “default”) in this work. The “default” is defined by values given from the standards or suggestions and findings from research observations and literature. Other building occupant scenarios are “spender” and “conserver” as well as “warm” and “cool”. Spender and conserver can be best described by behaving according to their awareness in energy related behaviour. In the case of “warm” and “cool” the focus is on individual perception of indoor climate conditions and the resulting behavioural actions to aim for desired temperatures. However, the latter two are not simulated within this work. The reason for this is a predictable intermediate energy consumption outcome that would not support the main aim of this study. Nevertheless, these behavioural patterns will be explained in the upcoming sections and might become part of future research. Table 4 gives an introducing overview of the defined building occupant scenarios.

Table 4: (Principle) User behaviour scenarios

Occupant	**Characterised by**	**Motivation**
Spender	high energy consumption	not concerned or not aware
Default	"default" energy consumption	based on norms and literature
Conserver	low energy consumption	concerned and aware
Warm	sensitivity to cool temp.	warm indoor condition
Cool	sensitivity to warm temp.	cool indoor condition

For the representative building of each cluster scenarios are created defining users according to the following energy-related behavioural aspects: (1) heating set-points during winter and cooling set-points in the summer, (2) natural ventilation (opening of windows), (3) use of shading appliances (during summer only), (4) occupancy state with associated levels of physical activity, and (5), use of lighting and electric equipment. It has to be mentioned that there are no actual air conditioning systems installed in the investigated building stock, given the fact that the observed buildings date back to earlier times. Besides, indoor cooling in Vienna's residential sector is in general quite uncommon so far. Therefore, the calculation of cooling energy loads on warm and hot days is illustrating a hypothetical assumption which is, due to an observed increase in extreme temperatures over the past years already a topic of interest. Vienna's main energy provider, for instance, is currently developing a model for district cooling, based on the assumption that by the year 2040 the cooling energy consumption would be as high as the heating energy (Wien Energie 2021).

The "default" occupant is indicated by unique values, while in the other four scenarios there is at least one identical behavioural action that is shared with another occupant type. For instance, in January, the occupant "conserver" shares an identical configuration with occupant "cool" for the thermostat heating set points and their associated schedules. The same applies for "spender" and "warm". In contrast, "conserver" and "warm" follow an identical ventilation behaviour configuration, while the same applies here for "spender" and "cool". The configuration of the occupant behaviour in in the warm season follows the same rules but in different order: "conserver" and "cool" as well as "warm" and "spender" have identical ventilation behaviour, whereas "conserver" and "warm" as well as "cool" and "spender" share the same cooling schemes. Additionally, in the summer season the shading parameter takes effect and unites the behavioural configuration of "spender" and "warm" as well as "conserver" and "cool".

To illustrate the behavioural actions of each user type and the correlations between them, Figures 6 shows the setups for the winter and summer period, respectively. The additional shading scenario for warm days is illustrated in Figure 7.

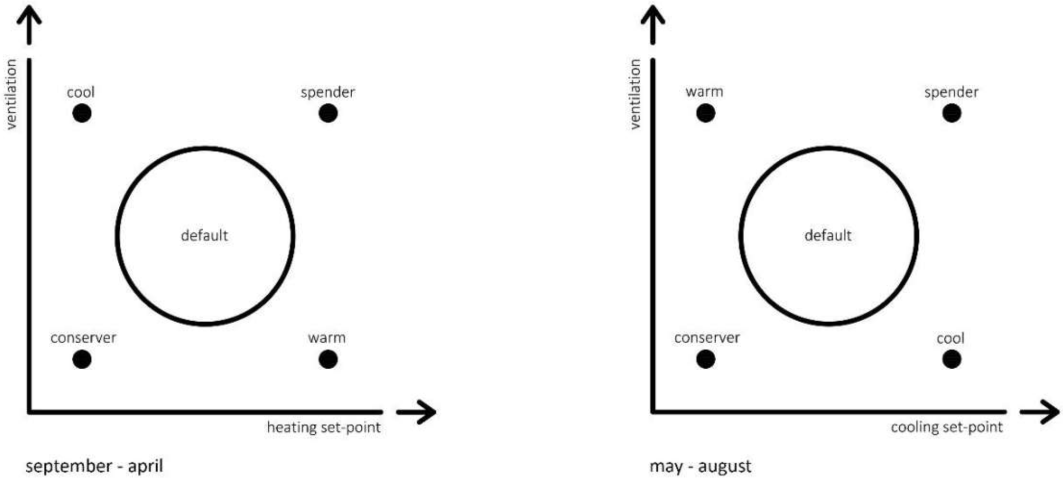

Figure 6: Occupant categorisation scheme. Left: heating season. Right: cooling season

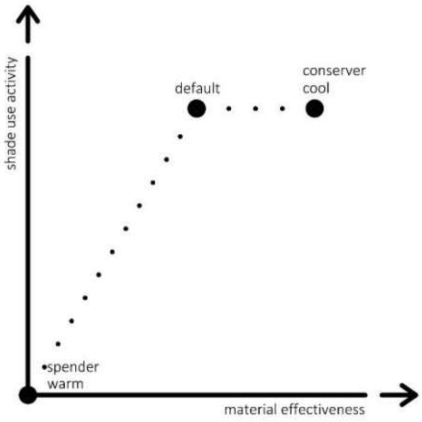

Figure 7: Use of shades during summer

Within the simulation, all of the user types share the same occupancy state and level of physical activity. This is, firstly, because these parameters cannot be directly linked to energy behaviour but are at the same time significant for the simulation to obtain realistic indoor temperature conditions. Secondly, an alteration of these attributes would significantly complicate the comparison between the different user types. Further specification is provided in section 2.5.4.

2.5.3 Semantic information about occupants

In this section, the application of natural ventilation, thermostat set points, and shading device controls will be described for the different occupant scenarios.

Section 2.3.2 explained the assumption of air leakages in the building envelope and the reason for chosen infiltration values of 0.3 h^{-1} and 0.15 h^{-1}, respectively. Additional natural ventilation values (due to window opening), usually range from 0.3 h^{-1} to 0.7 h^{-1} according to studies (e.g. Wolff 2002). As mentioned earlier, infiltration and ventilation have to be considered in conjunction (Sherman 2008) and are difficult to be determined as isolated values (Wolff 2002). For the user scenarios in this work, ventilation rates between 0.2 and 0.5 h-1 are chosen and assigned to the specific occupancy pattern, according to the approach introduced in chapter 2.5.2 and can be obtained from Tables 5 and 6.

Since in the investigated buildings no mechanical ventilation occurs and window operation is manually conducted, the ventilation rate is not considered an all-time constant factor. Therefore, the values from Tables 5 and 6 are adjusted so that either a significantly higher air change occurs in a shorter period of time or the ventilation-based air change equals zero. The institute for housing and environment (Institut Wohnen und Umwelt 2001) found an approximated air change rate of 9 h^{-1} to 15 h^{-1} in an average room when windows are open but no transverse ventilation occurs. In an exemplary study, Muenzenberg (2003) measured an average value of 8.8 h^{-1} for open windows. Needless to say, these numbers vary significantly dependent on the character of room (orientation, sise, etc.) and windows (types, operation, area, etc.). It would exceed the scope of the current study to calculate the corresponding room-window ratio for all investigated thermal zones. Therefore, ventilation values are set up for all habitable rooms, namely living rooms, combined kitchen and living rooms, bedrooms, and single-room apartments equally in EnergyPlus. The adjusted values for intense short-time ventilation for different occupant types can be obtained from Table 7.

The heating period was defined as active from September 1st to April 30th in this work, whereas the cooling season comprises the intermediate months from May to August. These intervals apply to all occupant types. Moreover, the thermostat heating set point temperatures are divided into day and night operation. Depending on the corresponding occupant type, these values vary between 18 and 24 degree Celsius during the day and 16 to 20 degree Celsius during the night for habitable rooms. Day and night time are delimited with 6:00 AM and 10:00 PM. Ancillary rooms, which are not considered as spaces intended for a longer stay, are for the occupant profiles “conserver” and “default” operated with reduced heating set point temperatures, while occupant “spender” operates set points balanced for all rooms. The specified values can be obtained from Table 5. The thermostat cooling set points are chosen to be constant values throughout the 24-hour period (within the concerned months) and are listed in Table 6.

Table 5: Ventilation air change rates and thermostat heating set points, September to April

INDICATOR	ZONE	OCCUPANT				
		CONSERVER	DEFAULT	SPENDER	COOL	WARM
VENTILATION [AC/h]	Living room, combined living room – kitchen, single-room apartment	0.2	0.35	0.5	0.5	0.2
	Bedroom	0.2	0.35	0.5	0.5	0.2
HEATING SP. [°C]	Living room, combined living room – kitchen, single-room apartment	16 / 18	16 / 20	20 / 24	16 / 18	20 / 24
	Bedroom	16 / 18	16 / 20	20 / 24	16 / 18	20 / 24
	Kitchen	16 / 18	16 / 20	20 / 24	16 / 18	20 / 24
	Bathroom	16	16 / 20	20 / 24	16	20 / 24
	Hall	16	16	20 / 24	16	20 / 24
	Toilet	16	16	20 / 24	16	20 / 24
	Storage room	16	16	20 / 24	16	20 / 24

Table 6: Ventilation air change rates and thermostat cooling set points, May to August

INDICATOR	ZONE	OCCUPANT				
		CONSERVER	DEFAULT	SPENDER	COOL	WARM
VENTILATION [ACH]	Living room, combined living room – kitchen, single-room apartment	0.2	0.35	0.5	0.2	0.5
	Bedroom	0.2	0.35	0.5	0.2	0.5
COOLING SP. [°C]	Living room, combined living room – kitchen, single-room apartment	30	25	20	20	30
	Bedroom	30	25	20	20	30
	Kitchen	-	-	20	20	-
	Bathroom	-	-	20	20	-
	Hall	-	-	20	20	-
	Toilet	-	-	20	20	-
	Storage room	-	-	20	20	-

Table 7: Time and duration of opening windows

OCCUPANT	Daily windows opening times	ACR
"Conserver", "Cool" (summer), "Warm" (winter)	08:00 - 08:10 and 20:00 - 20:10	14.4
"Default"	08:00 - 08:15 and 14:00 - 14:15 and 20:00 - 20:15	11.2
"Spender", "Cool" (winter), "Warm" (summer)	08:00 - 08:30 and 14:00 - 14:30, and 20:00 - 20:30	8.0
All occupants	All other times	0

In addition to thermostat settings and ventilation behaviour, shading devices are another significant influencing factor in occupant related thermal energy consumption. Within this study, the use of shades is considered in summer season only. For occupant scenarios "spender" (and "warm") no shading blinds or textiles are considered at all. "Conserver" (and "cool") are set up to use a highly reflective shades with very low solar transmittance, whereas user "default" uses a medium reflective/medium transmittance shade. All deployed shading materials are scheduled to be active from 8:00 AM to 8:00 PM on a daily basis between May 1st and August 31st.

2.5.4 Occupancy and electric equipment

The defined building occupants show significant differences in their behavioural aspects related to thermal energy consumption, as previously explained. To establish realistic simulation models, other minor influential factors on heating and cooling energy consumption are included as well, however, defined equally in all user scenario cases. The reason for this is that too many different parameters would complicate or even irritate appropriate comparison. These additional parameters include: 1) residential occupancy, 2) activity levels, and 3) use of electric equipment. Residential occupancy is closely related to the occupants' activity level, meaning that if nobody is home there is no activity. Furthermore, activity levels change depending on the activity carried out. The use of electric equipment is presumably higher in times when residents are at home, but it might also occur in the other case. Needless to say, human activity and electric equipment give off heat and slightly increase indoor temperatures. Realistic values to allow for a neutral contribution of the described "minor" influential factors are taken from a declaration the IBPSA contributed for a student competition to calculate the energy consumption of a residential home (IBPSA, 2013). The provided data includes detailed schedules for typical daily occupancy, activity levels according to the task carried out, including for instance sleeping or cooking, and the use of electric equipment. Table 8 provides information about the values used for the simulations.

Table 8: Occupancy and activity levels of building residents

INDICATOR	ZONE	ALL OCCUPANT SCENARIOS		
People number (range 0-1 with reference to number of occupants)	Living room	SCHEDULED VALUES	RANGE 0-1	0, 0.5, 1
	Bedroom			0, 1
	Kitchen			0, 0.5, 1
	Bathroom			0, 0.5
	Storage, Toilet, Hall			0
People activity [W] (true if people number ≠ 0)	Living room		CONSTANT	120
	Bedroom			80
	Kitchen			120
	Bathroom			80
	Storage, Toilet, Hall			0
Internal gains [W]	Living room		NUMBER	10, 110, 150
	Bedroom			0, 60
	Kitchen			40, 540, 1040
	Bathroom			0, 100, 500, 800
	Storage, Toilet, Hall			0

2.5.5 Occupant count and distribution

Since the actual number of people living in the investigated apartments and buildings is not easily determinable, this value has been approximated utilizing statistical sources. Two different approaches have been considered on how to estimate these numbers: First, according to the average number of people living in one apartment and, second, based on how much living area the average person has at one's disposal. Needless to say, city districts and areas in Vienna significantly vary in building and population density. Both approaches are justifiable but still they deliver slightly different results. According to latest publications by Statistics Austria (2019), in Vienna the average number of people living in an apartment is 2.07 while at the same time individuals in Vienna claim 36,1m^2 of living space for themselves. Due to the fact that the size of apartments varies significantly in the investigated sample buildings, the square meter-per-person method has been chosen as input for the simulation models. The occupancy level is described by numbers 0, 0.5, and 1, based on the IBPSA competition (IBPSA, 2013). The number 0 indicates that no occupant is present, whereas 1 signifies 2.07 occupants, and 0.5 means that 50 % of the occupants are present.

Naturally, different individual persons living together in one building unit or one household will not show the exact same or even similar behaviour. Nevertheless, for the simulation one specific user behaviour per household is assumed. This has been mapped on the different building units. Methodologically, this means that we assume one imaginary person, and adjust the relevant factors according to the average number of square meters a Vienna resident inhabits. This is obviously a simplification of reality. However, variation amongst single users (considered as agents), could be subject of further investigation in future research. Letting various user behaviour interact simultaneously in one apartment would – even if realistic - probably lead to overlaps in the outcomes of different scenarios. This was excluded in this pioneering approach to gain insights to the impact of occupancy levels on a wider scale for large building portfolios. However, also this aspect could be a matter of further enquiries. Moreover, occupancy schedules, activity levels (metabolic rates) and general behaviour differ in individual zones. In other words, for example bedroom activity is different from kitchen activity but bathroom activity in apartment 3 equals bathroom activity in apartment 7 (within the same scenario, meaning that the same occupant, for instance "default", is investigated).

The occupant behaviour types, here "conserver", "default", and "spender", are arranged and distributed throughout the different apartments within the chosen storeys of the building clusters. In each case one user type is defined to be dominant in terms of occupation, allocated to 60 % of the conditioned net floor area. The two other occupant types share the remaining 40 % (the percentage values need to be seen as an approximation, since an exact distribution is not manageable within the context of the number and size of the apartments). The occupancy groups are always dominated by one specific user type and will, from this point on, be denoted as "population" with an additional label of the respective dominant type. The described distribution of user behaviour types for the creation of populations is shown in Figure 8. Each population scenario is by itself integrated into all of the clusters, resulting in three scenarios for each building. The sequence of assignment is in a sense randomly chosen but with the primary focus on satisfying the convergence to the requested percentage share. Figure 9 illustrates the method how populations are allocated in the building storeys from cluster buildings A-E. This allocation pattern remains consistent for all population scenarios. For instance, if the as "dominant" denoted apartments in buildings storey A (Figure 9) are occupied by user type "conserver", they are in the second and third population scenario occupied by "default" and "spender", respectively. In other words, given this example, apartments 1, 3, 5, 8-11, 13, 15, 17 and 19 always have in common the same occupant type per simulation scenario.

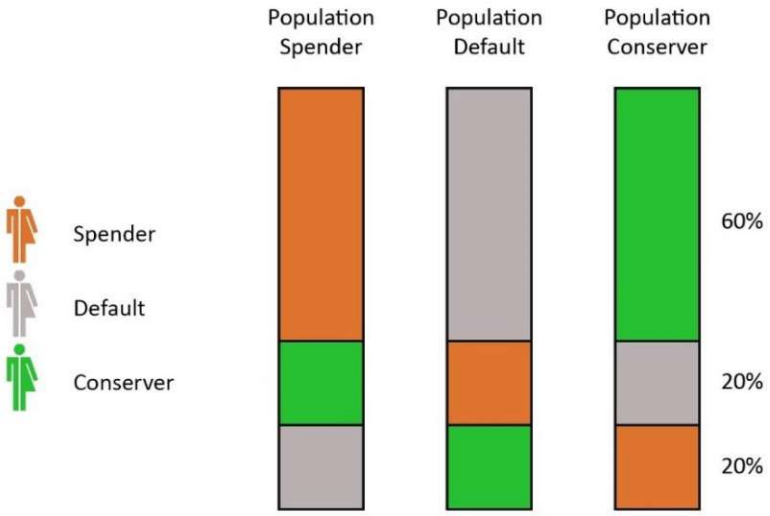

Figure 8: Distribution of occupant types for the simulation scenarios

Figure 9: Distribution of populations in the building storeys

2.6 Investigated key performance indicators

The key performance indicators (KPIs) observed in this work are, first, heating loads, second, cooling loads, and, third, indoor temperatures and overheating. The heating and cooling loads are observed in watt-hours and total values presented as kWh, MWh, and GWh, according to the magnitude of the outcome. Area- and time-related heating and cooling loads are expressed in kWh/(m²*a). Indoor temperatures are presented in degree Celsius [°C] in the form of cumulative. Overheating occurrences are calculated as a total for all habitable rooms and per population type. The results are presented in Kelvin hours [Kh] and observed for different assumptions of overheating barriers: 25°C, 26°C, and 27°C.

2.7 Upscaling

At this stage it should be recalled that the five representative buildings were originally found by Ghiassi (2017) via a method to represent an urban area by reducing it to a small number of instances, each representing one cluster. In Ghiassi's so-called "reductive module" some information was lost due to simplification. The aim of this current work can be described as an attempt to benefit from these "information gaps" and include detailed data about the building's operation, especially in terms of occupant behaviour scenarios. The latter was explained in the preceding sections and is adapted as a "relaunch" to the urban area.

For this study each of the representative buildings was reduced to one typical building storey for the simulations. In this context, the total building energy loads have to be estimated before the actual upscaling process to the urban area is conducted. The projection from storey-scale to building-scale is calculated according to Equation 1:

$$Q_b = (V_b/V_s) * Q_s \qquad (1)$$

, where Q_b is the total heating demand of the building, Q_s is the total heating demand of the simulated building storey, V_b is the total heated volume of the building, and V_s is the storey volume.

Ghiassi (2017) computed a list of all the buildings from each cluster, providing information about the "arbitrary" building's u-values, glazing ratios and more. For this work, the crucial information from this list is the total heated volume for each of the buildings in the urban area. The upscaling process from building to urban scale is executed according to Equation 2, found by Ghiassi (2017):

$$Q_{i,h} = (Q_{Sim,i,h} / V_{reference,i}) \times V_{n,i} \qquad (2)$$

, where $Q_{i,h}$ is the heating demand of an arbitrary building *i* from the clusters in the timestep *h* [kWh], $Q_{Sim,i}$ is the total heating demand of the representative building from the related cluster, $V_{reference,i}$ is the volume of the simulated building, and $V_{n,i}$ ist the volume of any building from the cluster list.

One drawback here is that no detailed information about the actual floor / room heights of the buildings is provided in the above-mentioned list. This implies that no accurate knowledge about the building's heated area is available at this stage to clearly identify heating loads per square meter (an identification of accurate floor heights would require information from the floor plans from each building, a factor which fails the scope of this work). Therefore, three different - in Vienna commonly found - floor heights are assumed, namely 2.50 m, 3.00 m, and 3.50 m, respectively. Given these assumptions, area-related energy loads can be calculated based on the simulation results. The range in area-related energy loads for differing floor height assumptions are illustrated and discussed in the results section.

2.8 Workflow

Figure 10 summarises and illustrates the processing steps of this work.

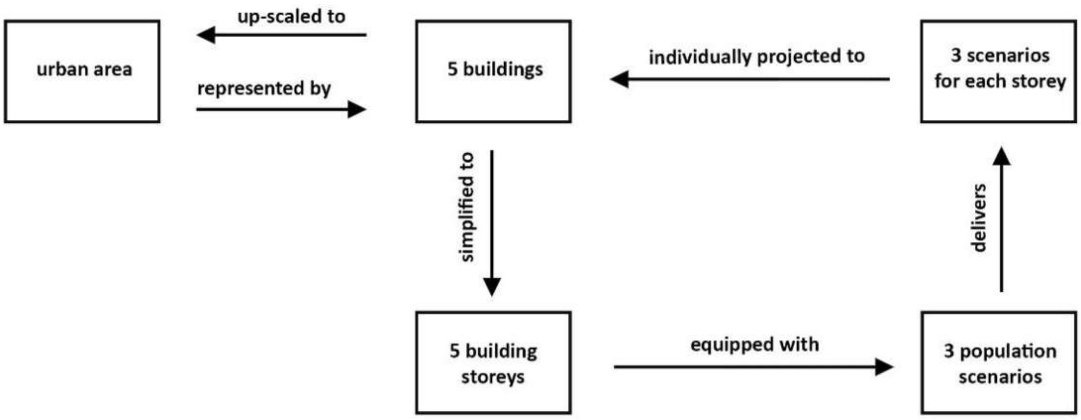

Figure 10: Schematic explanation of the work flow

3 RESULTS AND DISCUSSION

3.1 Overview

The fact that the building storeys of the representative buildings A, B, C, D, and E were modeled with high richness in detail and equipped with three different occupant scenarios, opens a wide range of possible simulation applications and research directions and thus a broad field for analyses of the outcomes. Furthermore, the translation from building storey to building as well as from building scale to the neighbourhood offers room for discussion.

To allow for a straightforward presentation and discussion, the results from different building storeys but of identical motivation are illustrated in consecutive order or within the same context. In other words, the outcomes are structured according to the key performance indicators (introduced in section 2.6) rather than for each building (storey) isolated. The upcoming sections are arranged according to the following main structure, determined by the scale of analysis: (1) building storey scale, (2) building scale, and (3) urban scale.

The building storey scale includes and explains graphs showing heating and cooling loads of the investigated storeys from representative buildings A to E. Heating and cooling loads are presented based on different population scenario, which are mixed but always dominated by one, and the impact of different occupants within the population are also observed solely. The section includes total values (kWh, GWh, or MWh) as well as translations to the concerned living areas and investigation periods (kWh/(m²*a)). Total overheating hours as well as average overheating temperatures during the summer months (May to August) are presented.

The second main category focuses on the projection from building storey scale to whole building scale. Results for heating and cooling energy loads will be presented.

The third main category discusses the upscaling process to the urban area and shows possible energy load estimations as total values, but also an attempt for averages per square meter and year. Furthermore, possible energy reduction potentials for the urban area are presented.

To allow a homogeneous labeling of the presented results, the different population patterns and their relative amount of presence in the different scenarios is described as follows: Occupant “conserver” is denoted with “c”, “default” with “d”, and “spender” with “s”. The single letters are followed by a two-digit number, indicating the percentage to which amount the respective occupant type is present within the population scenario (based on Figure 8 and 9 in section 2.5.5). The three different occupant types per population and their percentage presence are set in relation using “:”. The following example shows a scenario for a conserver-dominant population: “c60:d20:s20”. Note that in representative building B a total of only three apartments were found in the simulated building storey. Therefore, to allow for more differentiated results, this storey is only populated by two different occupant types per scenario.

Not all of the results can be presented within this section. Additional figures can be found in the appendix section of this work.

3.2 Building storey scale

3.2.1 Heating and cooling energy loads per population

The up-following figures show the monthly and annual total heating and cooling loads for the investigated building storeys from cluster A (Fig. 11-13), B (Fig. 14-16), C (Fig. 17-19), D (Fig. 20-22), and E (Fig. 23-25) for each occupant population scenario. The following observations can be made for all of the investigated building storeys:

First, population conserver shows the lowest number in energy loads, population spender shows the highest number, population default is in-between. This applies to heating as well as cooling energy loads. Only building storey B shows deviations from this “rule”. This is due to the limited size of the building storey, featuring three apartments only, which did not allow a more diversified distribution of different occupant types. In this case, for the default-dominant population, the occupant spender was chosen as a contrary. Therefore, the default-dominant population produces almost the same amount of heating energy loads as the spender-dominant does. This, however, shows only little impact on cooling loads. Nevertheless, building storey B generally follows the same trend.

Second, the total cooling energy loads for building storeys A to D shows relatively low values in comparison to heating loads. This, however, is not true for building storey E. Here, monthly total cooling energy loads rise almost as high as heating loads do during winter time. In return, the heating loads are observed to be significantly lower than in the other buildings (with reference to the size of the heated volume). In this respect, it is recalled that building E features a more insulating thermal building envelope and less infiltration. The higher cooling energy loads and summer overheating tendency of storey E might be related to the following aspects: (i) The well-insulated envelope does reduce heat flux to the outside during nights in comparison to the storeys A to D; (ii) the building features lower ceiling heights and thus reduced volumetric buffer space in comparison to A to D; (iii) the internal organisation of rooms in storey E is significantly different from the older buildings A to D.

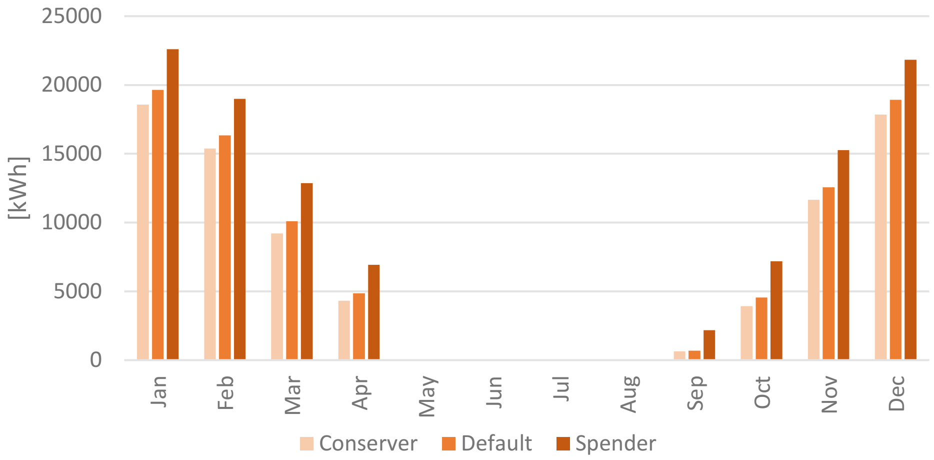

Figure 11: Total monthly heating loads, building storey A

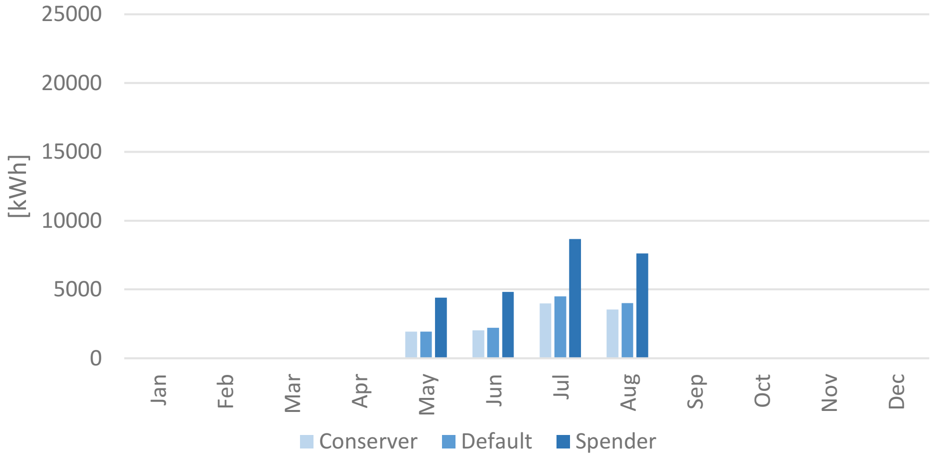

Figure 12: Total monthly cooling loads, building storey A

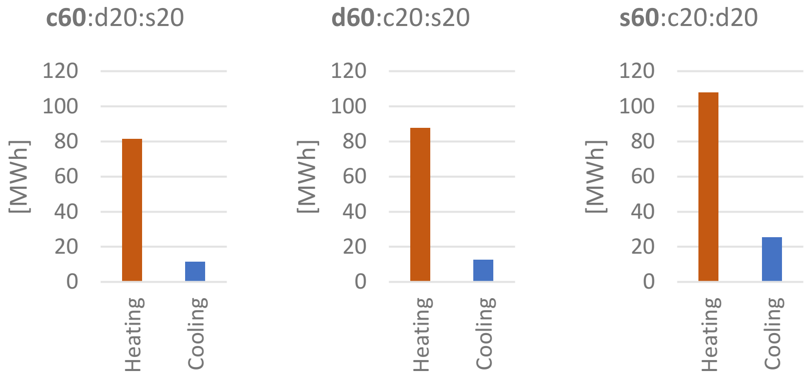

Figure 13: Annual heating and cooling loads for each population scenario, building storey A

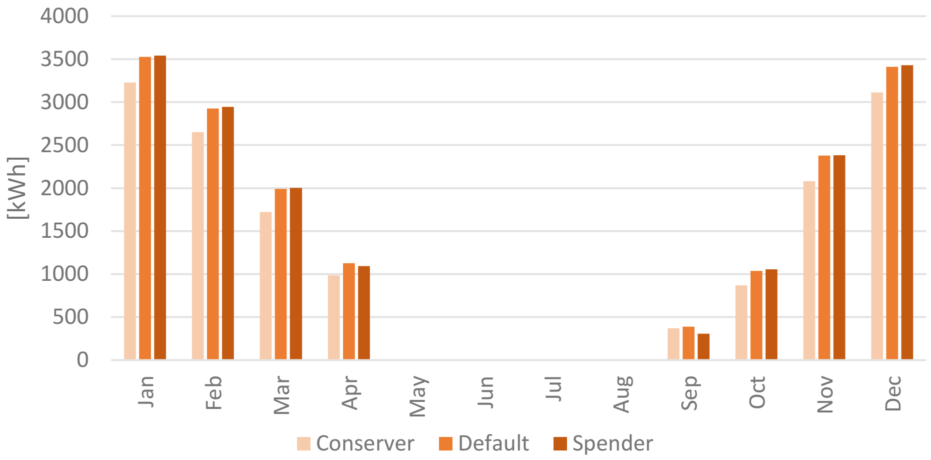

Figure 14: Total monthly heating loads, building storey B

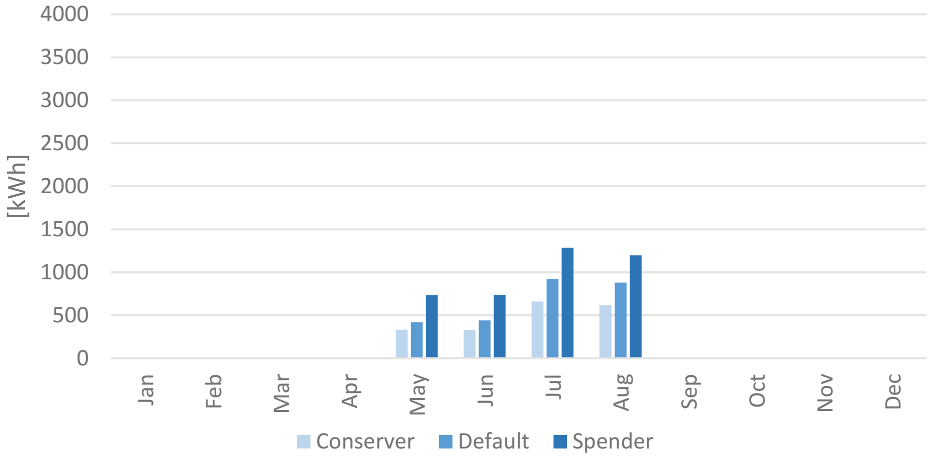

Figure 15: Total monthly cooling loads, building storey B

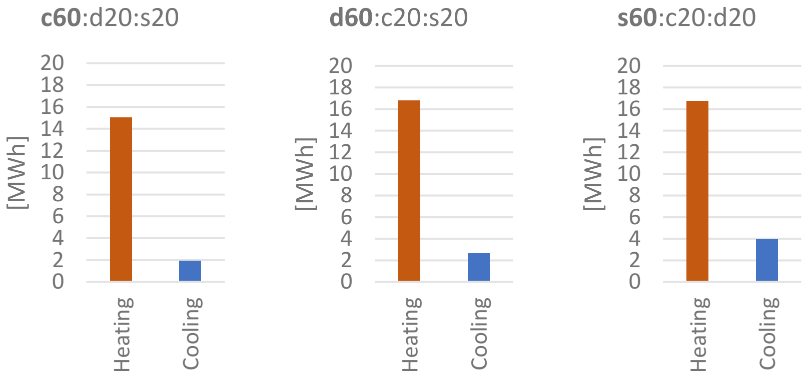

Figure 16: Annual heating and cooling loads for each population scenario, building storey B

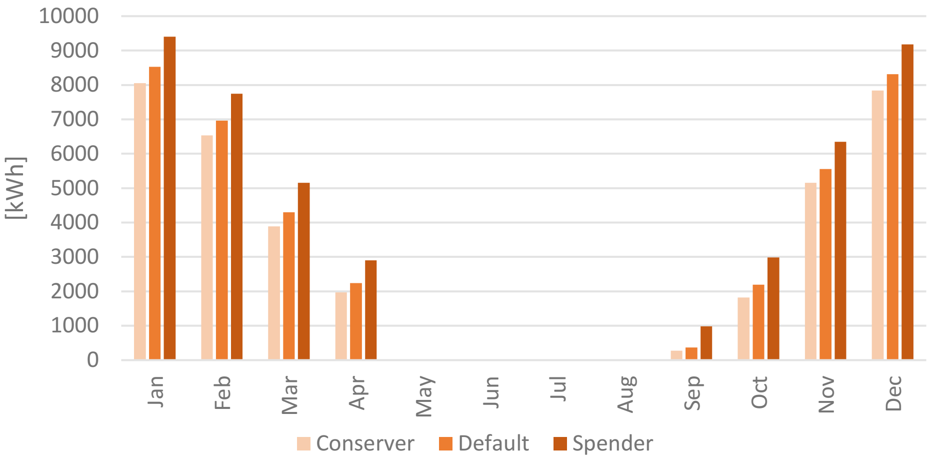

Figure 17: Total monthly heating loads, building storey C

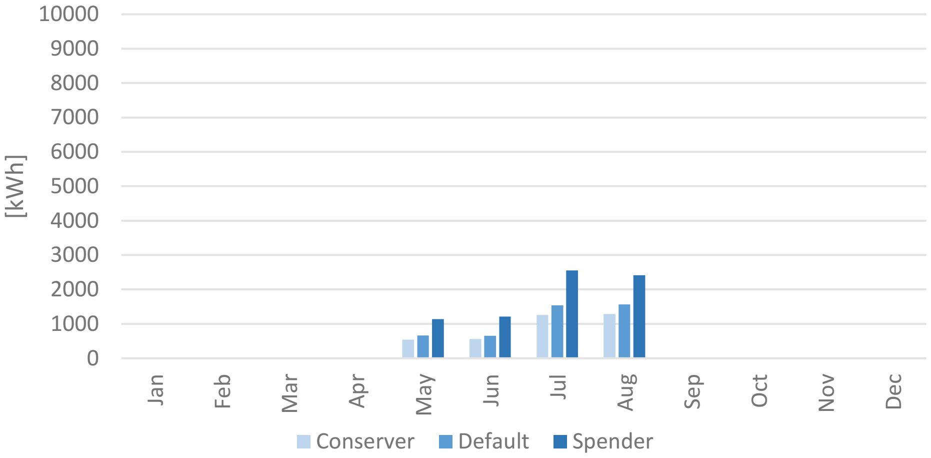

Figure 18: Total monthly cooling loads, building storey C

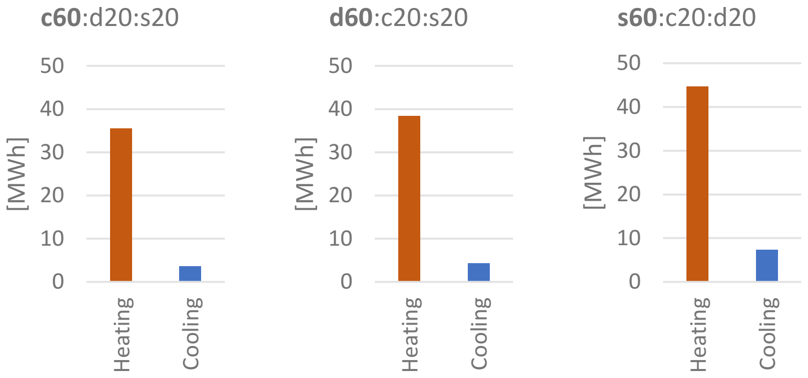

Figure 19: Annual heating and cooling loads for each population scenario, building storey C

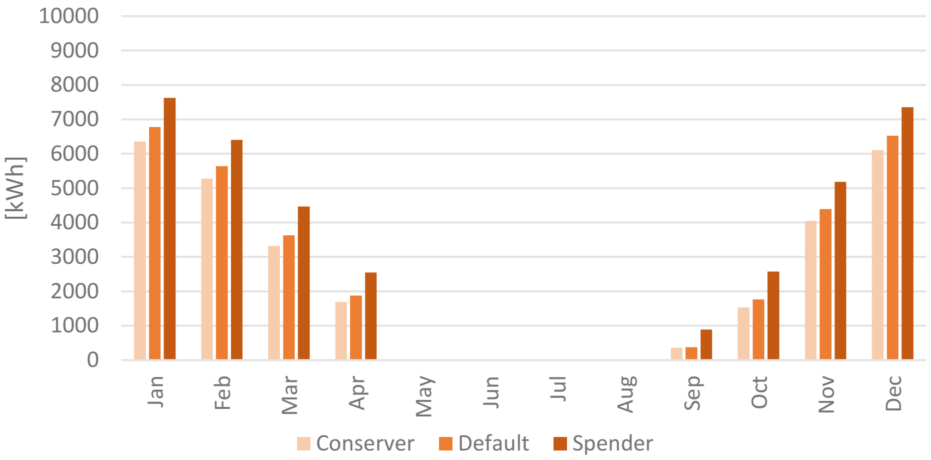

Figure 20: Total monthly heating loads, building storey D

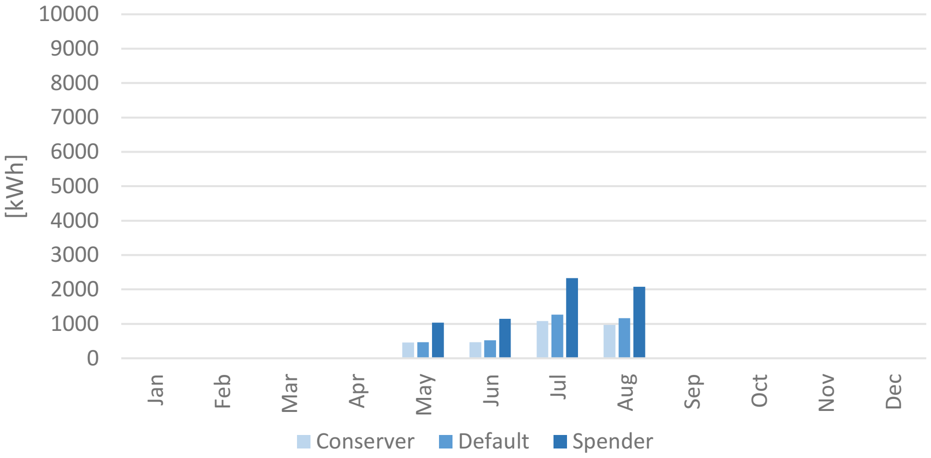

Figure 21: Total monthly cooling loads, building storey D

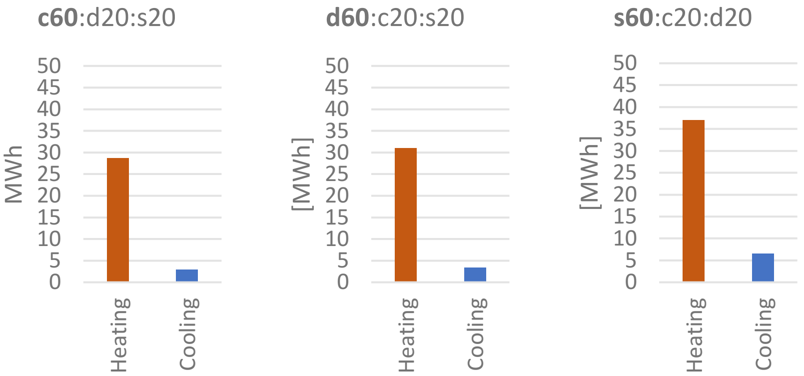

Figure 22: Annual heating and cooling loads for each population scenario, building storey D

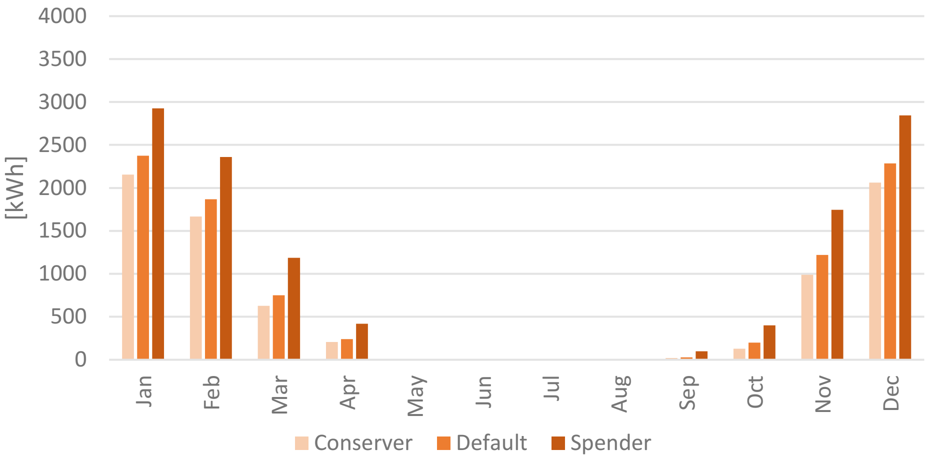

Figure 23: Total monthly heating loads, building storey E

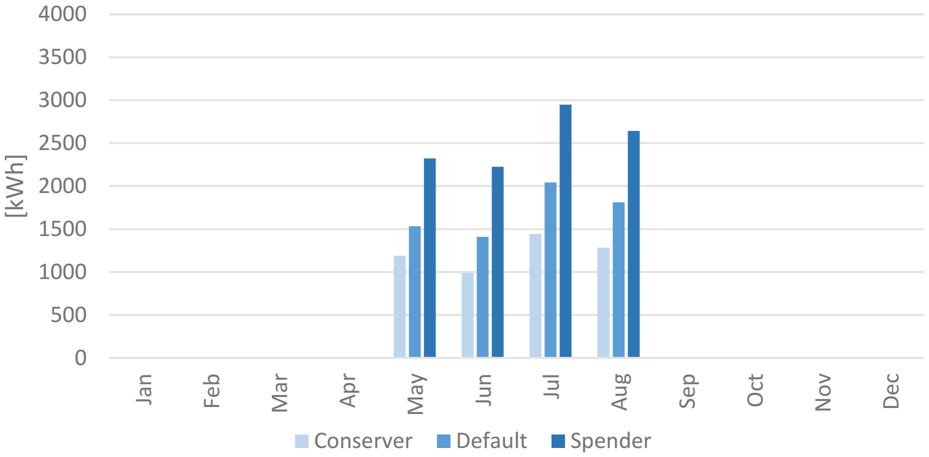

Figure 24: Total monthly cooling loads, building storey E

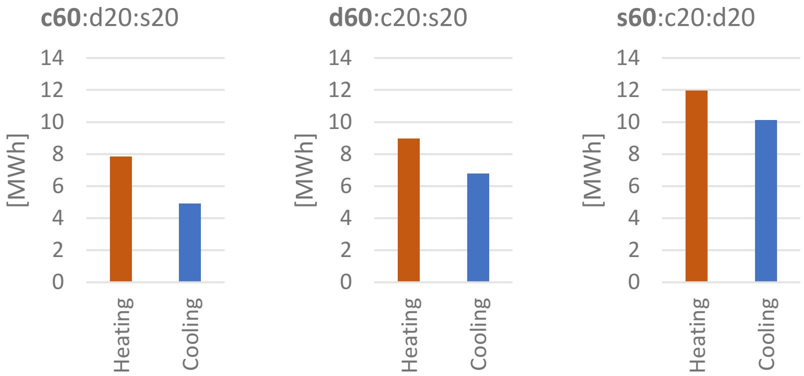

Figure 25: Annual heating and cooling loads for each population scenario, building storey E

Figure 26 illustrates the heating and cooling loads for each building storey and population in kWh per square meter and year and thus allows for a comparison. Obviously, population conserver is producing the smallest amount of energy loads while population spender shows the highest rates. Population default is in-between. Building storey B slightly deviates from this rule due to to the earlier explained distribution of occupants. Building storey E shows significantly lower values for heating loads, which was foreseeable due to the much higher thermal quality of the building envelope and lower infiltration rates. However, cooling loads during the summer months are considerably high, too, and reach almost the double amount of the other building storeys.

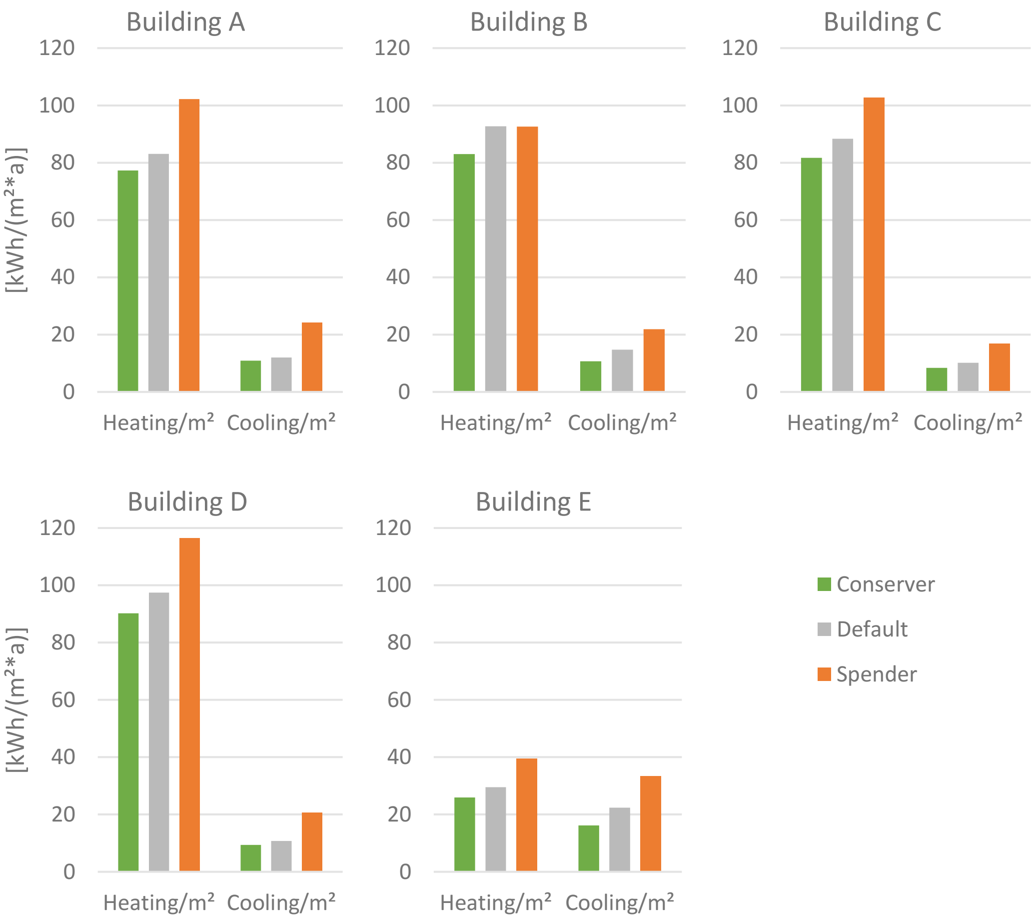

Figure 26: Annual heating and cooling loads per population

Figures 27-31 illustrate the heating and cooling loads of each occupant type within the population separately in kWh per square meter and year. The energy loads of apartments occupied by a specific user type are summed up and divided by the occupied area. The aim is to bring out a distinctive energy related behaviour type within the context of mixed-population behaviour. To provide an example, Figure 27 (c60:d20:s20) highlights the occupant “conserver” within the conserver-dominant population and shows the annual heating and cooling energy loads per square meter for this specific user type within the population. The gap between occupant conserver and spender is in all cases significant and suggests that heating and cooling related behaviour in adjacent residential building units strongly influences indoor temperature conditions and therefore heating and cooling loads.

For building storey D it can be observed that for the conserver- and spender-dominant populations, the default occupant type consumes less heating energy than the conserver occupant type. In both population scenarios, the default user type is occupying the same apartment, which has little exposure to the outside air and is adjacent to the unheated staircase. In the default-dominant population scenario, where the apartment is occupied by the conserver user type, this trend is confirmed.

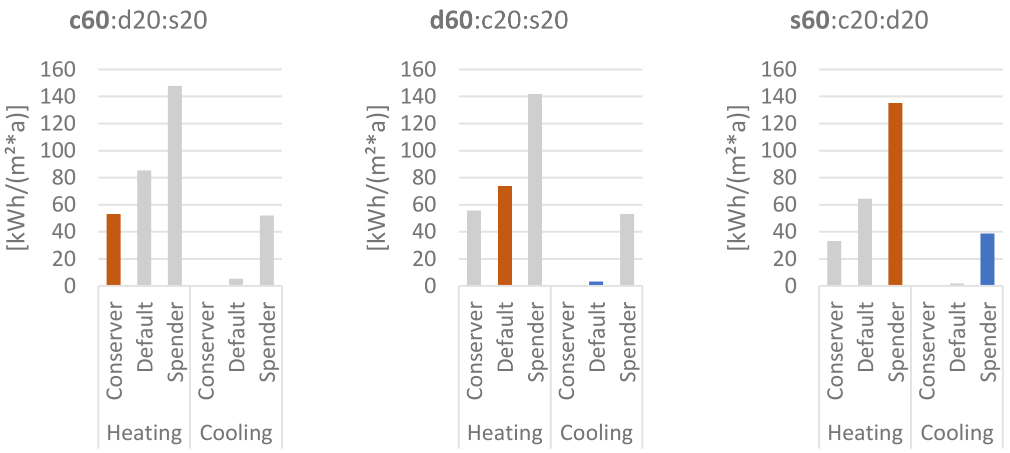

Figure 27: Annual heating and cooling loads per occupant type, building storey A

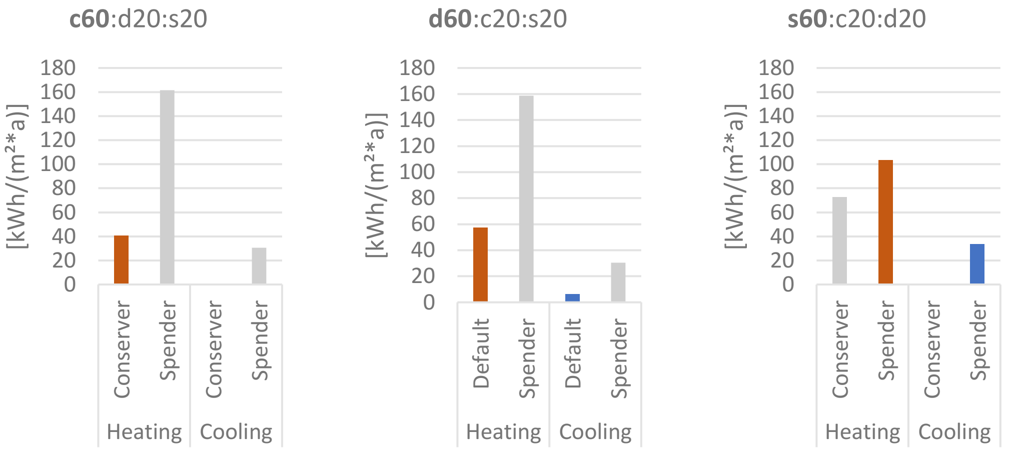

Figure 28: Annual heating and cooling loads per occupant type, building storey B

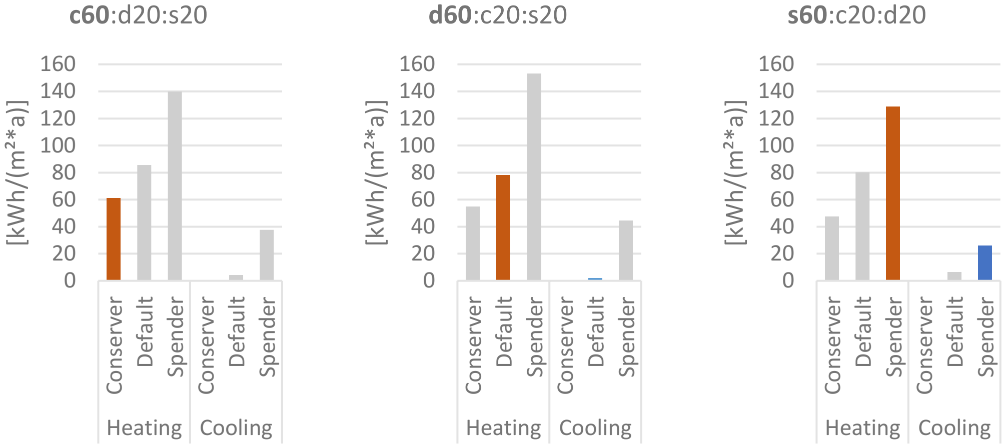

Figure 29: Annual heating and cooling loads per occupant type, building storey C

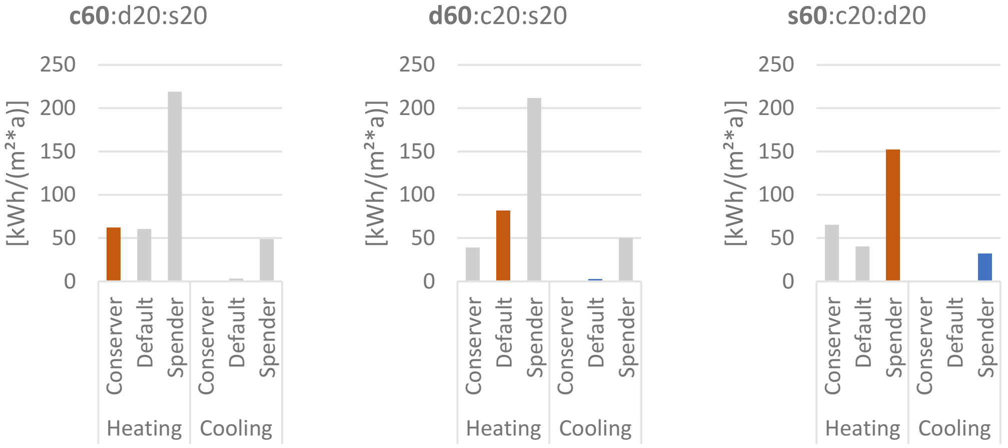

Figure 30: Annual heating and cooling loads per occupant type, building storey D

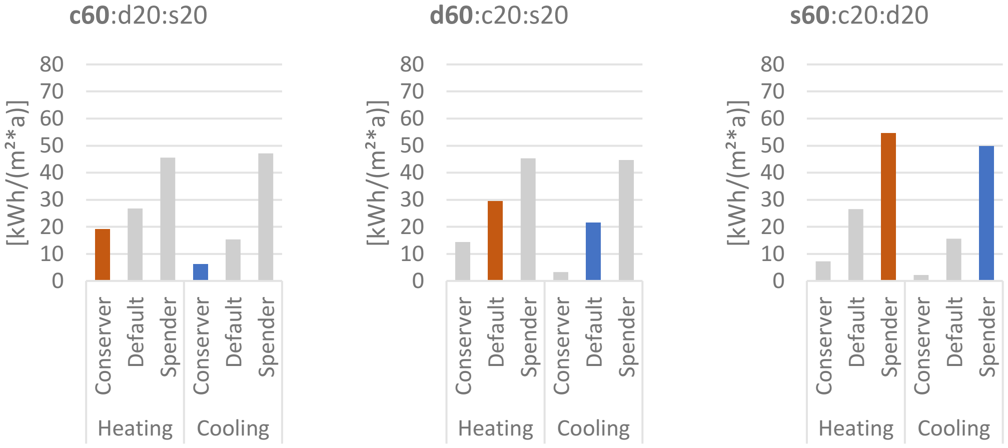

Figure 31: Annual heating and cooling loads per occupant type, building storey E

3.2.2 Cumulative temperatures

The figures in this section show the cumulative distributions of indoor temperatures for the three different occupant populations. The section is structured into three groups: summer temperatures, winter temperatures, and all year temperatures. To allow for a better readability only building storeys A and E are presented here (building storeys B, C, and D can be obtained from the appendix section).

Each line in the graphs indicates the average daily temperature per building occupant type in the investigated building storey based on the main room's operative temperatures (in other words, this temperature is the result of an averaged temperature for all habitable rooms occupied by each occupant type). Indoor temperatures of ancillary rooms do affect the overall apartment temperature as well due to intra-apartment heat transfer (indirect impact on the average operative apartment temperature). However, their operative temperatures have been omitted from the calculation of average apartment temperatures. For a better understanding of the cumulative distribution graphs, it can be said that very steep lines indicate a small temperature range (relatively constant temperatures). Moreover, the alignment of the curves regarding their relative left or right position in the graph indicate low or high temperatures.

The following observations can be made for all of the figures in this section: Generally, lines symbolising spender-occupancy types show a relatively constant temperature situated on the left side of the graphs (low and constant temperatures).

Summer temperatures (May – August):

For building storey A it is observed that the temperatures during the summer months for dominant populations conserver (Figure 32) and default (Figure 33) show a similar course. Figure 34 shows that dominant spender redirects all occupant types within the population to a steeper trend. This is made clear by a significant rise in the overall average temperature. In building storeys B to D similar trends can be overserved. Building storey E deviates from the temperature distributions in A to D: Figures 35-37 show much steeper line courses for all populations and occupant types and, therefore, more stable temperature conditions during the summer time. In this storey (E), the conserver occupant type tends to experience significant overheating in all population scenarios, while at the same time spender occupant type is in control of keeping low temperatures stable and fully avoid overheating. This observation can be made for the storey A-D as well, however, less significant.

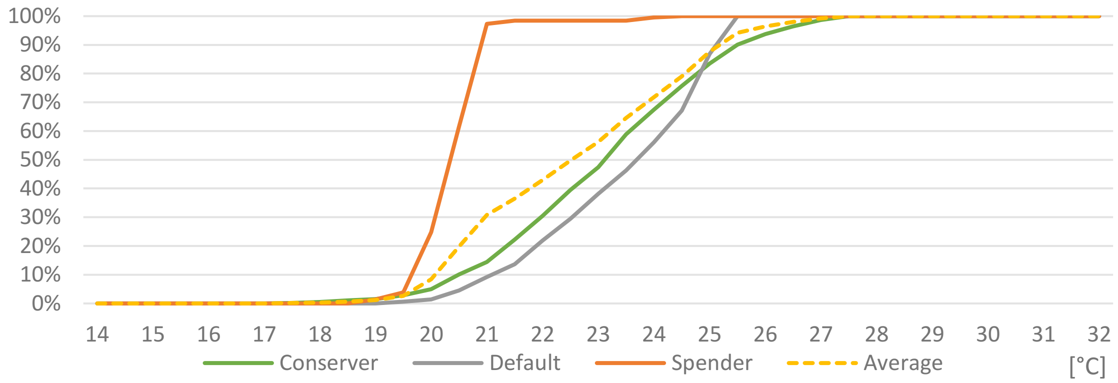

Figure 32: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey A, summer season

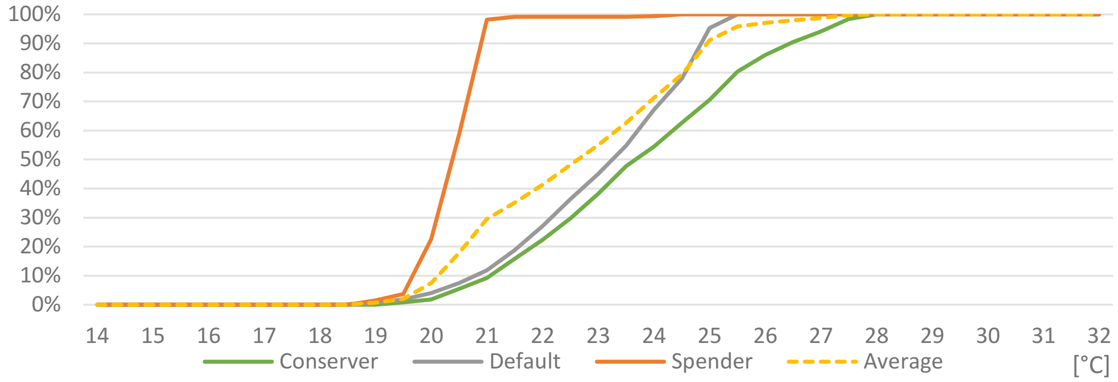

Figure 33: Dominant population: Conserver (d60:c20:s20), cumulative distribution by occupant type, building storey A, summer season

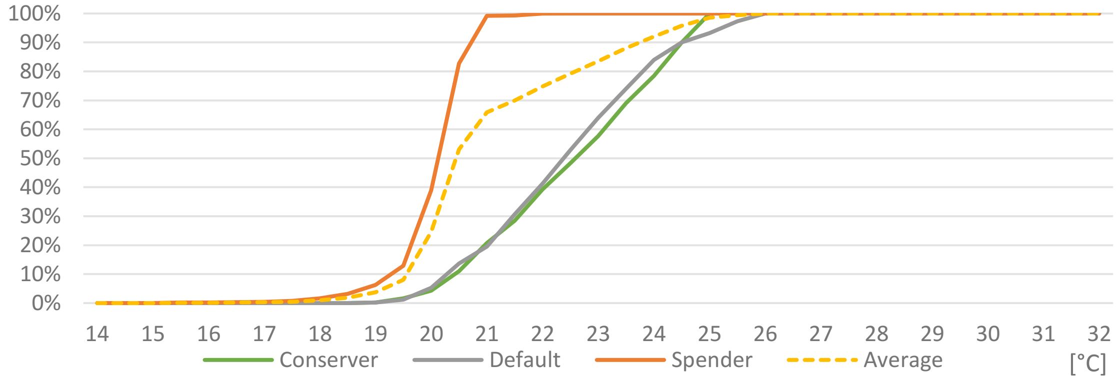

Figure 34: Dominant population: Conserver (s60:c20:d20), cumulative distribution by occupant type, building storey A, summer season

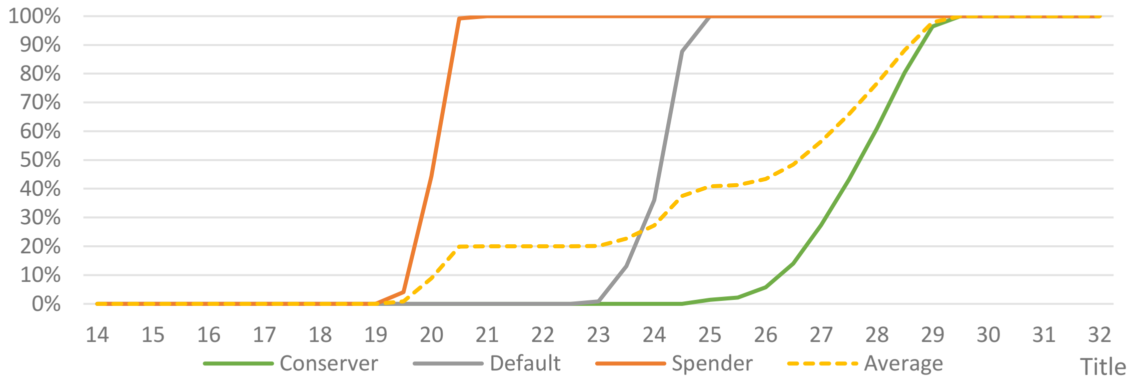

Figure 35: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey E, summer season

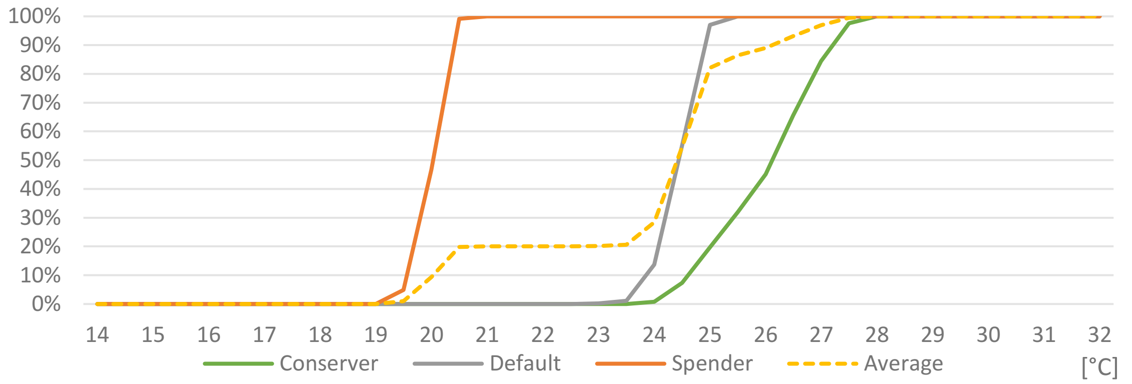

Figure 36: Dominant population: Conserver (d60:c20:s20), cumulative distribution by occupant type, building storey E, summer season

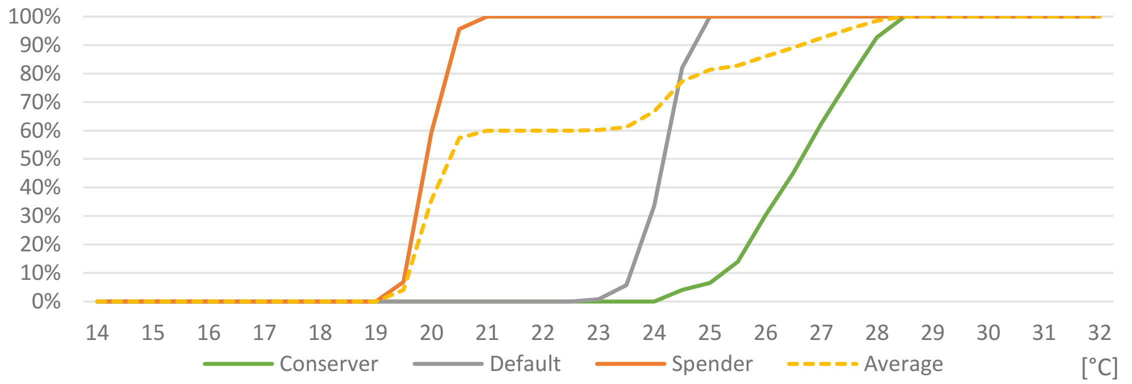

Figure 37: Dominant population: Conserver (s60:c20:d20), cumulative distribution by occupant type, building storey E, summer season

Winter temperatures (September – April):

Indoor temperatures during the winter months show significant differences to the summer time. As seen in Figures 38-40 (building storey A), the curves are shifted to the left on the temperature scale, indicating relatively low indoor temperatures, especially for the conserver- and default-dominant population scenarios. Furthermore, the temperature curves for the occupant types conserver and default show a much steeper trend (as compared with summer temperatures). However, at approximately 70% on the vertical axes, the lines change directions and proceed flatter in all scenarios for building storeys A to D.

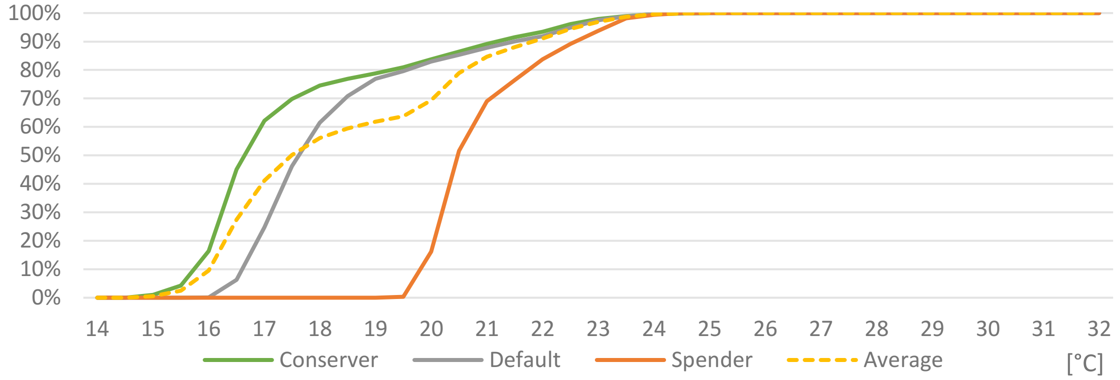

Figure 38: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey A, winter season

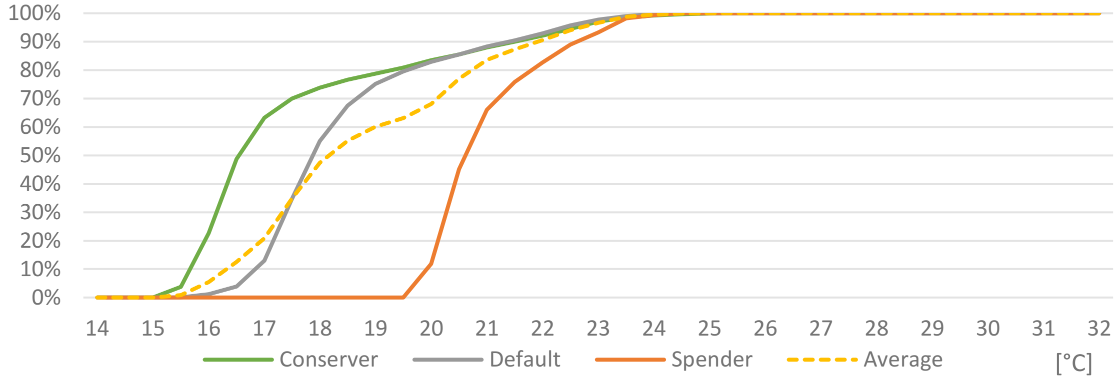

Figure 39: Dominant population: Conserver (d60:c20:s20), cumulative distribution by occupant type, building storey A, winter season

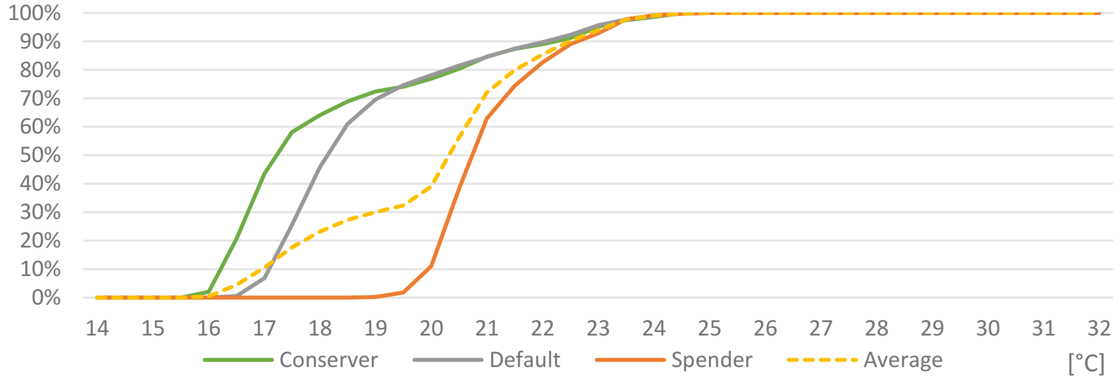

Figure 40: Dominant population: Conserver (s60:c20:d20), cumulative distribution by occupant type, building storey A, winter season

A similar trend can be monitored in Figures 41-43 for building storey E. In this case, however, the bend of the lines already occurs at around 40-50%. The bending can be explained as follows: the relatively stable low temperatures are met by thermostat set-backs during the night time (occurring in all population scenarios for all building storeys) and significant differences in thermostat settings for each occupant type during the day. Building storey E, with its superior thermal envelope, allows a more rapid increase in temperatures than the other buildings.

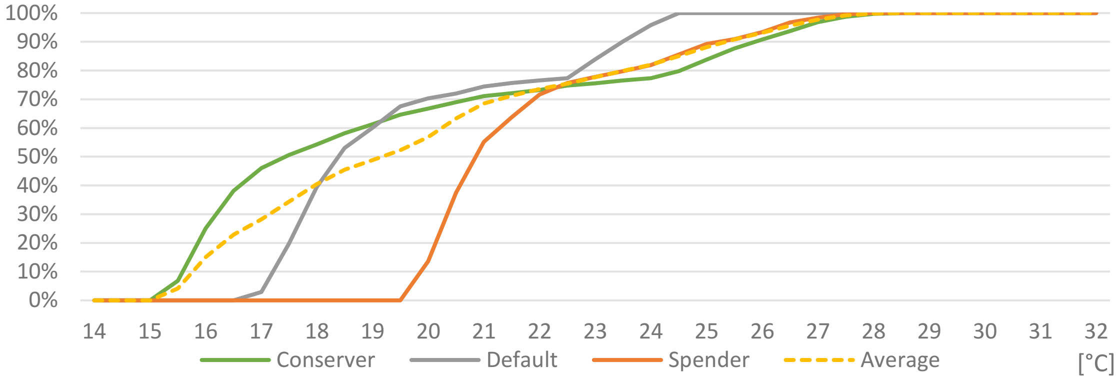

Figure 41: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey E, winter season

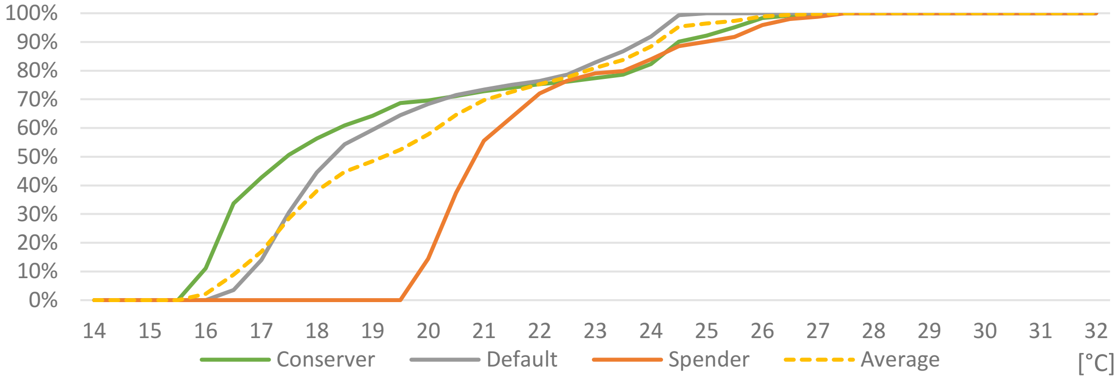

Figure 42: Dominant population: Conserver (d60:c20:s20), cumulative distribution by occupant type, building storey E, winter season

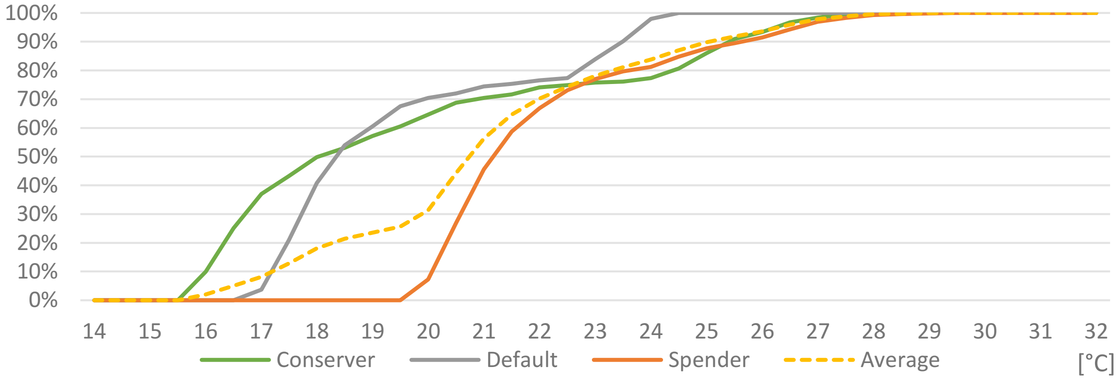

Figure 43: Dominant population: Conserver (s60:c20:d20), cumulative distribution by occupant type, building storey E, winter season

Whole year temperatures:

Figures 44-49 show the temperature distributions over the whole year. These figures impressively underline the small temperature ranges as well as the stable temperature conditions the spender occupant type experiences. Analogically, the other two occupant types are confronted with a broader range of temperatures. Thereby, the temperature ranges experienced by the conserver occupant type are distinctly larger than those of the default occupant type.

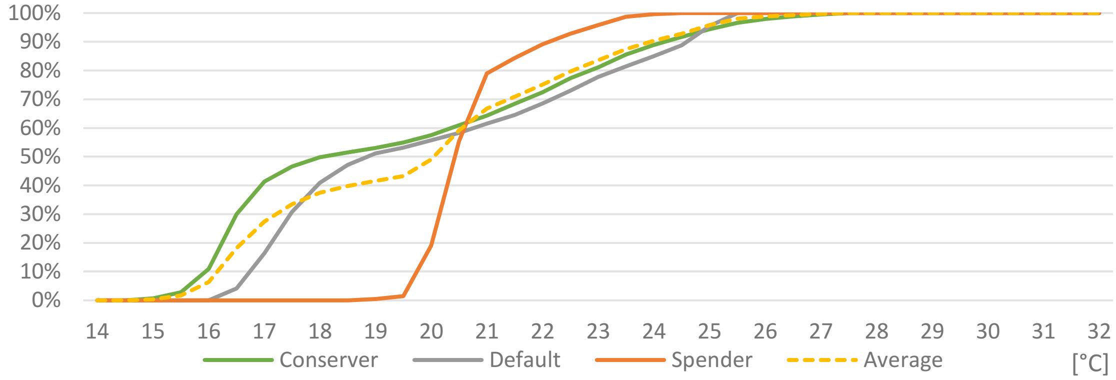

Figure 44: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey A, whole year

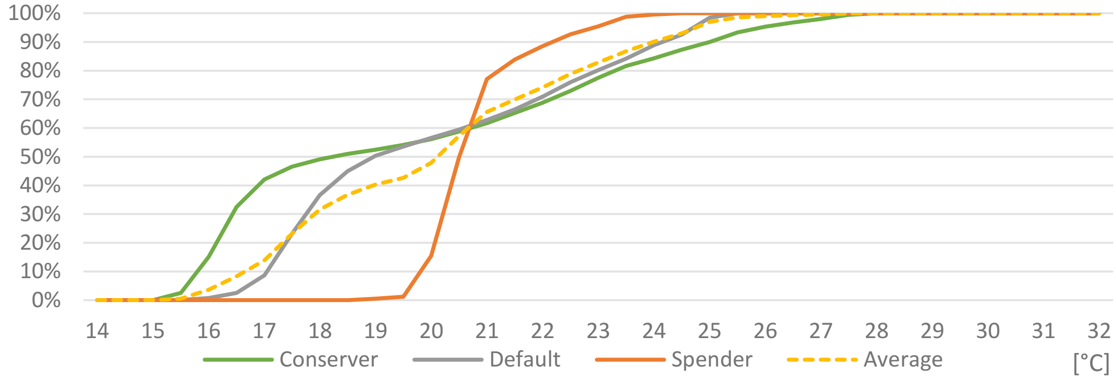

Figure 45: Dominant population: Conserver (d60:c20:s20), cumulative distribution by occupant type, building storey A, whole year

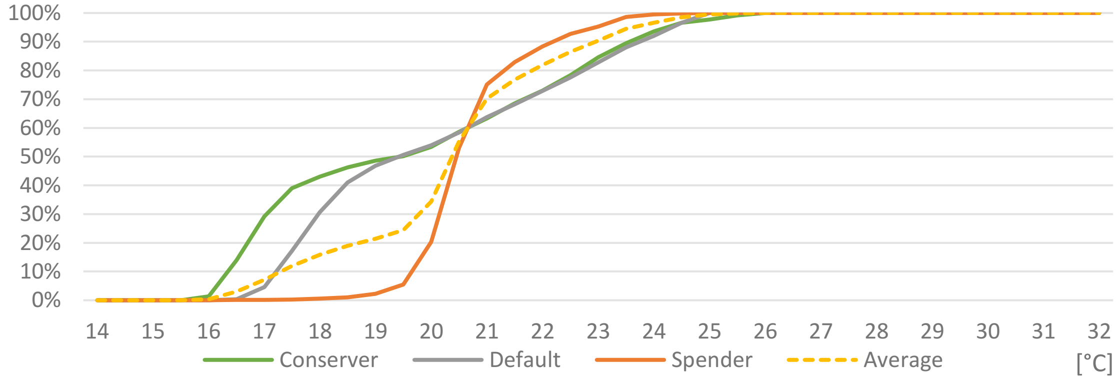

Figure 46: Dominant population: Conserver (s60:c20:d20), cumulative distribution by occupant type, building storey A, whole season

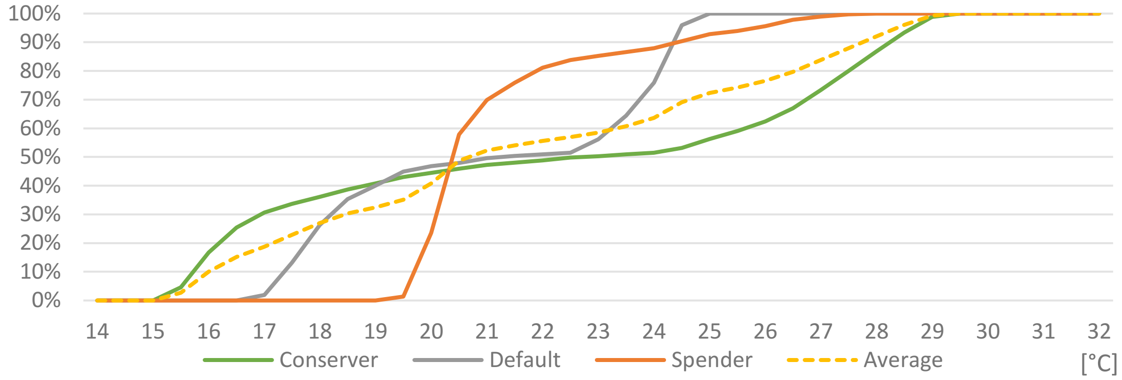

Figure 47: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey E, whole year

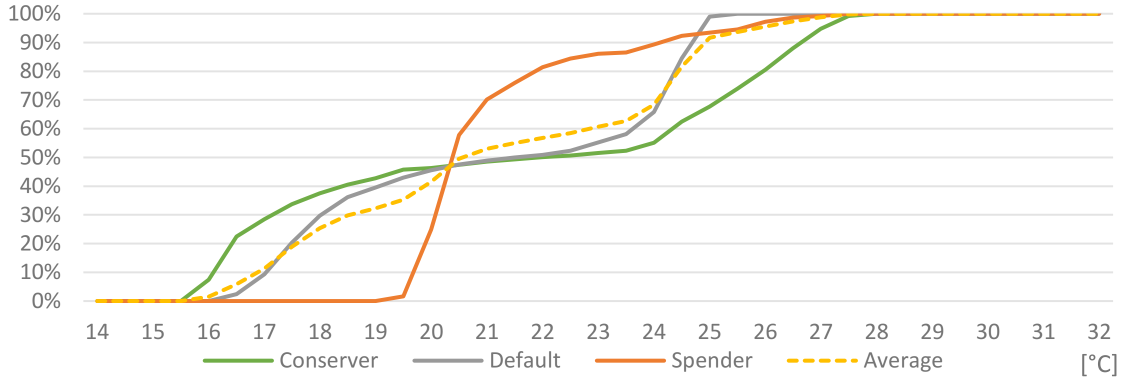

Figure 48: Dominant population: Conserver (d60:c20:s20), cumulative distribution by occupant type, building storey E, whole year

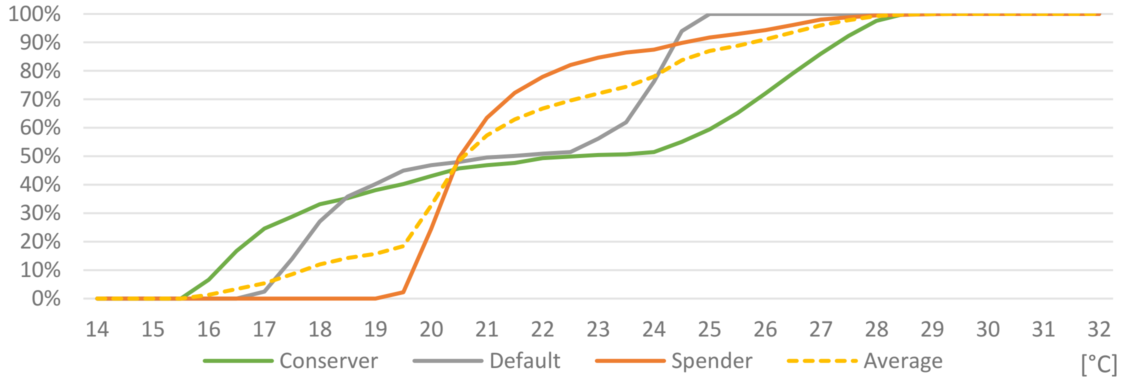

Figure 49: Dominant population: Conserver (s60:c20:d20), cumulative distribution by occupant type, building storey E, whole season

3.2.3 Overheating

Overheating occurrences are derived for temperatures above 25°C, 26°C, and 27°C according to ÖNORM B 8110-3:2020 (ASI 2020). The total amount of overheating is presented in Kelvin hours. In Figures 50 to 54 the total Kelvin hours for each building storey and population scenario are presented for the above-mentioned temperature limits. Given the upper limit of 25° Celsius, it can be stated that overheating occurs very frequently in all of the observed building storeys. Regularly, the highest number of overheating hours can be found amongst the conserver occupant type, followed by the default occupant type. Except in the case of storey E (Figure 54) only small numbers of overheating exceeding the 27°C threshold temperature can be found. The comparably strong overheating tendency of storey E can be explained by the same aspects already mentioned in the analysis of cooling loads ((i) The well-insulated envelope does reduce heat flux to the outside during nights in comparison to the storeys A to D; (ii) the building features lower ceiling heights and thus reduced volumetric buffer space in comparison to A to D; (iii) the internal organisation of rooms in storey E is significantly different from the older buildings A to D.)

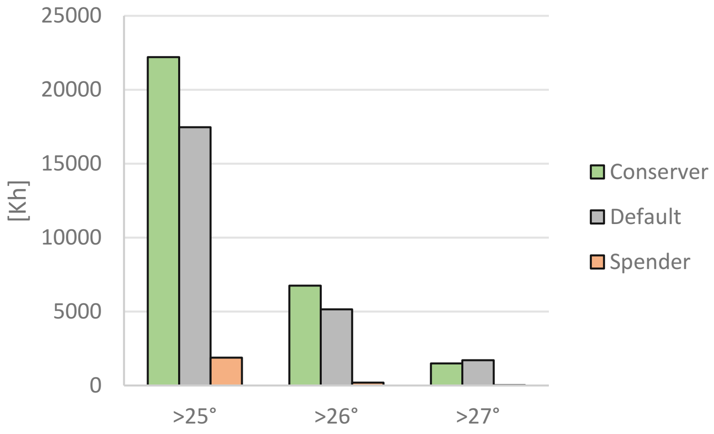

Figure 50: Total Kelvin hours for all populations, Building storey A

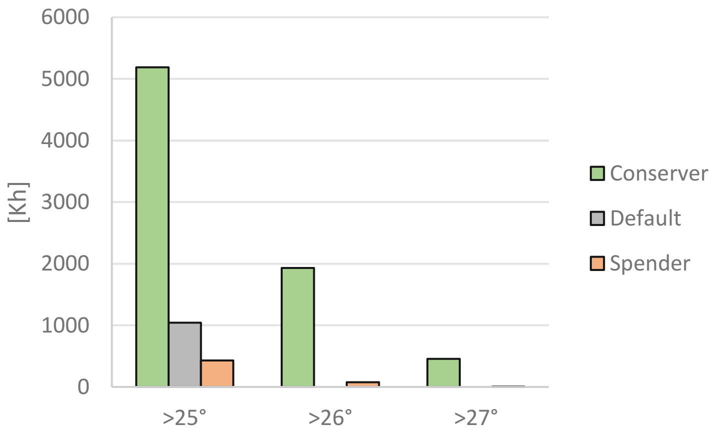

Figure 51: Total Kelvin hours for all populations, Building storey B

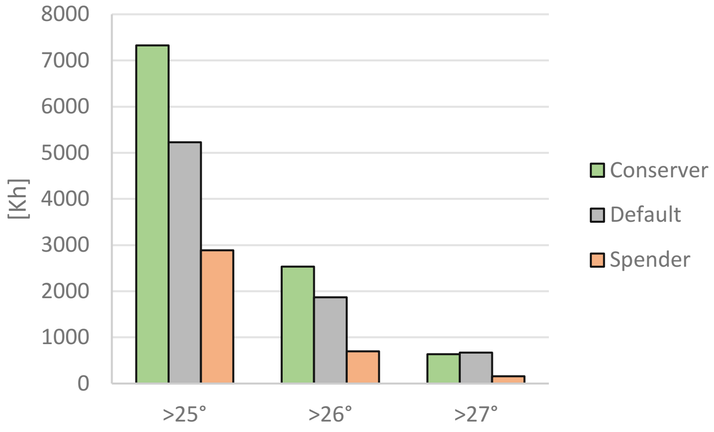

Figure 52: Total Kelvin hours for all populations, Building storey C

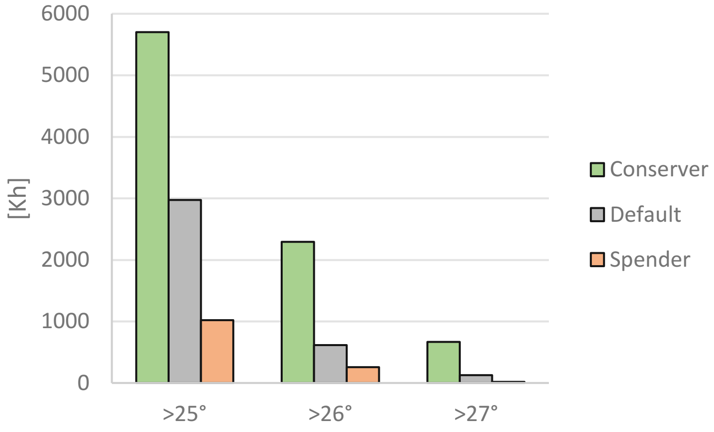

Figure 53: Total Kelvin hours for all populations, Building storey D

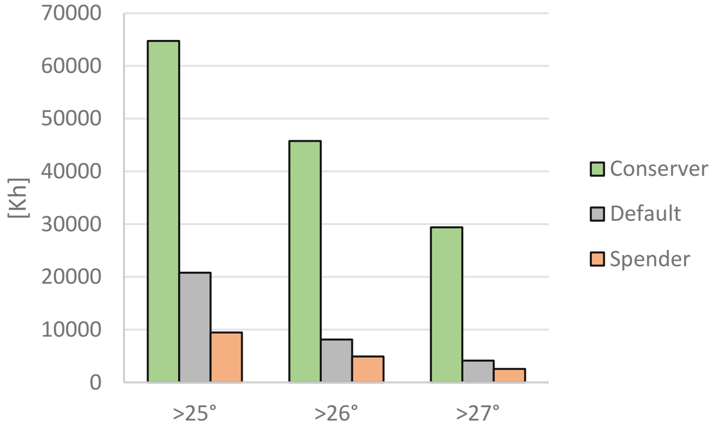

Figure 54: Total Kelvin hours for all populations, Building storey E

In addition to the total amount of overheating for each building storey and population scenario, it is also investigated how high the actual overheating temperatures are (Figure 55-59). As already suggested in Figure 54, overheating is most common in building storey E. Figure 59 confirms this trend and illustrates that indoor temperatures tend to be quite high during the summer months. For the dominant population conserver, the overheating temperatures show about three times the values compared to other building storeys.

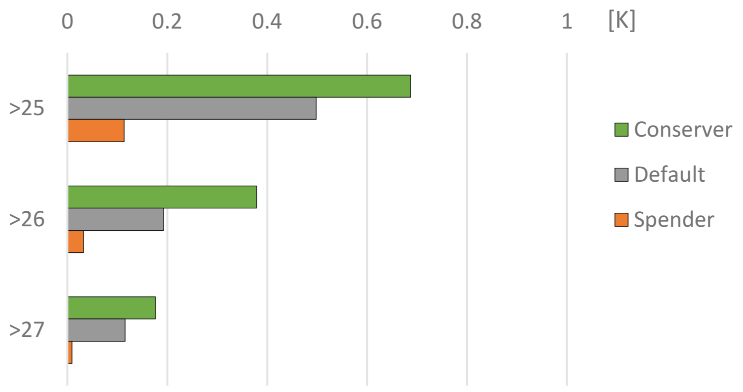

Figure 55: Average overheating temperatures for habitale rooms, Building storey A

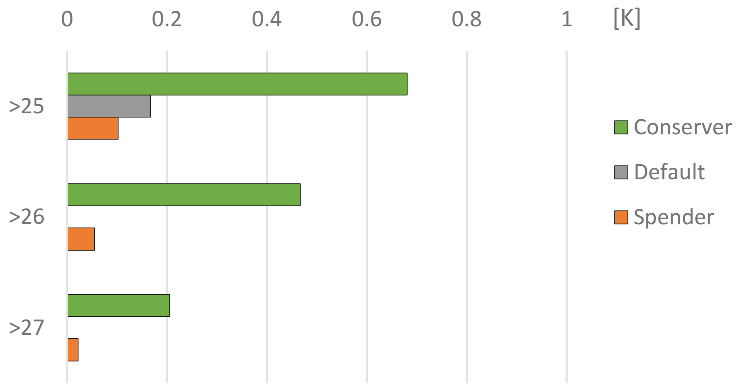

Figure 56: Average overheating temperatures for habitale rooms, Building storey B

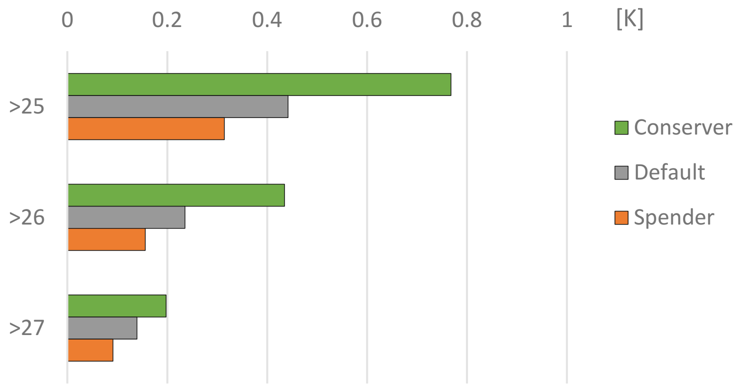

Figure 57: Average overheating temperatures for habitale rooms, Building storey C

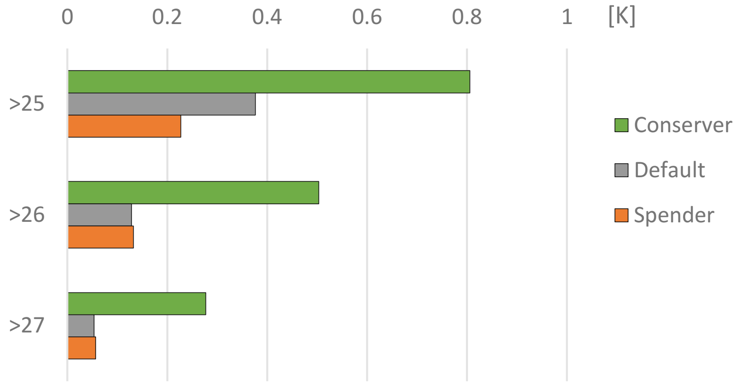

Figure 58: Average overheating temperatures for habitale rooms, Building storey D

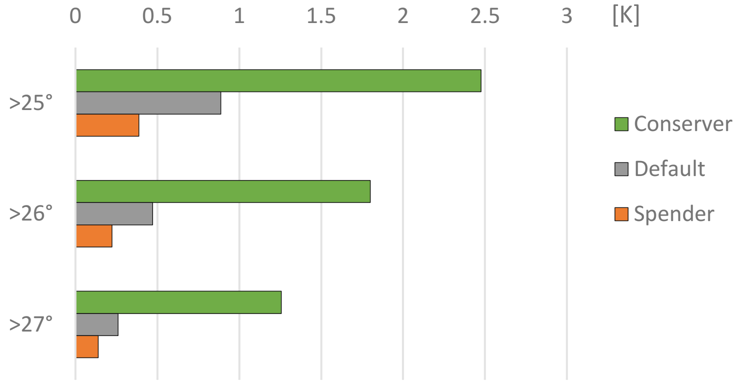

Figure 59: Average overheating temperatures for habitale rooms, Building storey E

In Figures 60 to 64 two different indicators for overheating are subjected to a comparison: The already presented total amount of Kelvin hours for each population scenario in all building storeys is compared to the dominant occupant only. Hereby, the intention is to demonstrate to which part the actual occupant type within the population is responsible for overheating occurrences. It can be observed that indoor temperatures above 25°C are found to the largest part in apartments occupied by the conserver occupant type. If looked upon overheating thresholds of >26° and >27°C within the conserver-dominant scenario of all storeys, the overheating hours of the conserver occupant type are congruent to the overheating hours of the overall storey (in case of storey B (Figure 61) this is already true for >25°C; in case of storey E there is a high degree of congruency for >25°C).

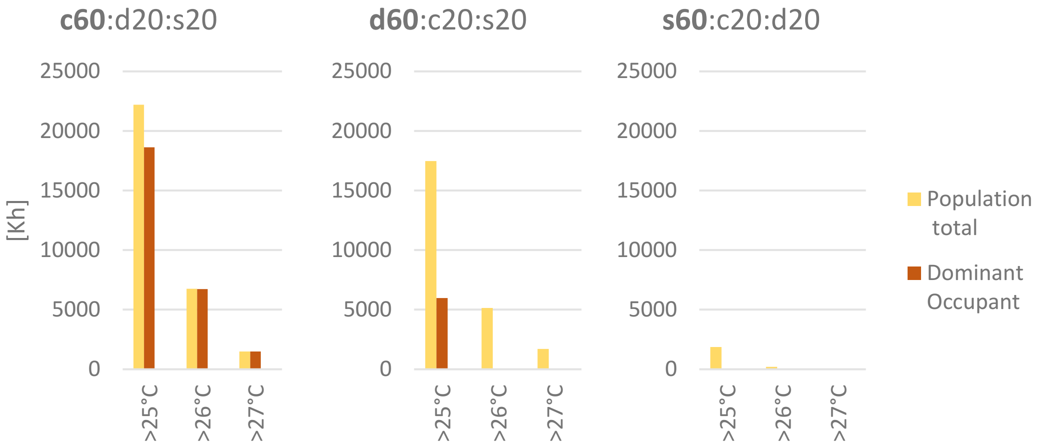

Figure 60: Total overheating and the amount caused by the major population, Building storey A

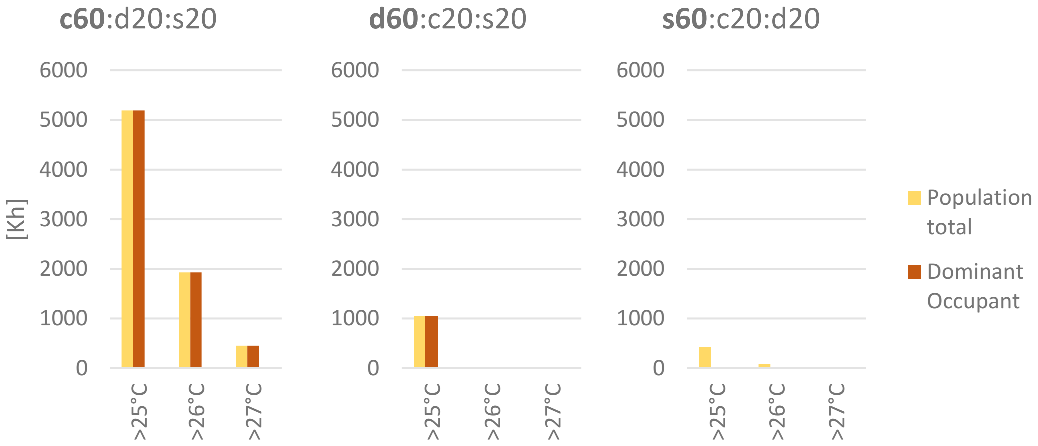

Figure 61: Total overheating and the amount caused by the major population, Building storey B

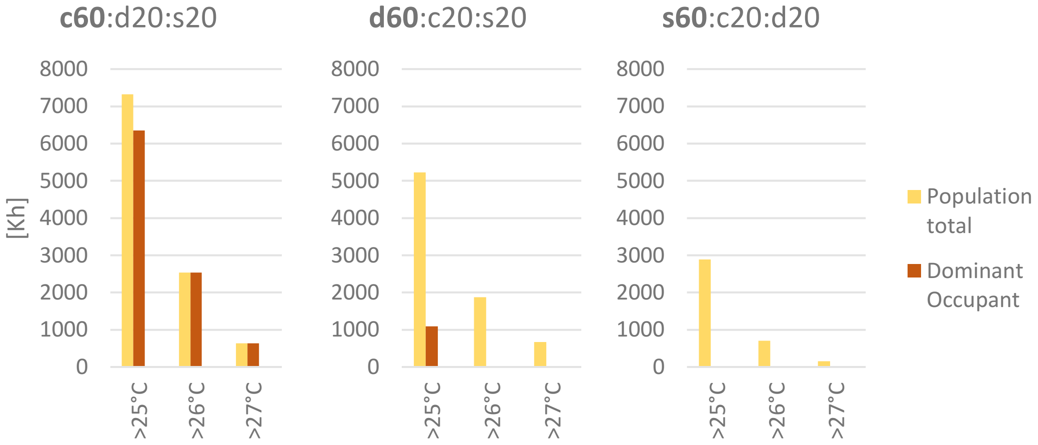

Figure 62: Total overheating and the amount caused by the major population, Building storey C

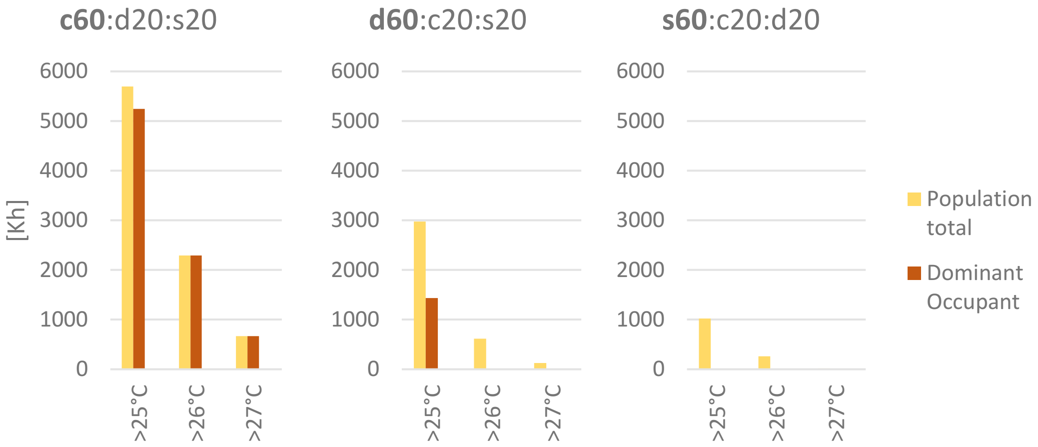

Figure 63: Total overheating and the amount caused by the major population, Building storey D

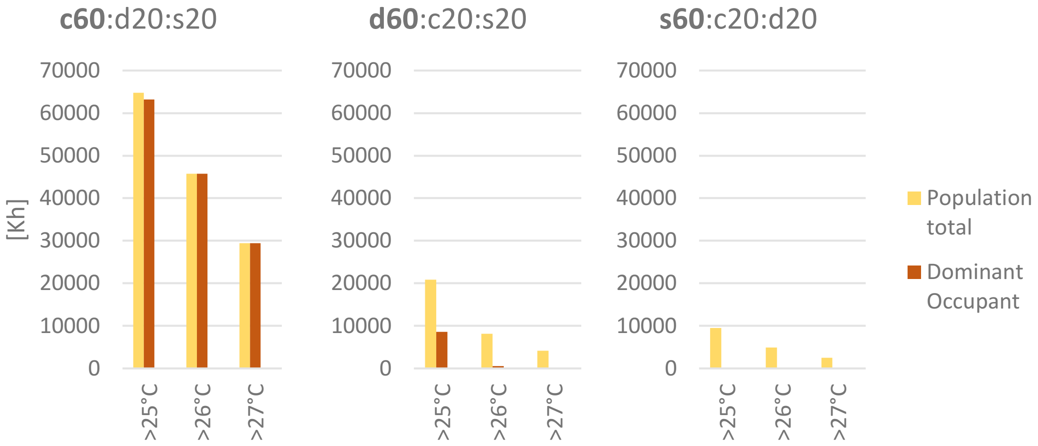

Figure 64: Total overheating and the amount caused by the major population, Building storey E

3.3 Projection to building scale

The projection from building storey to whole-building scale was undertaken by multiplying the heating and cooling loads (absolute as well as relative) for each occupant scenario by the one factor that results from dividing the total heated volume by the heated building storey volume, according to Equation 1.

In Figures 65 and 66 the heating and cooling loads for each of the representative buildings and population scenario are presented as total and area-related values, respectively. The total annual loads for building A spell out the clearly larger size of the building compared to buildings B-E. In contrast, the area-related heating loads are within a deviation of +/- 20 kWh/(m²*a) for buildings A-D (between 78 and 118 kWh/(m²*a)). Building E shows significantly lower heating loads. If looked upon cooling loads, buildings A-D feature rather low values, while building E shows considerably higher values.

Note that heating loads hereby refer to the months September to April (eight months) while cooling loads have been derived for May to August (four months).

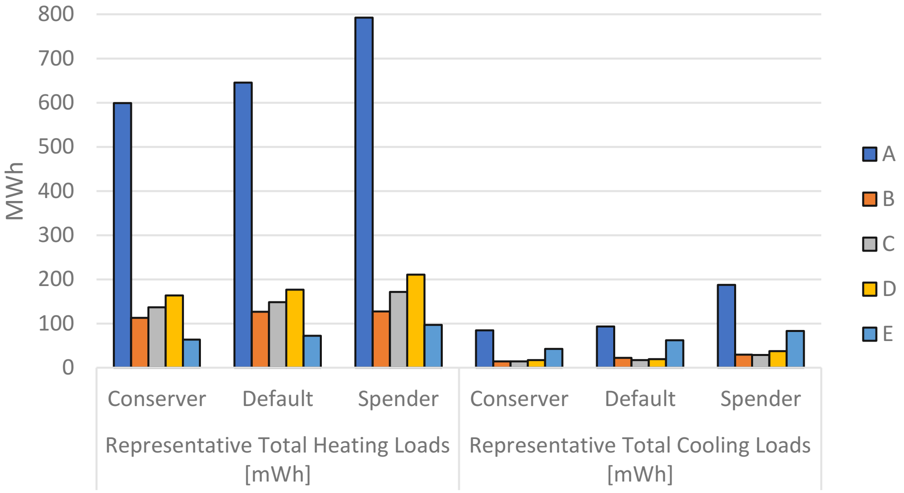

Figure 65: Total heating and cooling loads for the representative buildings A,B,C,D,E

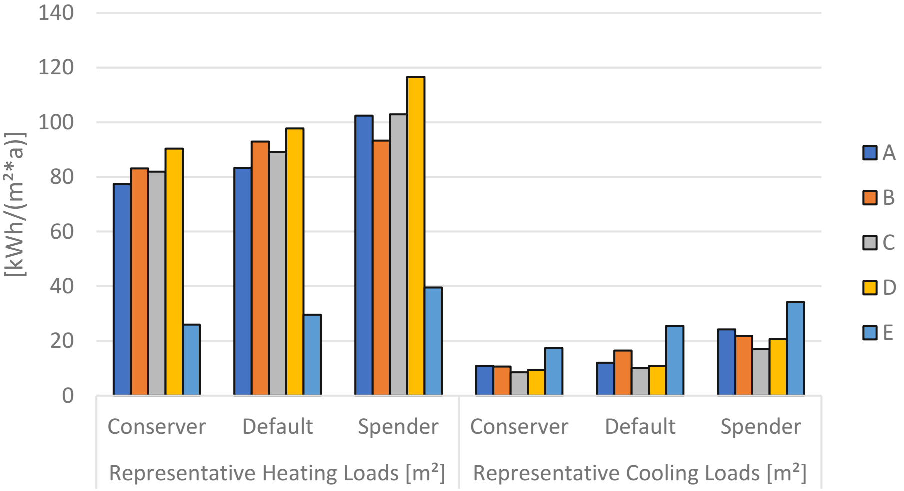

Figure 66: Heating and cooling loads per m² for the representative buildings A,B,C,D,E

Figures 67 and 68 illustrate the relative deviation of the occupancy scenarios conserver and spender based on the occupancy scenario default (=100%). In the case of heating loads (Figure 67), conserver-dominant population heating loads are 7 to 12% percent lower than the default. The heating loads for the spender-dominant population are 0 to 34% percent higher than the default. The 0% occurrence is attributable to building storey B, where default-dominant and spender-dominant populations show approximately the same numbers in heating loads.

The relative deviation for cooling loads (Figure 68) clearly emphasises saving potentials. Even though the actual cooling loads for buildings A to D are generally moderate, the relative deviations are high, whereas for building E, which shows the highest amount of cooling loads, the relative deviation is smaller.

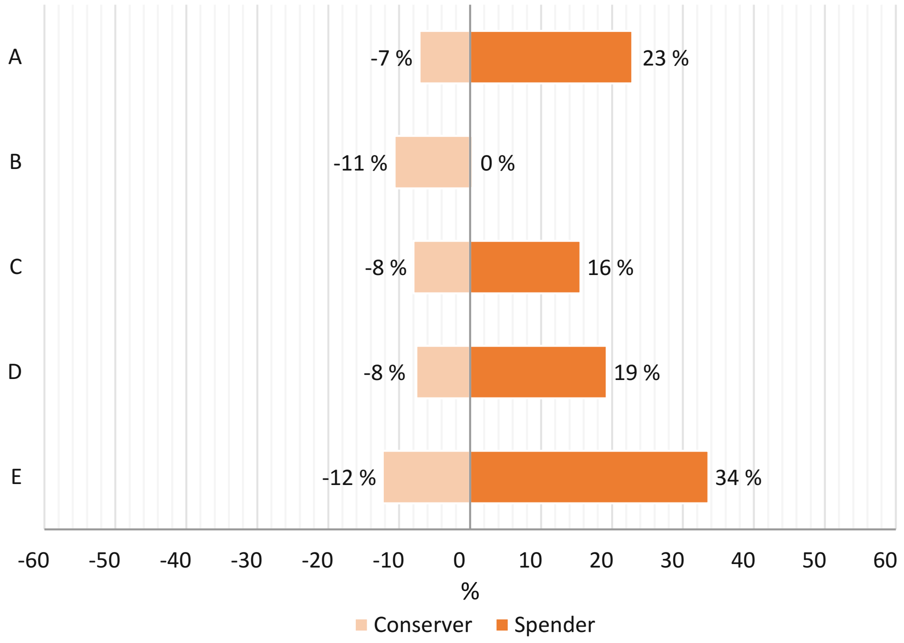

Figure 67: Saving potential for heating energy loads in representative buildings A-E

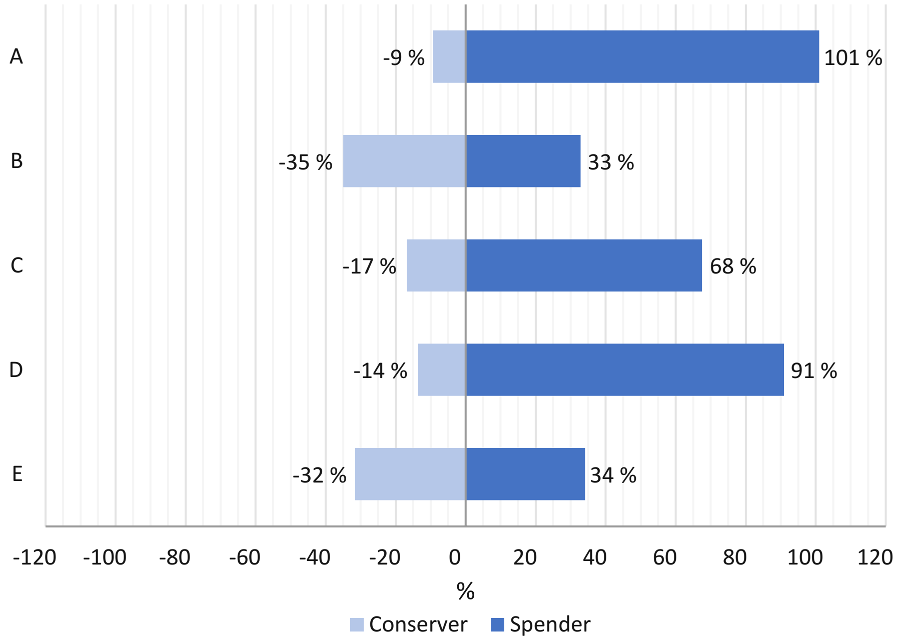

Figure 68: Saving potential for cooling energy loads in representative buildings A-E

3.4 Upscaling to urban area

In section 3.3, the heating and cooling loads for buildings A to E with each of the population scenarios was presented (to recall, the results from building storey scale were projected to building scale using Equation 1).

Subsequently, the heating and cooling loads from the representative building A to E are upscaled to a larger building portfolio. This list of buildings was found by Ghiassi (2017) and includes varied information. At this stage, for the upscaling process in this work, the core information needed is the heated volume for each of the buildings in the cluster list. Table 9 summarises the for this study relevant information from the set of buildings (the total number of buildings in each of the clusters varies significantly. Cluster building C, for instance, represents 201 buildings in the investigated area while representative building E represents a total of only six buildings).

Table 9: Total number of buildings and corresponding total heated volume in each cluster

Cluster	Building count	Total Heated volume [m³]
A	125	1656087
B	94	756496
C	201	1645866
D	109	612111
E	6	87538
Total	535	4758098

The upscaling process from building to urban scale is conducted using Equation 2 (the individual parameters of the equation are explained in section 2.7):

$$Q_{i,h} = (Q_{Sim,i,h} / V_{reference,i}) \times V_{n,i} \qquad (2)$$

The calculation is carried out for each arbitrary building from cluster A to E, given the arbitrary building’s individual heated volumes, the representative buildings’ (A to E) heated volumes, and the representative buildings’ (A to E) heating and cooling energy loads. Figure 69 shows the annual heating and cooling loads for the average building from each of the clusters A to E. To provide an example, cluster C (represented by building C) contains 201 arbitrary buildings. The averaged energy loads of these 201 buildings results in the grey columns presented in Figure 69.

As mentioned earlier in this study, the actual floor heights of the arbitrary buildings from each cluster are unknown in the context of this work (floor heights for 535 buildings would have to be taken from building plans for all of the buildings, which is, firstly, arduous work and, secondly misses the scope of this study). Therefore, assumptions concerning floor heights were made to estimate the area-related energy loads, including 2.50, 3.00, and 3.50 meters. The results can be obtained from Figures 70 to 74.

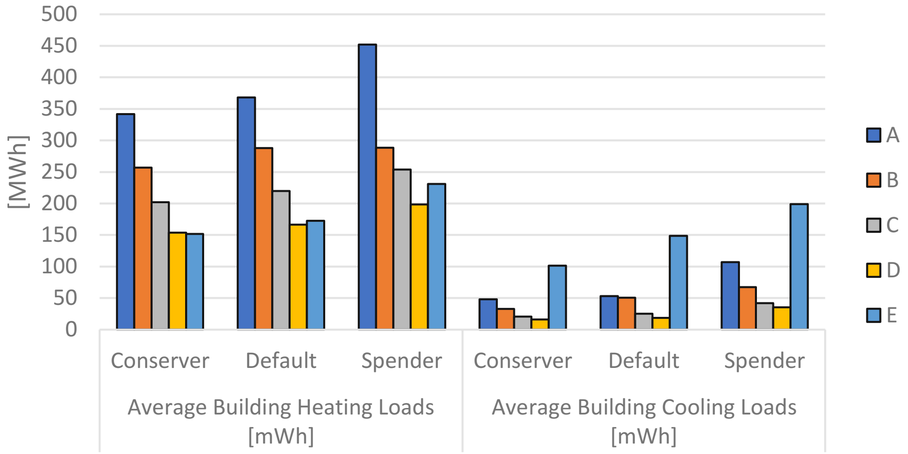

Figure 69: Total heating and cooling loads for the average building from the respective clusters A,B,C,D,E

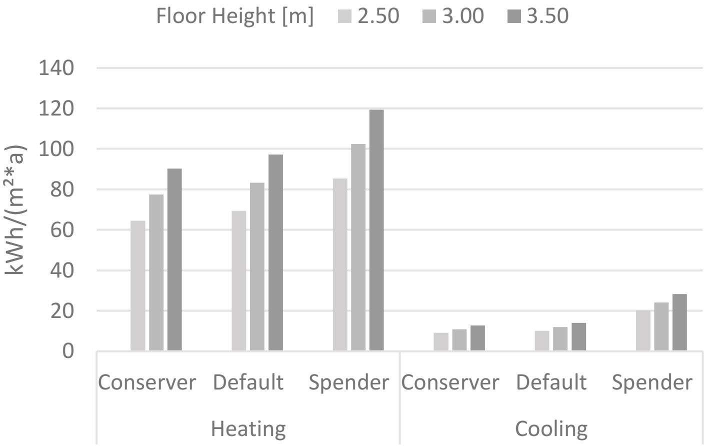

Figure 70: Estimated heating and cooling loads per m² according to floor height assumptions, average building from cluster A

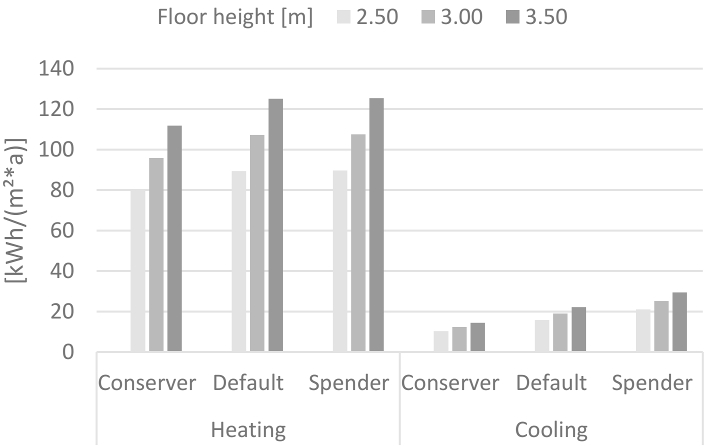

Figure 71: Estimated heating and cooling loads per m² according to floor height assumptions, average building from cluster B

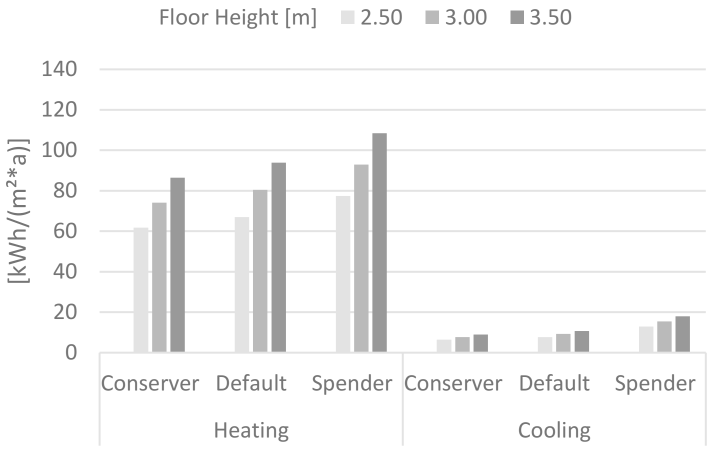

Figure 72: Estimated heating and cooling loads per m² according to floor height assumptions, average building from cluster C

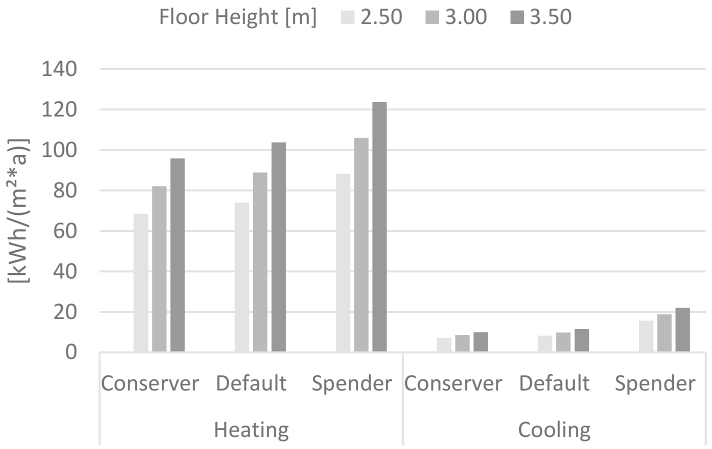

Figure 73: Estimated heating and cooling loads per m² according to floor height assumptions, average building from cluster D

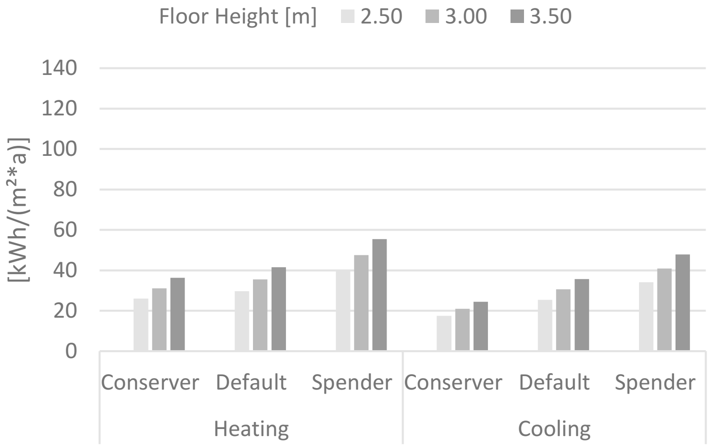

Figure 74: Estimated heating and cooling loads per m² according to floor height assumptions, average building from cluster E

Figure 75 presents the total heating and cooling energy loads for all arbitrary buildings from each of the clusters. In this context, the results for cluster E stand out. This is due to the fact that cluster E contains 6 buildings only and is therefore not expressive for an evaluation of absolute values. In Figure 76 the total values are compared next to each other, amplifying this circumstance.

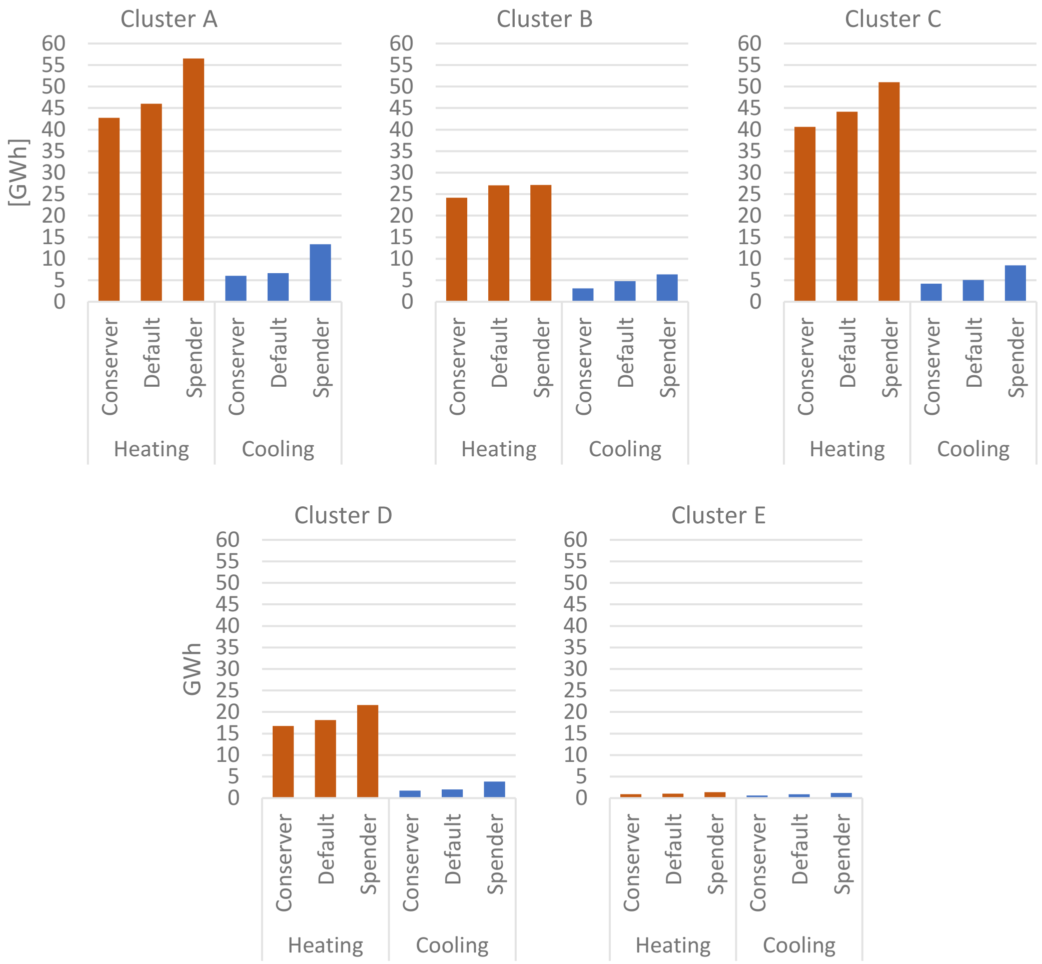

Figure 75: Total heating and cooling loads for all buildings in clusters A to E

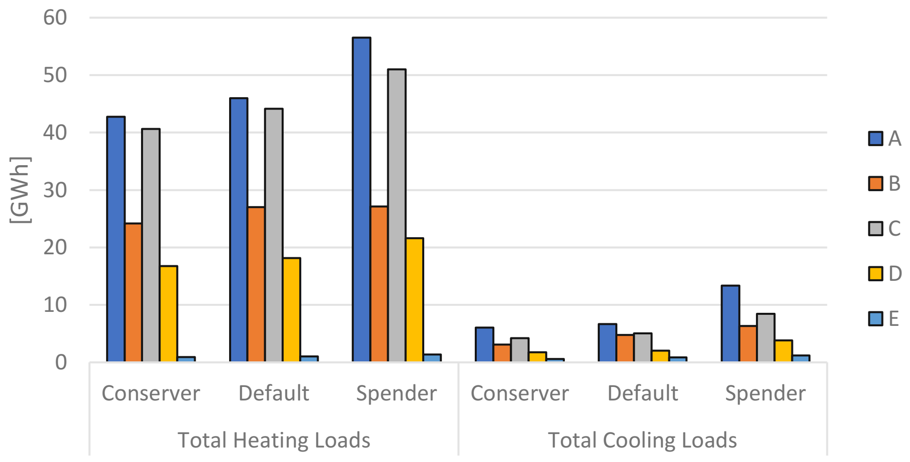

Figure 76: Total heating and cooling loads for all buildings in cluster A,B,C,D,E

The concluding method to finalise the upscaling process is undertaken by summing up the results obtained from each cluster group. Figure 77 shows the total annual heating and cooling loads [GWh] for the investigated urban area with respect to the different occupant population scenarios. An estimation of area-related heating and cooling energy consumption is presented in Figure 78. The uncertainty about actual floor heights (in the context of this study) hardens an appropriate, area-related estimation of energy loads.

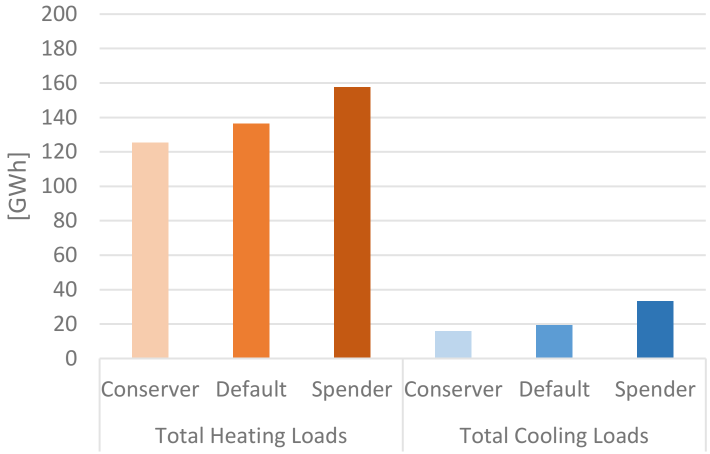

Figure 77: Total heating and cooling loads for the investigated urban area

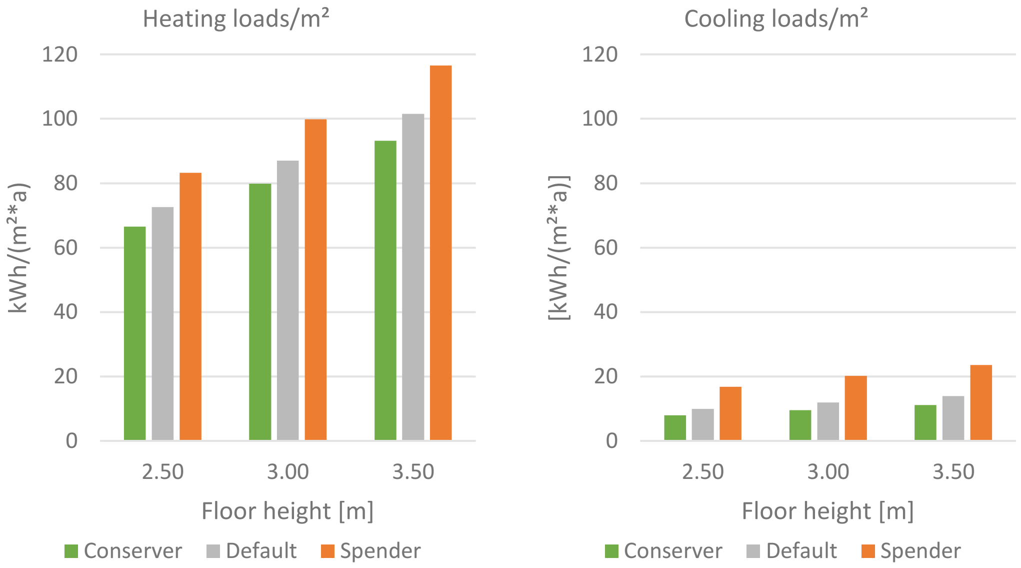

Figure 78: Upscaled average yearly heating and cooling loads per m² for different occupant population scenarios in respect of different floor heights

Figure 79 shows the computed potential energy saving potential for the investigated area. For the heating loads, the conserver-dominant population shows an 8% reduction compared to the default-dominant population (=100%), while the spender-dominant population shows a

15 % increase. The saving potential for cooling loads is significantly higher, although, cooling loads as such are generally much lower. This circumstance was already observed at building scale in section 3.3.

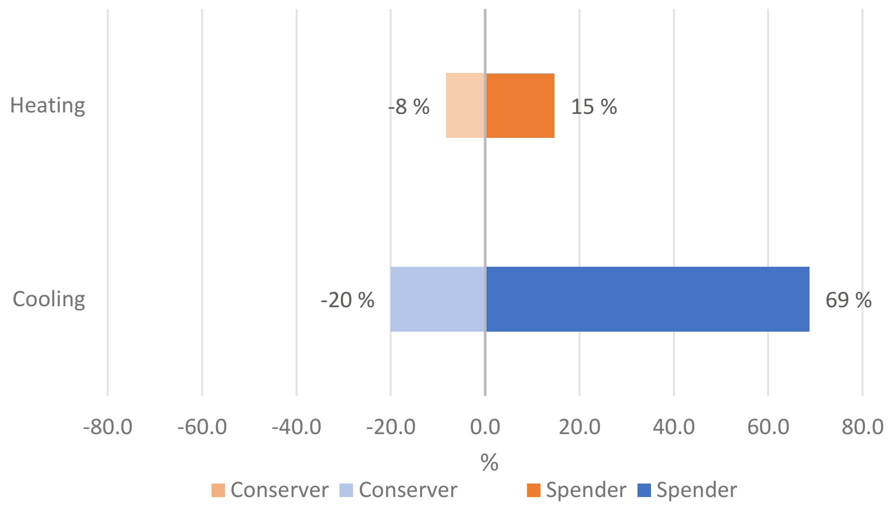

Figure 79: Saving potential for heating and cooling loads, urban area total

3.5 Summary of Results and Analysis

Generally speaking, it can be observed that the conserver occupant type as well as the conserver-dominant population show the lowest heating and cooling energy loads. The opposite is true for the spender occupant type and the spender-dominant population. The default occupant type and the default-dominant population regularly feature loads in-between. There are some exceptions to this general pattern, in which the default and the conserver occupant type can be found to be in an opposite order (in the conserver-dominant as well as the spender-dominant scenario, the default occupant type shows slightly higher heating energy loads than the conserver occupant type). This is due to the different conditions (exposure to sunlight, outside air, room size, etc.) of the apartments within the building storeys. Furthermore, the conserver and default occupant types majorly show less differences in resulting energy (that is heating and cooling) loads than the default and the spender occupant type.

It can be monitored that the conserver occupant shows the lowest indoor temperatures during winter and the highest during summer. For the spender occupant type the opposite is true, while the default occupant type can be found in between in most cases. The above mentioned "change of role" regarding conserver and default occupant can also be observed for indoor temperatures in few cases. This is probably due to the already mentioned reasons.

Under the assumed conditions, overheating is common amongst all buildings and populations. This primarily occurs in the apartments occupied by the conserver occupant type. The highest overheating temperatures can be found in building storey E. This might be due to reduced heat transmission via the thermal envelope, low infiltration rates and smaller room sizes in this building in comparison to the buildings A-D.

At building scale the area related heating loads for buildings A-D within the different population scenarios show similar deviations (+/- 20% kWh/(m²*a)), while building D shows significantly lower heating loads. Building B, however, has the highest cooling loads, compared to building A-D. It can be observed that the relative deviation between the default-dominant and the spender-dominant population is much higher than between the default-dominant and the conserver-dominant population. The latter applies to cooling loads as well. Cooling loads are observed to be relatively low in buildings A-D, although, the saving potential remains high. Building E shows higher cooling loads than buildings A-D, but the saving potential is limited due to less deviation between the different population scenarios.

Upscaled to the urban area, the total heating energy loads for the conserver-dominant population are slightly above 120 GWh and for the spender-dominant slightly below 160 GWh. The default-dominant population shows values close to 140 GWh, being more closely located to the energy saving population. Similar observations regarding the ratio of energy loads between the different populations can be made for cooling. Although, the total cooling loads are significantly lower compared to heating loads (around 15 GWh for the conserver-dominant, slightly below 20 GWh for the default-dominant, and slightly above 30 GWh for the spender-dominant population).

The saving potential for heating is illustrated relative to the default-dominant population (=100%). The conserver-dominant population thereby shows 8 % reduced heating energy loads, the spender-dominant population shows 15 % increased heating loads. The saving potential for cooling loads is much higher (although, total cooling loads are relatively low). For the conserver-dominant population 20 % reduced cooling loads were found, compared to the default. The spender-dominant population shows a significantly high increase by 69 %.

4 CONCLUSION

4.1 Research questions

The results from this work have been summarised in section 3.5. Based on the hypothesis the corresponding research questions will be answered here.

"The application of user behaviour scenarios on sample buildings of diverse physical properties in an urban context delivers a wide range of outcomes concerning energy consumption."

Needless to say, in an iterative approach it is not possible to consider all combinations of user potential user behaviour scenarios. As such, an educated selection of combinations has been deployed for this master thesis. Based on this selection the research questions as formulated in 1.5 can be answered:

Q1: Is it possible to obtain estimations about the impact of building occupant's behaviour onto building energy performance indicators via the cluster/upscaling method for a whole district or city? If yes, what kind of uncertainties can be monitored?

The simulations in EnergyPlus were performed at building storey scale and deliver versatile outcomes. The impact of building occupant's behaviour onto the investigated building storeys can be estimated well. Clear statements can be formulated regarding occupant-determined tendencies in heating and cooling energy consumption as well as indoor temperatures.

The projection to building scale creates minor uncertainties due to the fact that divergences in other building storeys were ignored. Nevertheless, within the context of a particular residential building this simplified method is justifiable.

The upscaling process to the whole area was executed via a relatively simple calculation method and results in plausible estimations for heating and cooling energy loads. However, uncertainties can be monitored. These include: (i) the representative buildings and occupant types were modelled meticulously and to the best of knowledge, yet deviations to reality in just one of these representative buildings are passed on to a whole set of buildings and eventually to the whole investigated area; (ii) only little information is – in the context of this study - available about the arbitrary buildings from the cluster list. Therefore, exact outcomes cannot be expected and an area-related estimation is difficult. Nevertheless, estimations for the energy loads within an urban area can be made, provided that a solid model – in this case developed by Ghiassi (2017) – exists.

Q2: Given that Q1 can be answered with a yes, which saving potential for building-related energy consumption would be possible in view of changes in the user behaviour?

The behaviour pattern for the default occupant type is to the major part based on values given by the standards. The occupant types conserver and spender were defined based on estimations from literature. Given these virtualities, the computed results do not claim to portray the reality. Nevertheless, it can easily be observed from the results that changes in user behaviour can definitely reduce the energy consumption. On the other hand, an increase is theoretically even more likely to occur – given that the default-occupant population reflects the actual state. Additionally, the computed saving potential in cooling energy was found to be significantly higher than for heating. This highlights the importance for an awareness in behavioural actions related to energy consumption.

4.2 Limitations

There are several limitations to this study which are exemplified here. Due to the uncertainties in realistic occupant behaviour many indicators were chosen to the best of knowledge. The method for calculating the occupant number was assumed as a statistical value. Although, behavioural actions in each occupancy scenario were configured meticulously for the simulations, internal gains were chosen as constant schedules values for all occupants. Furthermore, the scale of the urban area as well as of the representative buidings themselves is rather extensive and had to be simplified. In this context one typical storey of each investigated buildings was modelled in detailed and then projected to the whole building. Commercially used building parts and adjacing floors and neighbouring buildings were considered as adiabatic. Ghiassi (2017) - as the foundation for this work – found seven building clusters represented by one building each. Since two of the buildings are not residentially used, they were not considered in the context of this work.

Heating and cooling energy from the simulations was provided as energy loads in Joule (here converted to kWh, MWh, GWh) and has to be distinguished from actual energy consumption.

For the buildings from the cluster lists only values for the heated volumes but no floor heights were available. Therefore, the actual heated area is unknown in this context and is approximated by dividing volumes by assumed floor heights.

In the final upscaling process, scenarios for dominant populations conserver, default, and spender were created. In this context, it was assumed that cluster buildings A, B, C, D, and E do – for each scenario – always refer to the results of one specific population type. Mixing populations here would deliver results without value added for this work, since the energy loads would lie in-between and not provide expressive outcomes. This might become of interest in future research.

Eventually, the simulation results in this work do not claim to give a precise portrayal of the actual energy consumption in the investigated area. The core idea is to deploy occupant behaviour patterns and find possible ranges at an urban scale, where uncertainties are to a certain extent acceptable. Generally, a validation of simulation results, especially at urban scale, is difficult and an exact mapping of the reality is not possible.

4.3 Future research

In section 2.5.2 of this work, the occupant behaviour types “cool” and “warm” (which were inspired by Van Raaij and Verhallen (1983)) were introduced. The integration of these types might be of interest for future research for the following reason: The consideration of physically-oriented behaviour (based on individual perception) in addition to economically and ecologically motivated behaviour patterns, opens room for investigation and discussion.

In this context, the occupant type “warm” can easily be integrated in the simulation process. However, to allow for an occupant type in the fashion of “cool”, cooling systems need to be considered in the simulation. To this point, cooling systems are not quite frequent in Vienna’s residential sector. Given the advancing climate change, this matter will most probably gain in importance in the next few years. Additionally, it can be assumed that Vienna residents are not familiar with air condition systems at this stage. In this regard, it might be of interest to question how users can be informed and motivated. In this context, guidelines for an appropriate use of cooling systems might be a possibility to support building occupants from the “beginning”. Guidelines, however, might not only bring considerable advantages (in advance) for the use of cooling systems, but also in terms of an appropriate usage in behavioural actions related to heating energy consumption.

Needless to say, in recent years home-office work has grown in popularity and this trend intensified massively within the COVID-19 pandemic, resulting in a shift from office to increased residential occupancy. Residential buildings are – at present - more and more taking over the role of office buildings. This emphasises the importance of a better understanding of residential occupant behaviour. Possibly, residential occupancy needs to be reconsidered as such and individual building units might be defined as mixed-usage units.

Conclusively, it should be noted that simulations are based on static schedules and are not capable of integrating actual real-life behaviours (which are for instance provided from on-site measurements). In this context, the energy performance gap describes the divergences between simulated or projected and actual use of energy. Recently, efforts have been conducted to provide an analysis of surveys and literature approaching this matter (Mahdavi 2021).

5 INDEX

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6 LITERATURE

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7 APPENDIX

A. Illustrations

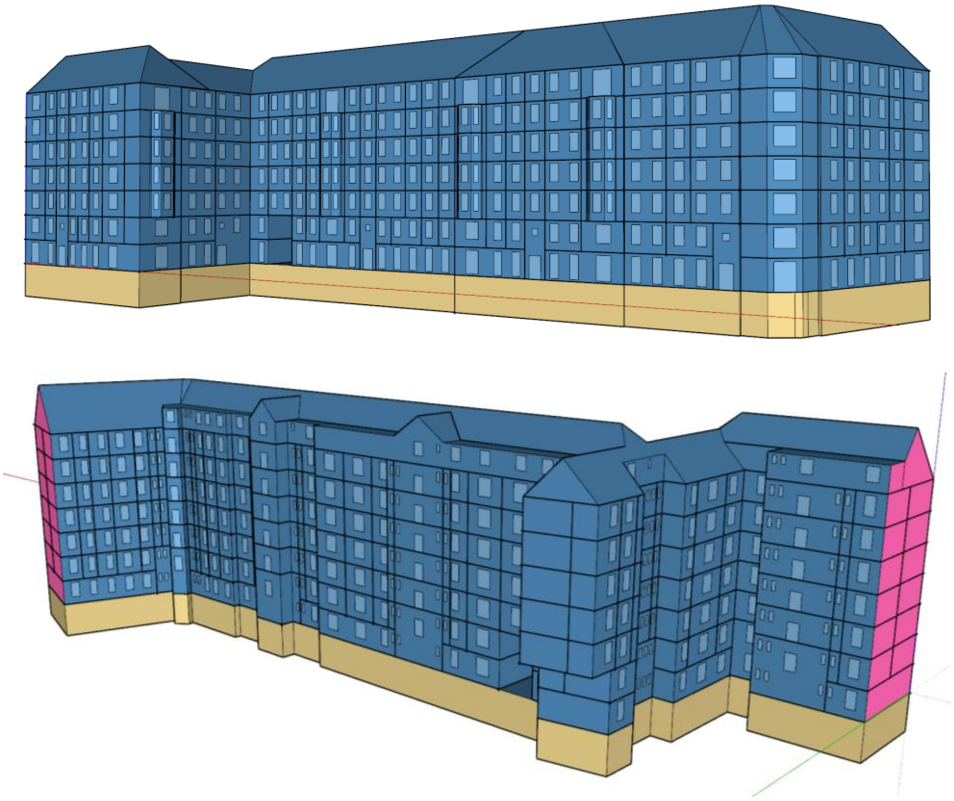


Figure 80: 3-dimensional front and rear perspective view, building A

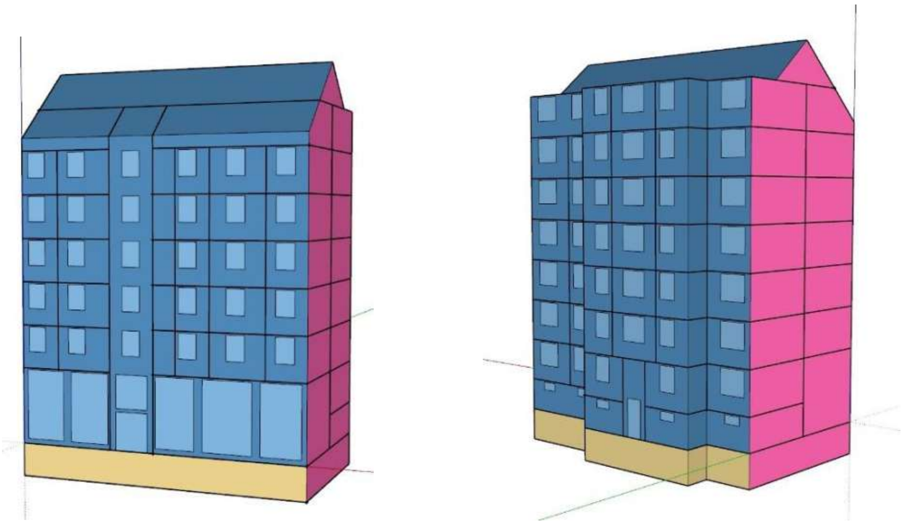


Figure 81: 3-dimensional front and rear perspective view, building B

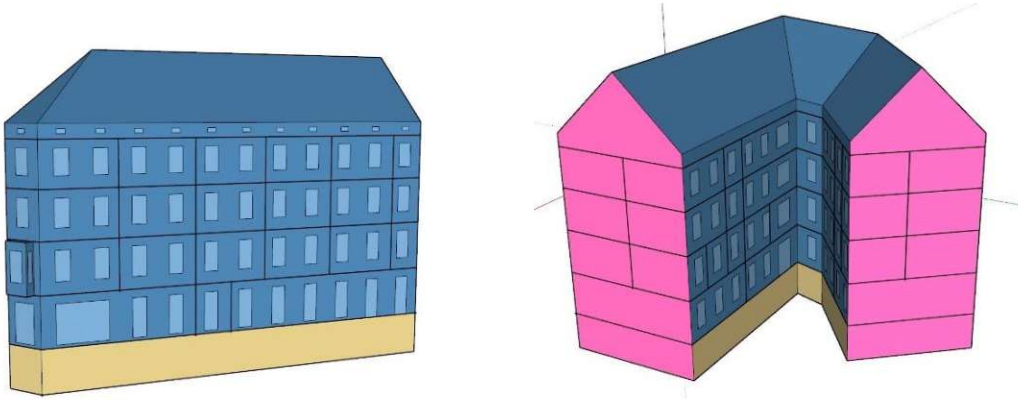


Figure 82: 3-dimensional front and rear perspective view, building C

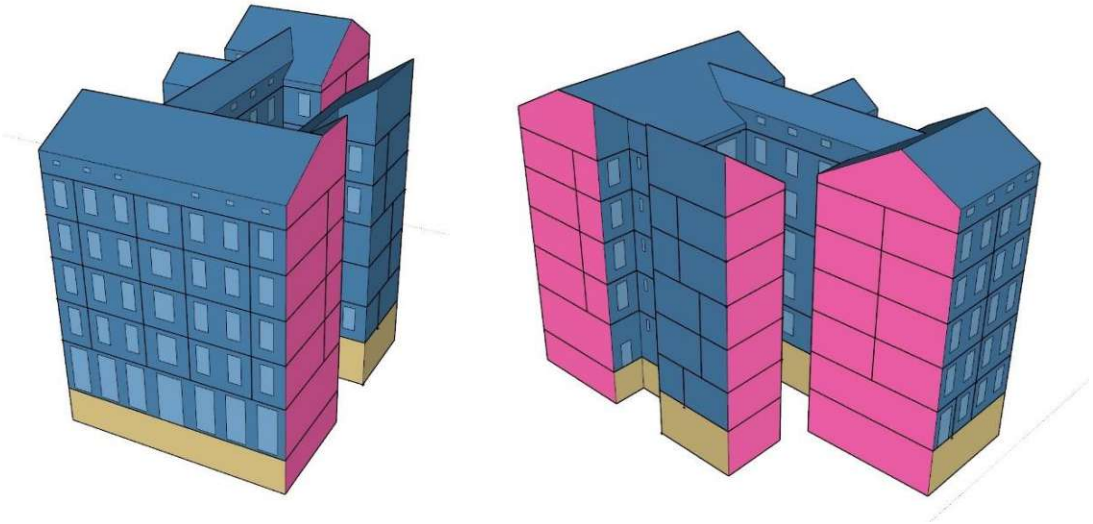


Figure 83: 3-dimensional front and rear perspective view, building D

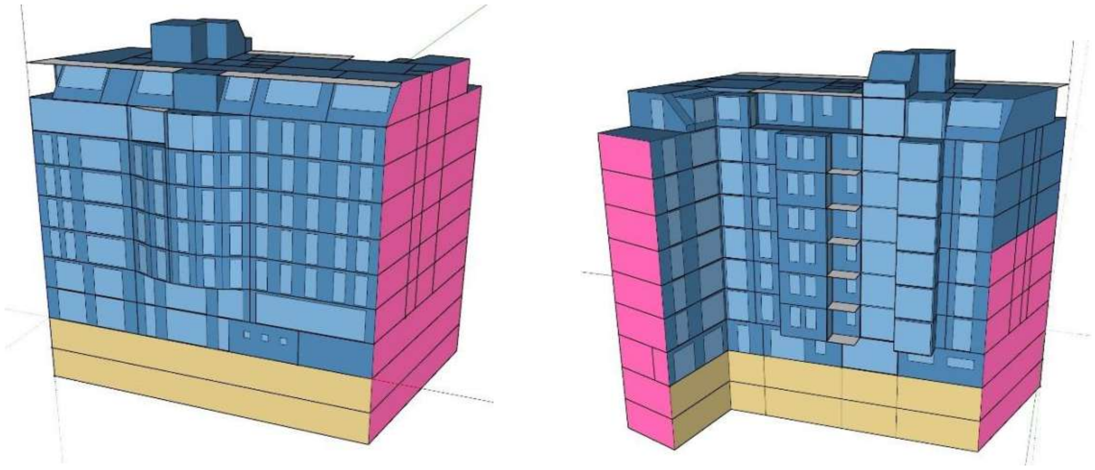


Figure 84: 3-dimensional front and rear perspective view, building E

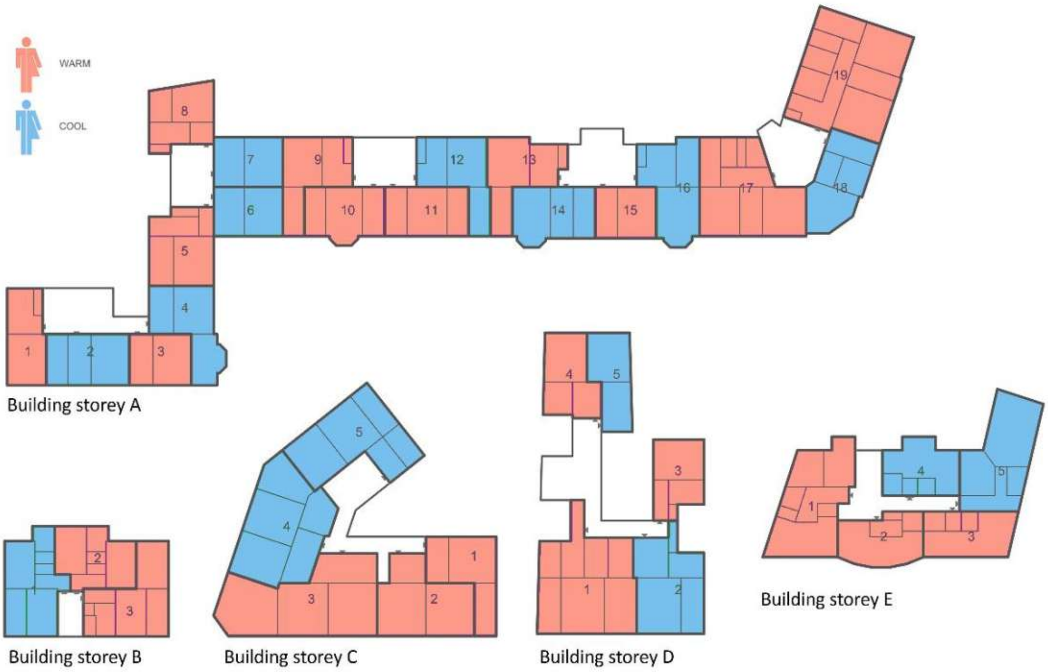
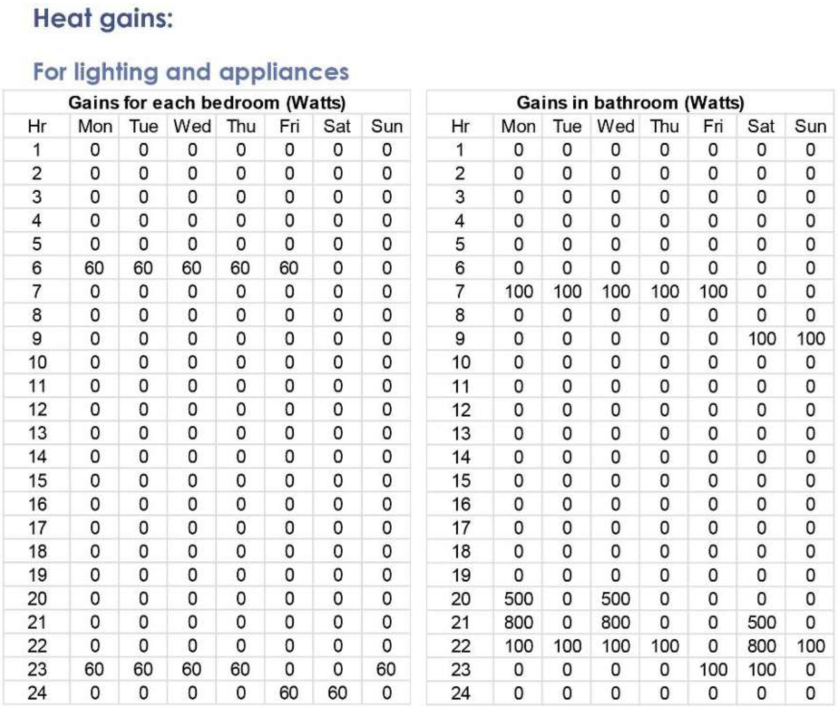


Figure 85: Distribution suggestion for occupant types "warm" and "cool", illustrated first scenario: warm occupant type = dominant, second scenario: vice versa

B. Tables

Table 10: Schedules used for internal gains taken from the IBPSA (2013) document (1/3)



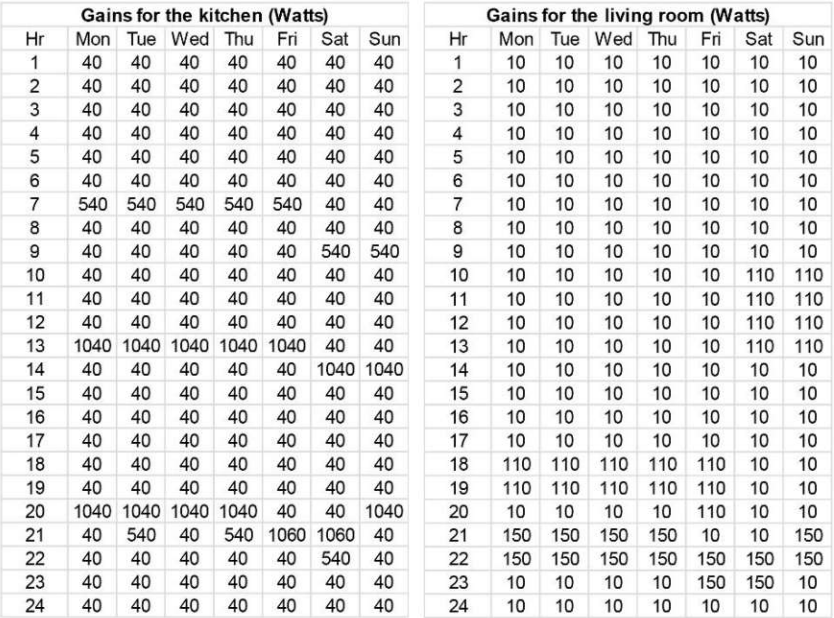
Heat gains:

For lighting and appliances

Gains for each bedroom (Watts)							
Hr	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	60	60	60	60	60	0	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
23	60	60	60	60	0	0	60
24	0	0	0	0	60	60	0

Gains in bathroom (Watts)							
Hr	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	100	100	100	100	100	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	100	100
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	500	0	500	0	0	0	0
21	800	0	800	0	0	500	0
22	100	100	100	100	0	800	100
23	0	0	0	0	100	100	0
24	0	0	0	0	0	0	0

Table 11: Schedules used for internal gains taken from the IBPSA (2013) document (2/3)

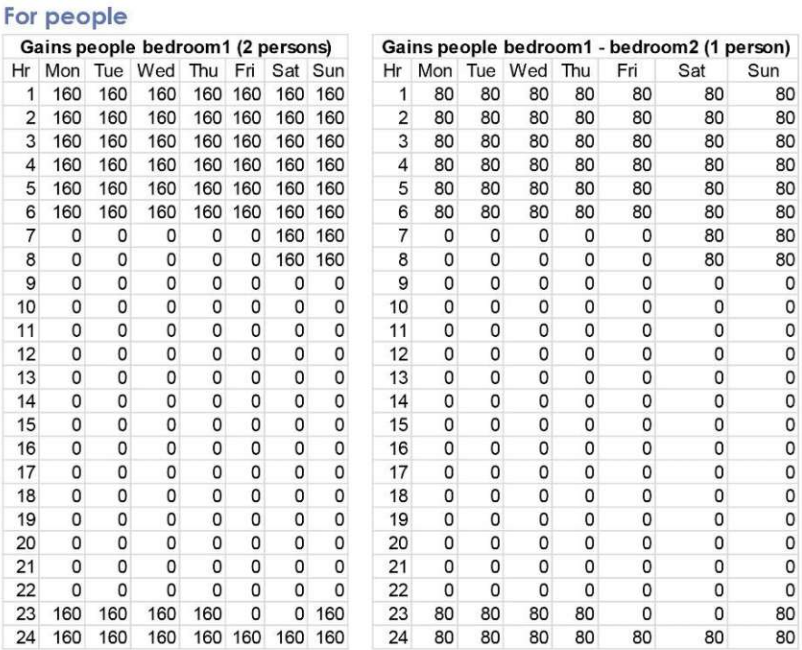


Gains for the kitchen (Watts)

Hr	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	40	40	40	40	40	40	40
2	40	40	40	40	40	40	40
3	40	40	40	40	40	40	40
4	40	40	40	40	40	40	40
5	40	40	40	40	40	40	40
6	40	40	40	40	40	40	40
7	540	540	540	540	540	40	40
8	40	40	40	40	40	40	40
9	40	40	40	40	40	540	540
10	40	40	40	40	40	40	40
11	40	40	40	40	40	40	40
12	40	40	40	40	40	40	40
13	1040	1040	1040	1040	1040	40	40
14	40	40	40	40	40	1040	1040
15	40	40	40	40	40	40	40
16	40	40	40	40	40	40	40
17	40	40	40	40	40	40	40
18	40	40	40	40	40	40	40
19	40	40	40	40	40	40	40
20	1040	1040	1040	1040	40	40	1040
21	40	540	40	540	1060	1060	40
22	40	40	40	40	40	540	40
23	40	40	40	40	40	40	40
24	40	40	40	40	40	40	40

Gains for the living room (Watts)

Hr	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	10	10	10	10	10	10	10
2	10	10	10	10	10	10	10
3	10	10	10	10	10	10	10
4	10	10	10	10	10	10	10
5	10	10	10	10	10	10	10
6	10	10	10	10	10	10	10
7	10	10	10	10	10	10	10
8	10	10	10	10	10	10	10
9	10	10	10	10	10	10	10
10	10	10	10	10	10	110	110
11	10	10	10	10	10	110	110
12	10	10	10	10	10	110	110
13	10	10	10	10	10	110	110
14	10	10	10	10	10	10	10
15	10	10	10	10	10	10	10
16	10	10	10	10	10	10	10
17	10	10	10	10	10	10	10
18	110	110	110	110	110	10	10
19	110	110	110	110	110	10	10
20	10	10	10	10	110	10	10
21	150	150	150	150	10	10	150
22	150	150	150	150	150	150	150
23	10	10	10	10	150	150	10
24	10	10	10	10	10	10	10



For people

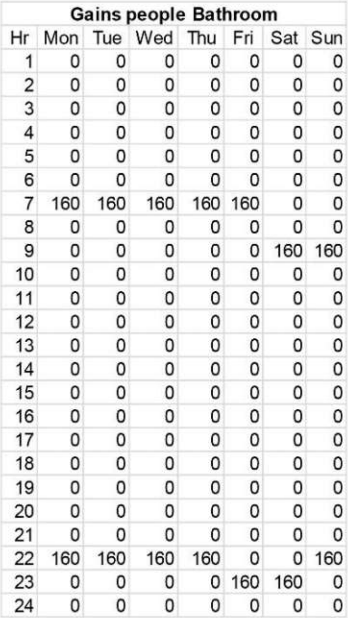
Gains people bedroom1 (2 persons)

Hr	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	160	160	160	160	160	160	160
2	160	160	160	160	160	160	160
3	160	160	160	160	160	160	160
4	160	160	160	160	160	160	160
5	160	160	160	160	160	160	160
6	160	160	160	160	160	160	160
7	0	0	0	0	0	160	160
8	0	0	0	0	0	160	160
9	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
23	160	160	160	160	0	0	160
24	160	160	160	160	160	160	160

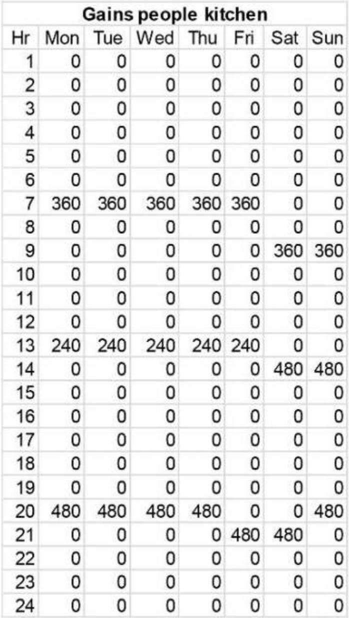
Gains people bedroom1 - bedroom2 (1 person)

Hr	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	80	80	80	80	80	80	80
2	80	80	80	80	80	80	80
3	80	80	80	80	80	80	80
4	80	80	80	80	80	80	80
5	80	80	80	80	80	80	80
6	80	80	80	80	80	80	80
7	0	0	0	0	0	80	80
8	0	0	0	0	0	80	80
9	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
23	80	80	80	80	0	0	80
24	80	80	80	80	80	80	80

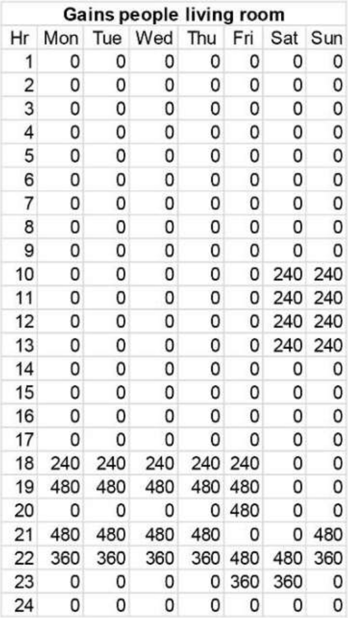
Table 12: Schedules used for internal gains taken from the IBPSA (2013) document (3/3)



Gains people Bathroom							
Hr	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	160	160	160	160	160	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	160	160
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0
22	160	160	160	160	0	0	160
23	0	0	0	0	160	160	0
24	0	0	0	0	0	0	0



Gains people kitchen							
Hr	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	360	360	360	360	360	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	360	360
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
13	240	240	240	240	240	0	0
14	0	0	0	0	0	480	480
15	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	480	480	480	480	0	0	480
21	0	0	0	0	480	480	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0



Gains people living room							
Hr	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	0	0	0	0	240	240
11	0	0	0	0	0	240	240
12	0	0	0	0	0	240	240
13	0	0	0	0	0	240	240
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0
18	240	240	240	240	240	0	0
19	480	480	480	480	480	0	0
20	0	0	0	0	480	0	0
21	480	480	480	480	0	0	480
22	360	360	360	360	480	480	360
23	0	0	0	0	360	360	0
24	0	0	0	0	0	0	0

Table 13: Constructions used for the simulations, buildings A to E

CONSTRUCTIONS

Cluster A

Name	Outside Layer	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Exterior Door	Holz_50mm					
Window	Fenster					
Wall_EXT	Putz_aussen_25mm	AW_Ziegel_45cm	Putz_innen_20mm			
Wall_Adiab	AW_Ziegel_45cm	Putz_innen_20mm				
Interior Wall	Putz_innen_20mm	IW_Ziegel_15cm	Putz_innen_20mm			
Interior Wall_thick	Putz_innen_20mm	IW_Ziegel_45cm	Putz_innen_20mm			
Wall_UG	AW_Ziegel_45cm					
Interior Ceiling	Schiffboden	Sand_8cm	Deckenschalung	Tramdecke	Deckenschalung	Putz_innen_25mm
Ceiling_UG-EG	Steinbelag_15mm	Sand_15cm	Deckengewoelbe			
Ceiling_OG5-ATT	Deckenziegel	Sand_8cm	Dippelbaumdecke_22cm	Putz_innen_25mm		
Interior Floor	Putz_innen_25mm	Deckenschalung	Tramdecke	Deckenschalung	Sand_8cm	Schiffboden
Floor_Outside	Putz_aussen_25mm	Deckenschalung	Tramdecke	Deckenschalung	Sand_8cm	Schiffboden
Floor_ATT	Putz_innen_25mm	Dippelbaumdecke_22cm	Sand_8cm	Deckenziegel		
Floor_EG-UG	Deckengewoelbe	Sand_15cm	Steinbelag_15mm			
Floor_UG	Deckenziegel					
Roof_steep	Dachziegel	Dachschalung				
Window_Sh_Cons	Fenster	HIGH REFLECT - LOW TRANS SHADE				
Interior Door	Holz_25mm					
Window_Sh_Normal	Fenster	MEDIUM REFLECT - MEDIUM TRANS SHADE				

CONSTRUCTIONS

Cluster B

Name	Outside Layer	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Wall_EXT	Putz_aussen_10mm	Ziegelsplittbeton_30cm	Putz_innen_10mm			
Wall_Adiab+UG	Ziegelsplittbeton_30cm					
Interior Wall	Putz_innen_10mm	Ziegel_12cm	Putz_innen_10mm			
Wall_INT_thick	Putz_innen_10mm	Ziegelsplittbeton_45cm	Putz_innen_10mm			
Floor_HtoH	Putz_innen_10mm	STB_20cm	Schuettung_3cm	TSD_5mm	Estrich_5cm	Parkett_15mm
Floor_HtoUNH	STB_20cm	Schuettung_3cm	STB_20cm	Estrich_5cm	Steinboden_1cm	
Floor_UG	Rollierung_25cm	STB_20cm				
Floor_Attic	Putz_innen_10mm	STB_20cm	TSD_20mm			
Ceiling_HtoH	Parkett_15mm	Estrich_5cm	TSD_5mm	Schuettung_3cm	STB_20cm	Putz_innen_10mm
Ceiling_UNHtoH	Steinboden_1cm	Estrich_5cm	STB_20cm	Schuettung_3cm	STB_20cm	
Ceiling_DG	TSD_20mm	STB_20cm	Putz_innen_10mm			
Roof_flat	Blecheindeckung	TSD_20mm	STB_20cm	Putz_innen_10mm		
Roof_steep	Blecheindeckung	Schalung				
Fenster	Fenster_einfach					
Interior Door	Holz_25mm					
Aussentuere	Holz_50mm					
Fenster_Sh_Cons	Fenster_einfach	HIGH REFLECT - LOW TRANS SHADE				
Fenster_Sh_Normal	Fenster_Normal	MEDIUM REFLECT - MEDIUM TRANS SHADE				

CONSTRUCTIONS

Cluster C

Name	Outside Layer	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Exterior Door	Holz_50mm					
Interior Door	Holz_25mm					
Window	Fenster					
Wall_EXT	Putz_aussen_25mm	AW_Ziegel_45cm	Putz_innen_10mm			
Wall_Adiab	AW_Ziegel_45cm	Putz_innen_10mm				
Interior Wall	Putz_innen_20mm	IW_Ziegel_15cm	Putz_innen_20mm			
Interior Wall_thick	**Putz_innen_20mm**	IW_Ziegel_45cm	Putz_innen_20mm			
Wall_UG	AW_Ziegel_45cm					
Interior Ceiling	Schiffboden	Sand_8cm	Deckenschalung	Tramdecke	Deckenschalung	Putz_innen_25mm
Ceiling_UG-EG	Steinbelag_15mm	Sand_15cm	Deckengewoelbe			
Ceiling_OG3-ATT	Deckenziegel	Sand_8cm	Dippelbaumdecke_22cm	Putz_innen_25mm		
Interior Floor	Putz_innen_25mm	Deckenschalung	Tramdecke	Deckenschalung	Sand_8cm	Schiffboden
Floor_Outside	Putz_aussen_25mm	Deckenschalung	Tramdecke	Deckenschalung	Sand_8cm	Schiffboden
Floor_ATT	Putz_innen_25mm	Dippelbaumdecke_22cm	Sand_8cm	Deckenziegel		
Floor_EG-UG	Deckengewoelbe	Sand_15cm	Steinbelag_15mm			
Floor_UG	Deckenziegel					
Roof_steep	Dachziegel	Dachschalung				
Fenster_Sh_Cons	Fenster	HIGH REFLECT - LOW TRANS SHADE				
Fenster_Sh_Normal	Fenster	MEDIUM REFLECT - MEDIUM TRANS SHADE				

CONSTRUCTIONS

Cluster D

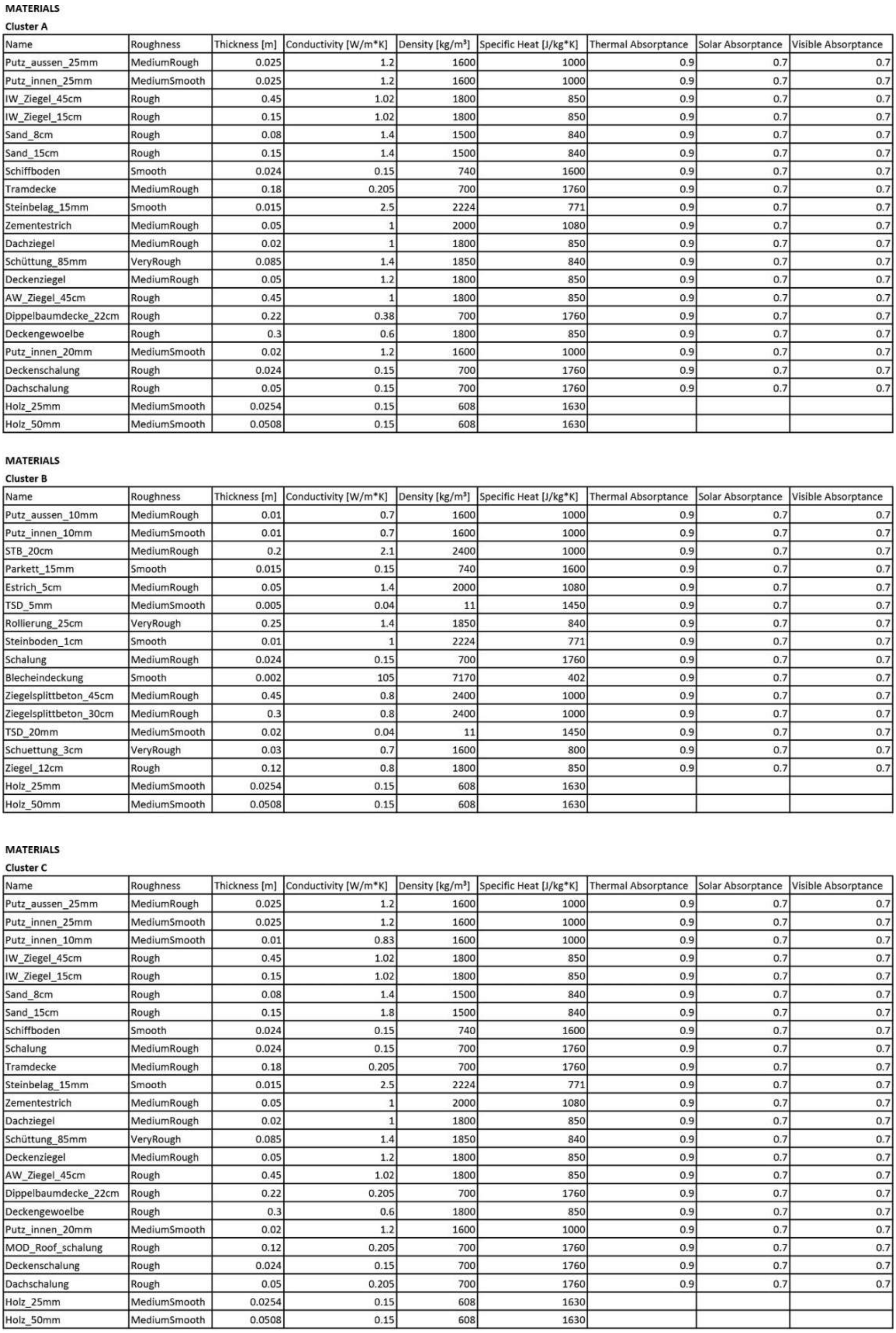
Name	Outside Layer	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Exterior Door	Holz_50mm					
Interior Door	Holz_25mm					
Interior Window	Fenster					
Window	Fenster					
Wall_EXT	Putz_aussen_25mm	Ziegel_45cm	Putz_innen_20mm			
Wall_Adiab	Ziegel_45cm	Putz_innen_20mm				
Interior Wall	Putz_innen_20mm	Ziegel_15cm	Putz_innen_20mm			
Interior Wall_thick	Putz_innen_20mm	Ziegel_45cm	Putz_innen_20mm			
Wall_UG	Ziegel_45cm					
Interior Ceiling	Schiffboden	Sand_8cm	Deckenschalung	Tramdecke	Deckenschalung	Putz_innen_25mm
Ceiling_UG-EG	Naturstein_15mm	Sand_15cm	Deckengewoelbe			
Ceiling_OG4-ATT	Deckenziegel	Sand_8cm	Dippelbaumdecke_22cm	Putz_innen_25mm		
Interior Floor	Putz_innen_25mm	Deckenschalung	Tramdecke	Deckenschalung	Sand_8cm	Schiffboden
Floor_Outside	Putz_aussen_25mm	Deckenschalung	Tramdecke	Deckenschalung	Sand_8cm	Schiffboden
Floor_ATT	Putz_innen_25mm	Dippelbaumdecke_22cm	Sand_8cm	Deckenziegel		
Floor_EG-UG	Deckengewoelbe	Sand_15cm	Naturstein_15mm			
Floor_UG	Deckenziegel					
Roof_steep	Dachziegel	Dachschalung				

CONSTRUCTIONS

Cluster E

Name	Outside Layer	Layer 2	Layer 3	Layer 4	Layer 5
Interior Ceiling	Parkett	Estrich_50mm	TSD	STB_22cm	Innenputz_15mm
Interior Door	Holz_50mm				
Interior Floor	Innenputz_15mm	STB_22cm	TSD	Estrich_50mm	Parkett
Interior Wall	Innenputz_15mm	Ziegel_10cm	Innenputz_15mm		
Roof_steep	Dachabdeckung	Schalung	Minderalwolle	STB_22cm	Innenputz_15mm
Wall_EXT	EPS_50mm	Ziegel_25cm	Innenputz_15mm		
Window	Fenster				
Exterior Door	Holz_50mm				
Ceiling_UG2-UG1	Estrich_25mm	Gefaellebeton_5cm	STB_22cm		
Ceiling_UG1-EG	Estrich_50mm	EPS_65mm	STB_22cm		
Ceiling_EG-OG1	Parkett	Estrich_50mm	TSD	STB_22cm	EPS_35mm
Ceiling_Terrasse	Betonplatte_4cm	Roofmate_18cm	Gefaellebeton_5cm	STB_22cm	Innenputz_15mm
Floor_UG1-UG2	STB_22cm	Gefaellebeton_5cm	Estrich_25mm		
Floor_OG1-EG	EPS_35mm	STB_22cm	TSD	Estrich_50mm	Parkett
Floor_EG-UG1	STB_22cm	EPS_65mm	Estrich_50mm		
Floor_UG2	Schuettung_25cm	STB_22cm	Gefaellebeton_5cm	Estrich_25mm	
Wall_STGH	Thermoputz_15mm	Ziegel_30cm	Thermoputz_15mm		
Wall_Adiab	EPS_50mm	Ziegel_25cm	Innenputz_15mm		
Fenster_Sh_Cons	Fenster	HIGH REFLECT - LOW TRANS SHADE			
Fenster_Sh_Normal	Fenster	MEDIUM REFLECT - MEDIUM TRANS SHADE			

Table 14: Constructions used for the simulations, buildings A to E



MATERIALS

Cluster A

Name	Roughness	Thickness [m]	Conductivity [W/m*K]	Density [kg/m³]	Specific Heat [J/kg*K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
Putz_aussen_25mm	MediumRough	0.025	1.2	1600	1000	0.9	0.7	0.7
Putz_innen_25mm	MediumSmooth	0.025	1.2	1600	1000	0.9	0.7	0.7
IW_Ziegel_45cm	Rough	0.45	1.02	1800	850	0.9	0.7	0.7
IW_Ziegel_15cm	Rough	0.15	1.02	1800	850	0.9	0.7	0.7
Sand_8cm	Rough	0.08	1.4	1500	840	0.9	0.7	0.7
Sand_15cm	Rough	0.15	1.4	1500	840	0.9	0.7	0.7
Schiffboden	Smooth	0.024	0.15	740	1600	0.9	0.7	0.7
Tramdecke	MediumRough	0.18	0.205	700	1760	0.9	0.7	0.7
Steinbelag_15mm	Smooth	0.015	2.5	2224	771	0.9	0.7	0.7
Zementestrich	MediumRough	0.05	1	2000	1080	0.9	0.7	0.7
Dachziegel	MediumRough	0.02	1	1800	850	0.9	0.7	0.7
Schüttung_85mm	VeryRough	0.085	1.4	1850	840	0.9	0.7	0.7
Deckenziegel	MediumRough	0.05	1.2	1800	850	0.9	0.7	0.7
AW_Ziegel_45cm	Rough	0.45	1	1800	850	0.9	0.7	0.7
Dippelbaumdecke_22cm	Rough	0.22	0.38	700	1760	0.9	0.7	0.7
Deckengewoelbe	Rough	0.3	0.6	1800	850	0.9	0.7	0.7
Putz_innen_20mm	MediumSmooth	0.02	1.2	1600	1000	0.9	0.7	0.7
Deckenschalung	Rough	0.024	0.15	700	1760	0.9	0.7	0.7
Dachschalung	Rough	0.05	0.15	700	1760	0.9	0.7	0.7
Holz_25mm	MediumSmooth	0.0254	0.15	608	1630			
Holz_50mm	MediumSmooth	0.0508	0.15	608	1630			

MATERIALS

Cluster B

Name	Roughness	Thickness [m]	Conductivity [W/m*K]	Density [kg/m³]	Specific Heat [J/kg*K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
Putz_aussen_10mm	MediumRough	0.01	0.7	1600	1000	0.9	0.7	0.7
Putz_innen_10mm	MediumSmooth	0.01	0.7	1600	1000	0.9	0.7	0.7
STB_20cm	MediumRough	0.2	2.1	2400	1000	0.9	0.7	0.7
Parkett_15mm	Smooth	0.015	0.15	740	1600	0.9	0.7	0.7
Estrich_5cm	MediumRough	0.05	1.4	2000	1080	0.9	0.7	0.7
TSD_5mm	MediumSmooth	0.005	0.04	11	1450	0.9	0.7	0.7
Rollierung_25cm	VeryRough	0.25	1.4	1850	840	0.9	0.7	0.7
Steinboden_1cm	Smooth	0.01	1	2224	771	0.9	0.7	0.7
Schalung	MediumRough	0.024	0.15	700	1760	0.9	0.7	0.7
Blecheindeckung	Smooth	0.002	105	7170	402	0.9	0.7	0.7
Ziegelsplittbeton_45cm	MediumRough	0.45	0.8	2400	1000	0.9	0.7	0.7
Ziegelsplittbeton_30cm	MediumRough	0.3	0.8	2400	1000	0.9	0.7	0.7
TSD_20mm	MediumSmooth	0.02	0.04	11	1450	0.9	0.7	0.7
Schuettung_3cm	VeryRough	0.03	0.7	1600	800	0.9	0.7	0.7
Ziegel_12cm	Rough	0.12	0.8	1800	850	0.9	0.7	0.7
Holz_25mm	MediumSmooth	0.0254	0.15	608	1630			
Holz_50mm	MediumSmooth	0.0508	0.15	608	1630			

MATERIALS

Cluster C

Name	Roughness	Thickness [m]	Conductivity [W/m*K]	Density [kg/m³]	Specific Heat [J/kg*K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
Putz_aussen_25mm	MediumRough	0.025	1.2	1600	1000	0.9	0.7	0.7
Putz_innen_25mm	MediumSmooth	0.025	1.2	1600	1000	0.9	0.7	0.7
Putz_innen_10mm	MediumSmooth	0.01	0.83	1600	1000	0.9	0.7	0.7
IW_Ziegel_45cm	Rough	0.45	1.02	1800	850	0.9	0.7	0.7
IW_Ziegel_15cm	Rough	0.15	1.02	1800	850	0.9	0.7	0.7
Sand_8cm	Rough	0.08	1.4	1500	840	0.9	0.7	0.7
Sand_15cm	Rough	0.15	1.8	1500	840	0.9	0.7	0.7
Schiffboden	Smooth	0.024	0.15	740	1600	0.9	0.7	0.7
Schalung	MediumRough	0.024	0.15	700	1760	0.9	0.7	0.7
Tramdecke	MediumRough	0.18	0.205	700	1760	0.9	0.7	0.7
Steinbelag_15mm	Smooth	0.015	2.5	2224	771	0.9	0.7	0.7
Zementestrich	MediumRough	0.05	1	2000	1080	0.9	0.7	0.7
Dachziegel	MediumRough	0.02	1	1800	850	0.9	0.7	0.7
Schüttung_85mm	VeryRough	0.085	1.4	1850	840	0.9	0.7	0.7
Deckenziegel	MediumRough	0.05	1.2	1800	850	0.9	0.7	0.7
AW_Ziegel_45cm	Rough	0.45	1.02	1800	850	0.9	0.7	0.7
Dippelbaumdecke_22cm	Rough	0.22	0.205	700	1760	0.9	0.7	0.7
Deckengewoelbe	Rough	0.3	0.6	1800	850	0.9	0.7	0.7
Putz_innen_20mm	MediumSmooth	0.02	1.2	1600	1000	0.9	0.7	0.7
MOD_Roof_schalung	Rough	0.12	0.205	700	1760	0.9	0.7	0.7
Deckenschalung	Rough	0.024	0.15	700	1760	0.9	0.7	0.7
Dachschalung	Rough	0.05	0.205	700	1760	0.9	0.7	0.7
Holz_25mm	MediumSmooth	0.0254	0.15	608	1630			
Holz_50mm	MediumSmooth	0.0508	0.15	608	1630			

MATERIALS

Cluster D

Name	Roughness	Thickness [m]	Conductivity [W/m*K]	Density [kg/m^3]	Specific Heat [J/kg*K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
Holz_25mm	MediumSmooth	0.0254	0.15	608	1630			
Holz_50mm	MediumSmooth	0.0508	0.15	608	1630			
Putz_aussen_25mm	MediumRough	0.025	1.2	1600	1000	0.9	0.7	0.7
Putz_innen_25mm	MediumSmooth	0.025	1.2	1600	1000	0.9	0.7	0.7
Putz_innen_10mm	MediumSmooth	0.01	0.83	1600	1000	0.9	0.7	0.7
Ziegel_45cm	Rough	0.45	1.02	1800	850	0.9	0.7	0.7
Ziegel_15cm	Rough	0.15	1.02	1800	850	0.9	0.7	0.7
Sand_8cm	Rough	0.08	1.4	1500	840	0.9	0.7	0.7
Sand_15cm	Rough	0.15	1.8	1500	840	0.9	0.7	0.7
Schiffboden	Smooth	0.024	0.15	740	1600	0.9	0.7	0.7
Schalung	MediumRough	0.024	0.15	700	1760	0.9	0.7	0.7
Tramdecke	MediumRough	0.18	0.205	700	1760	0.9	0.7	0.7
Naturstein_15mm	Smooth	0.015	2.5	2224	771	0.9	0.7	0.7
Estrich_5cm	MediumRough	0.05	1	2000	1080	0.9	0.7	0.7
Dachziegel	MediumRough	0.02	1	1800	850	0.9	0.7	0.7
Schuettung_85mm	VeryRough	0.085	1.4	1850	840	0.9	0.7	0.7
Deckenziegel	MediumRough	0.05	1.2	1800	850	0.9	0.7	0.7
Dippelbaumdecke_22cm	Rough	0.22	0.205	700	1760	0.9	0.7	0.7
Deckengewoelbe	Rough	0.3	0.6	1800	850	0.9	0.7	0.7
Putz_innen_20mm	MediumSmooth	0.02	1.2	1600	1000	0.9	0.7	0.7
Deckenschalung	Rough	0.024	0.15	700	1760	0.9	0.7	0.7
Dachschalung	Rough	0.12	0.205	700	1760	0.9	0.7	0.7

MATERIALS

Cluster E

Name	Roughness	Thickness [m]	Conductivity [W/m*K]	Density [kg/m^3]	Specific Heat [J/kg*K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
Betonplatte_4cm	MediumRough	0.04	2.1	2400	1000	0.9	0.7	0.7
Gefaellebeton_5cm	MediumRough	0.05	2.1	2400	1000	0.9	0.7	0.7
STB_22cm	MediumRough	0.22	2.1	2400	1000	0.9	0.7	0.7
STB_30cm	MediumRough	0.3	2.1	2400	1000	0.9	0.7	0.7
Estrich_25mm	MediumRough	0.025	1.4	2000	1080	0.9	0.7	0.7
Estrich_50mm	MediumRough	0.05	1.4	2000	1080	0.9	0.7	0.7
Roofmate_18cm	MediumRough	0.18	0.047	38	1450	0.9	0.7	0.7
Roofmate_5cm	MediumRough	0.05	0.047	38	1450	0.9	0.7	0.7
Innenputz_15mm	MediumSmooth	0.015	0.7	1600	1000	0.9	0.7	0.7
Schalung	MediumRough	0.024	0.15	700	1760	0.9	0.7	0.7
Ziegel_10cm	MediumRough	0.1	0.34	800	1000	0.9	0.7	0.7
Ziegel_25cm	MediumRough	0.25	0.64	1762	920	0.9	0.7	0.7
Ziegel_30cm	MediumRough	0.3	0.38	1553	920	0.9	0.7	0.7
TSD	MediumSmooth	0.03	0.033	11	1450	0.9	0.7	0.7
Schuettung_25cm	VeryRough	0.25	1.4	1850	840	0.9	0.7	0.7
Parkett	Smooth	0.02	0.15	740	1600	0.9	0.7	0.7
Minderalwolle	MediumRough	0.18	0.05	120	1030	0.9	0.7	0.7
EPS_35mm	MediumSmooth	0.035	0.035	15	1400	0.9	0.7	0.7
Thermoputz_15mm	MediumSmooth	0.015	0.13	450	1000	0.9	0.7	0.7
Dachabdeckung	Smooth	0.002	105	7170	402	0.9	0.7	0.7
EPS_65mm	MediumSmooth	0.065	0.035	15	1400	0.9	0.7	0.7
EPS_50mm	MediumSmooth	0.05	0.035	15	1400	0.9	0.7	0.7
Holz_50mm	MediumSmooth	0.0508	0.15	608	1630			

C. Results

Summer season by occupant type:

Building A

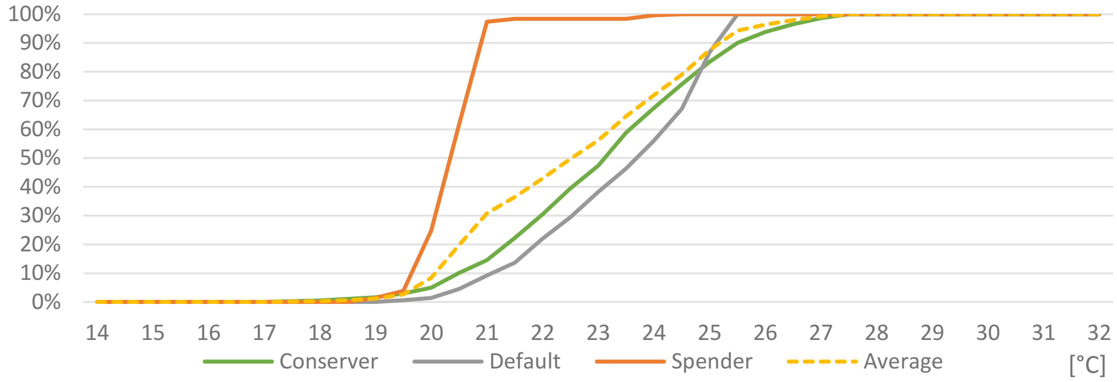


Figure 86: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey A, summer season

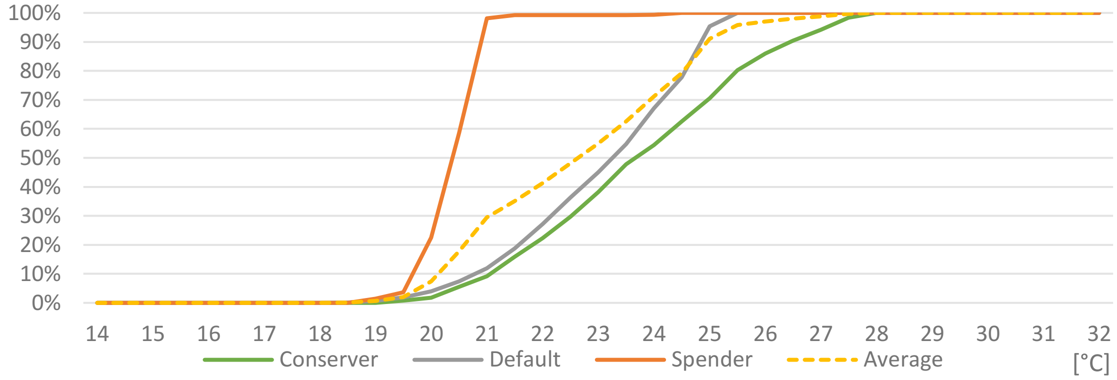


Figure 87: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey A, summer season

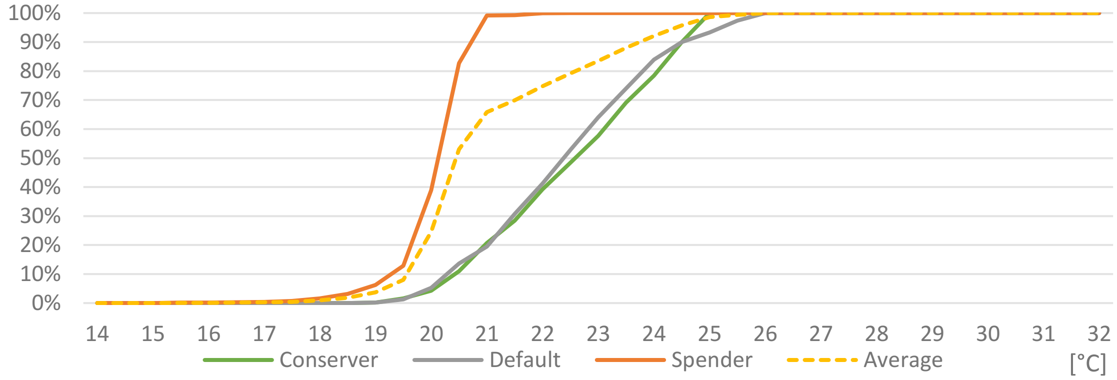


Figure 88: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey A, summer season

Building B

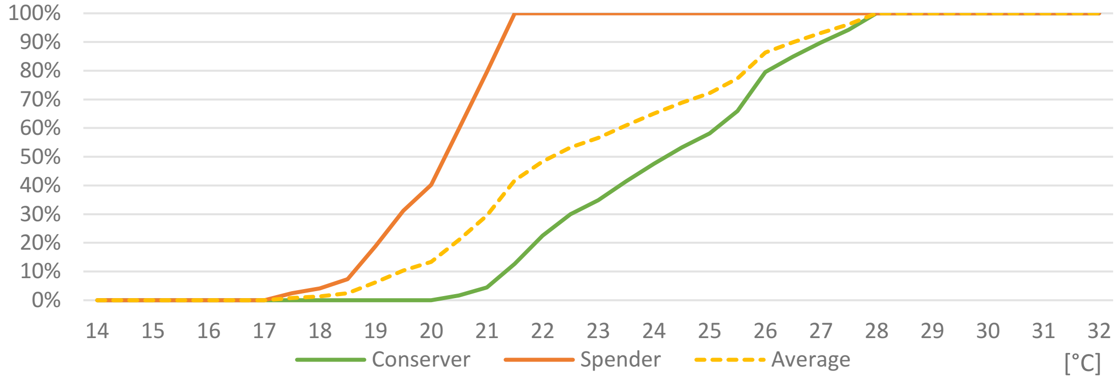


Figure 89: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey B, summer season

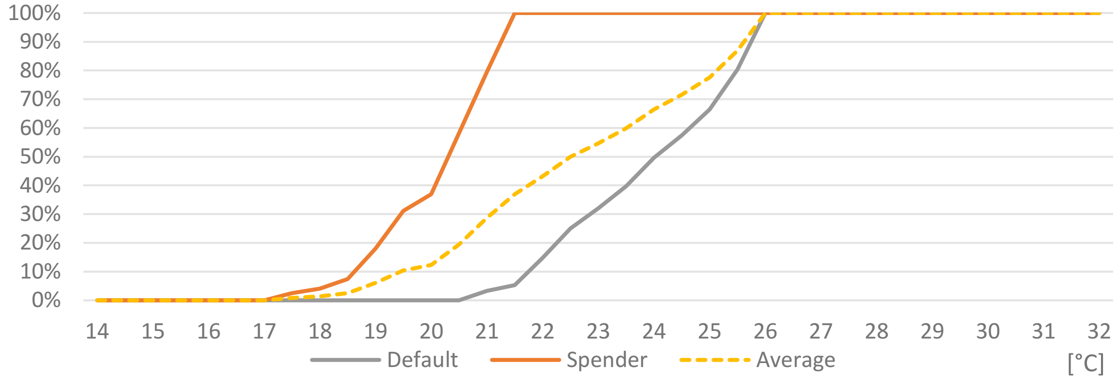


Figure 90: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey B, summer season

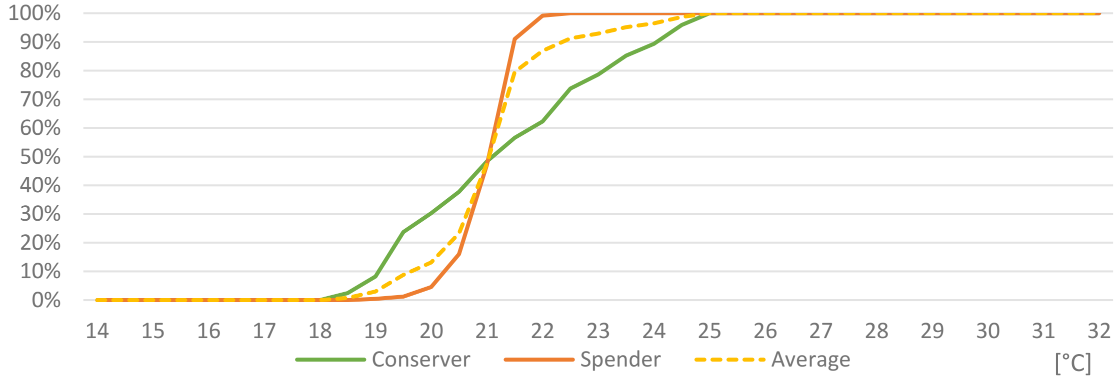


Figure 91: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey B, summer season

Building C

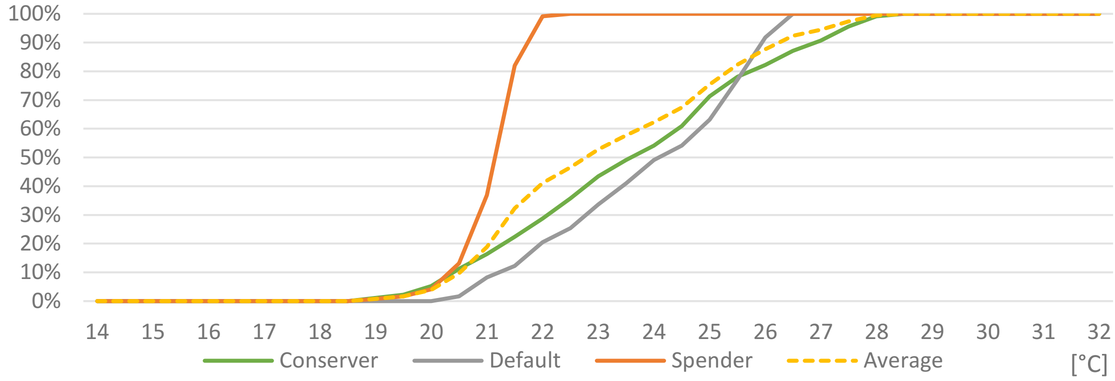


Figure 92: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey C, summer season

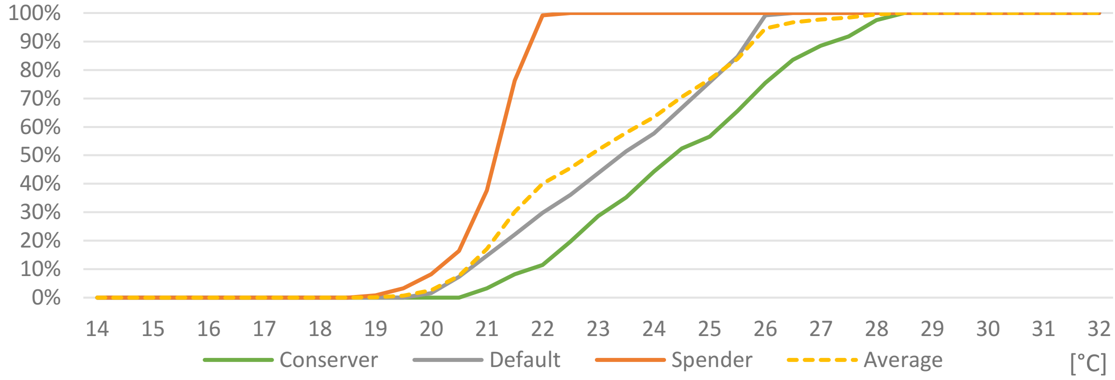


Figure 93: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey C, summer season

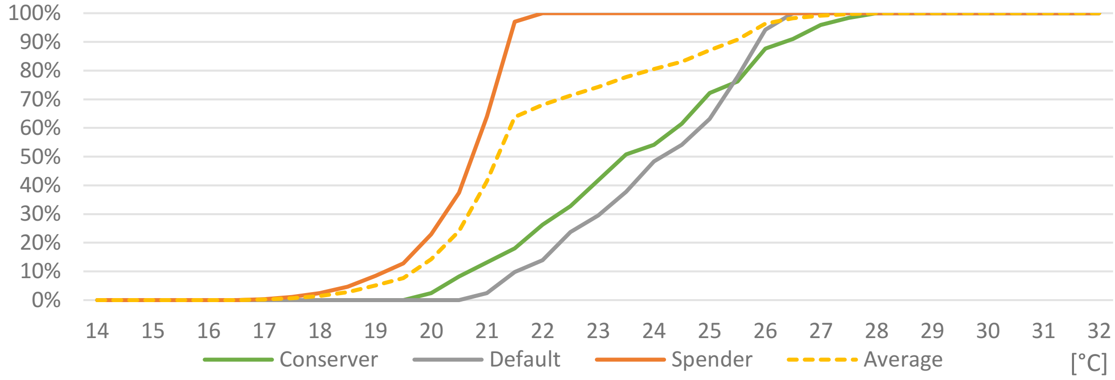


Figure 94: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey C, summer season

Building D

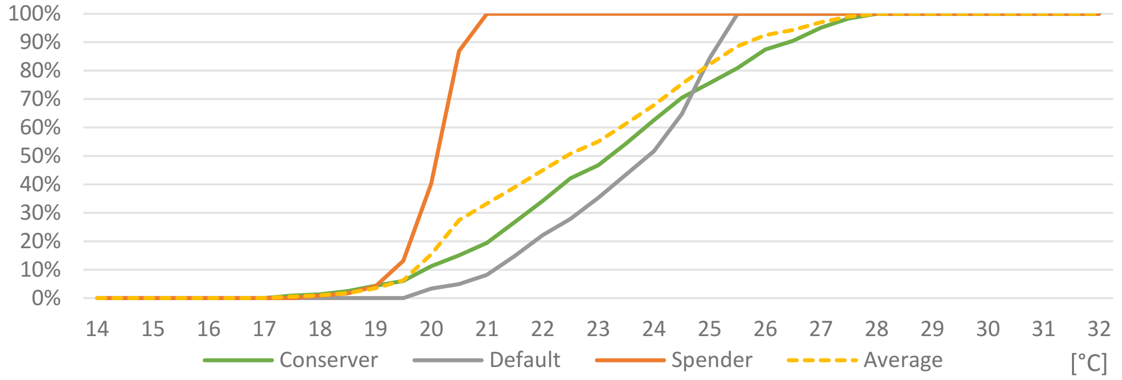


Figure 95: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey D, summer season

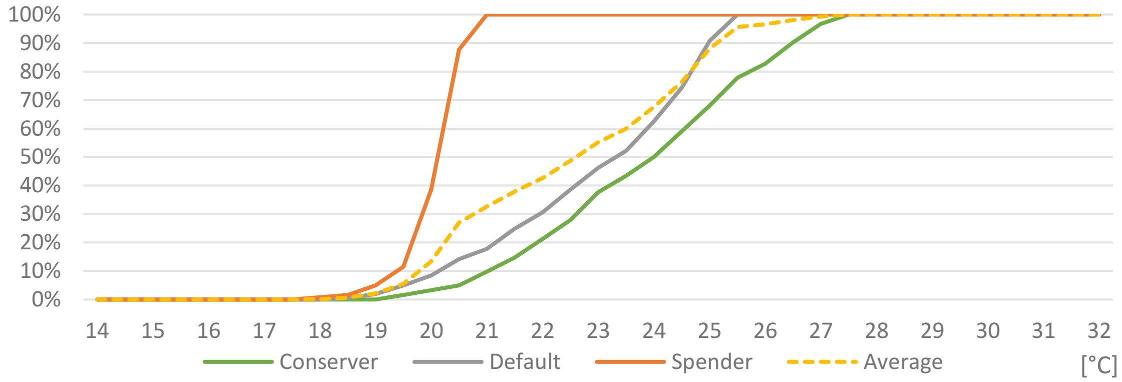


Figure 96: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey D, summer season

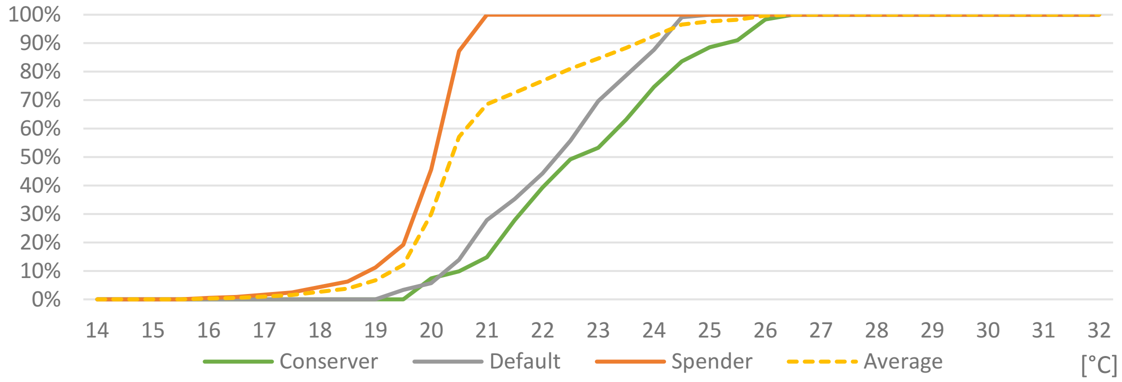


Figure 97: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey D, summer season

Building E

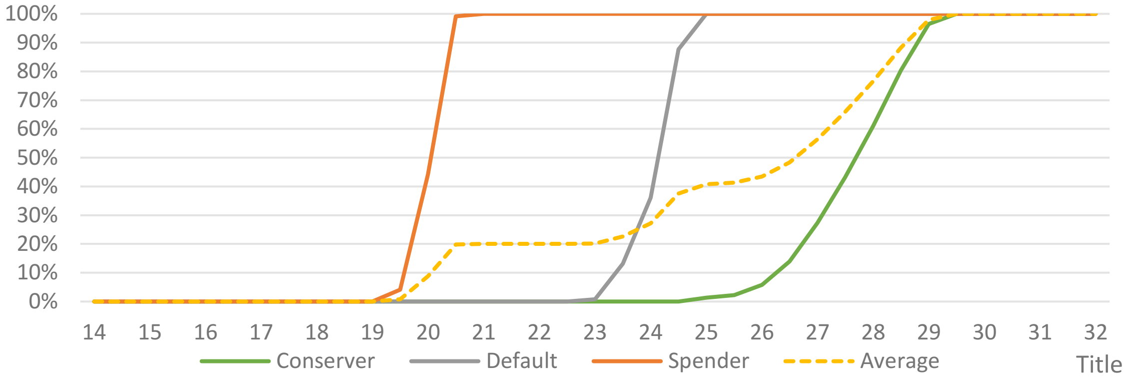


Figure 98: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey E, summer season

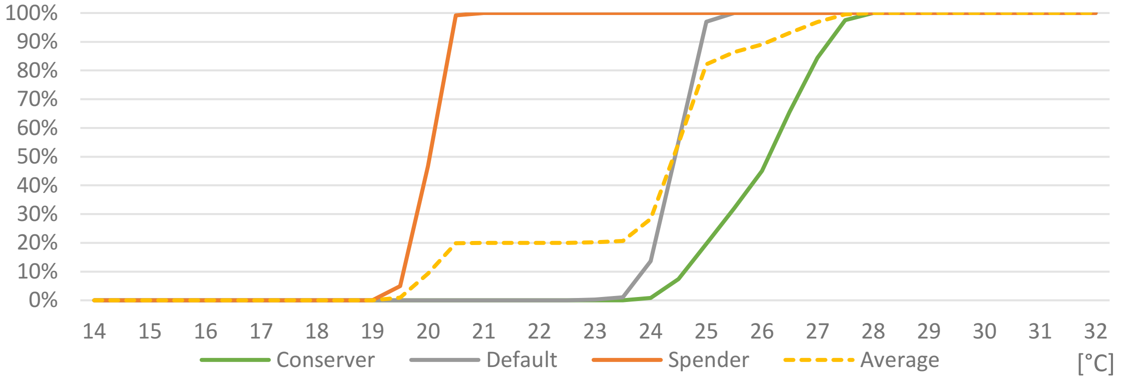


Figure 99: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey E, summer season

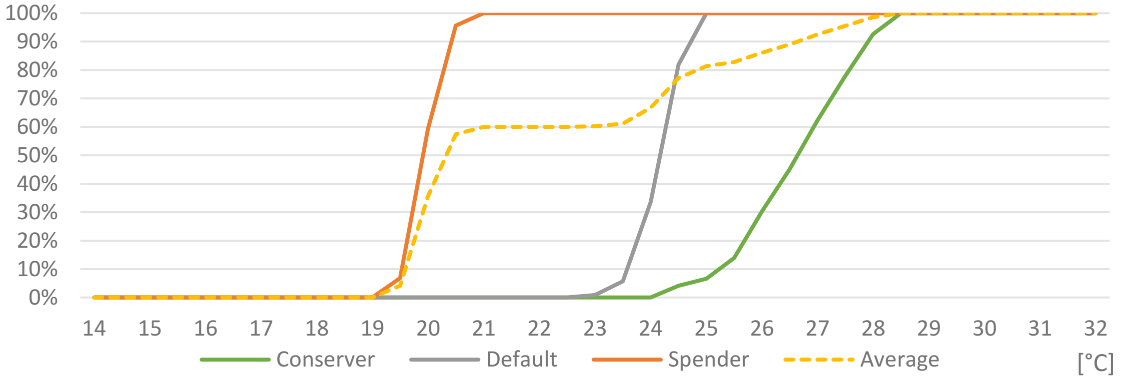


Figure 100: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey E, summer season

Summer season by apartment

Building A

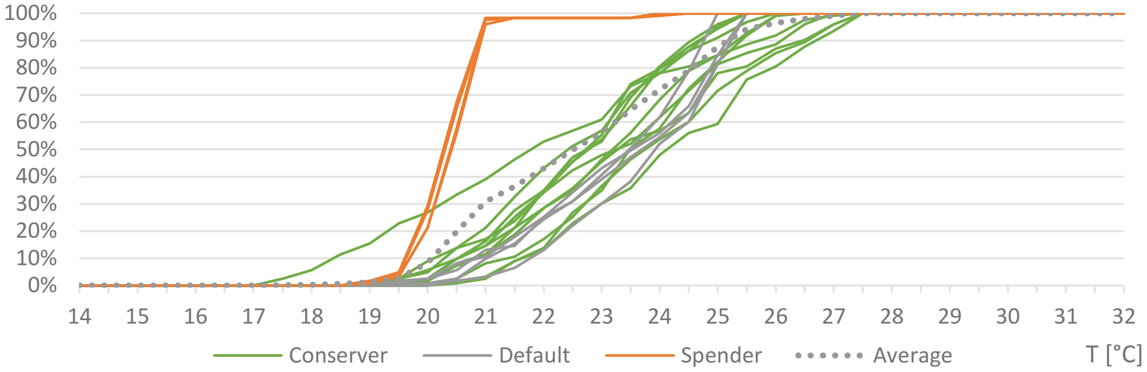


Figure 101: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey A, summer season

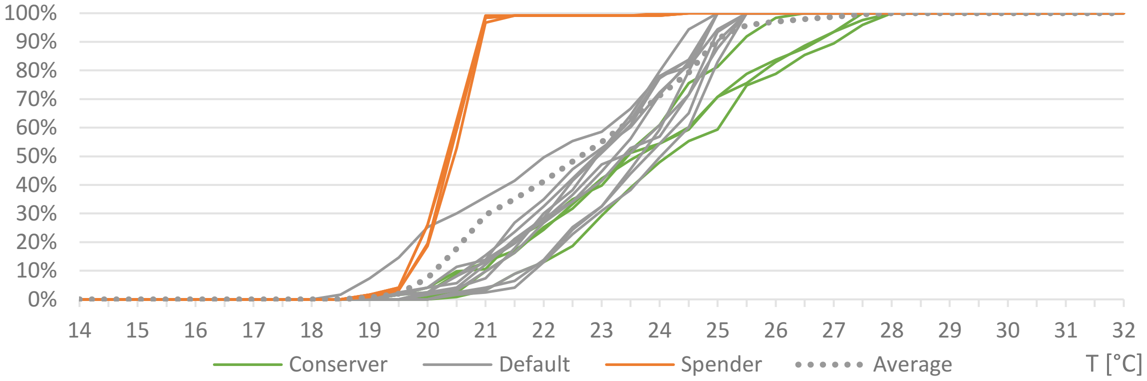


Figure 102: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey A, summer season

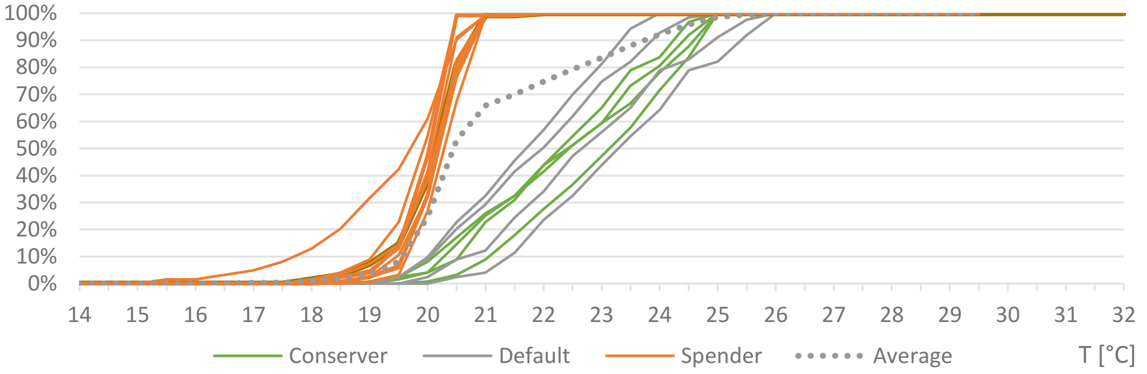


Figure 103: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey A, summer season

Building B

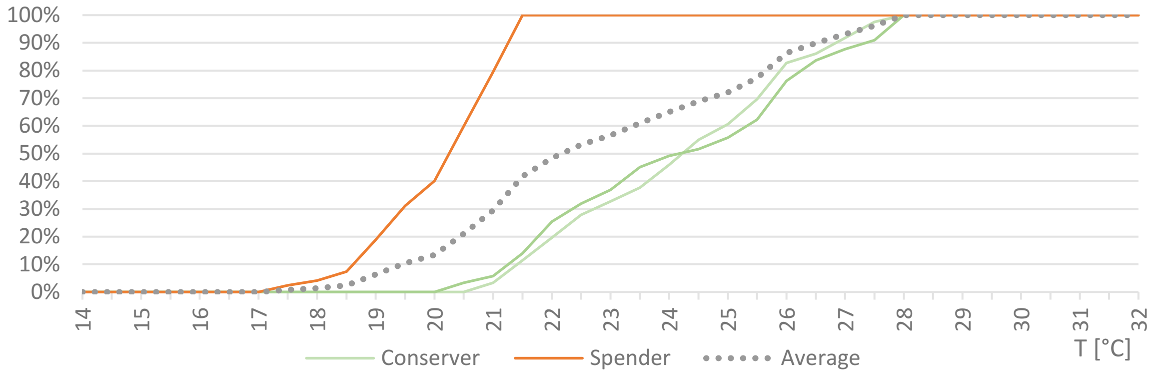


Figure 104: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey B, summer season

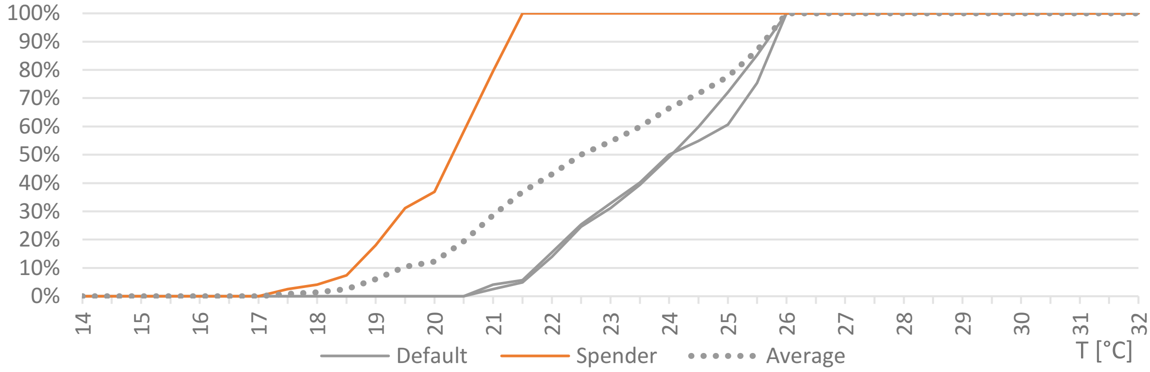


Figure 105: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey B, summer season

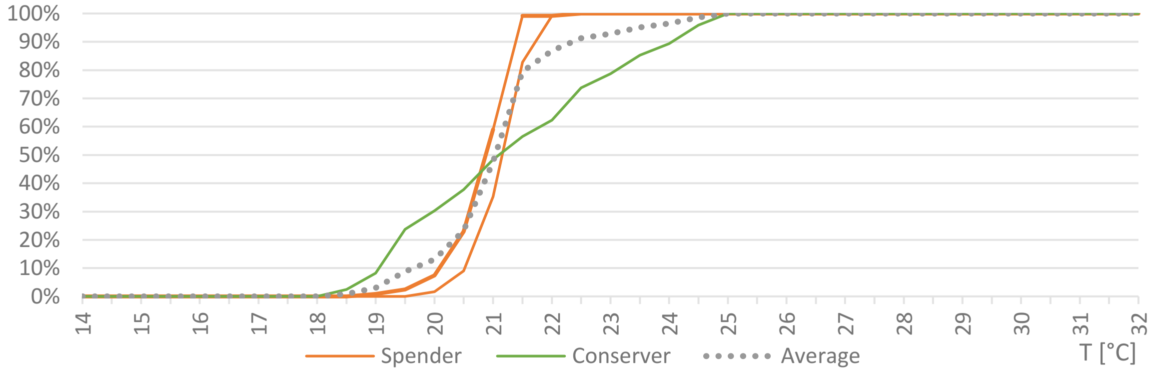


Figure 106: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey B, summer season

Building C

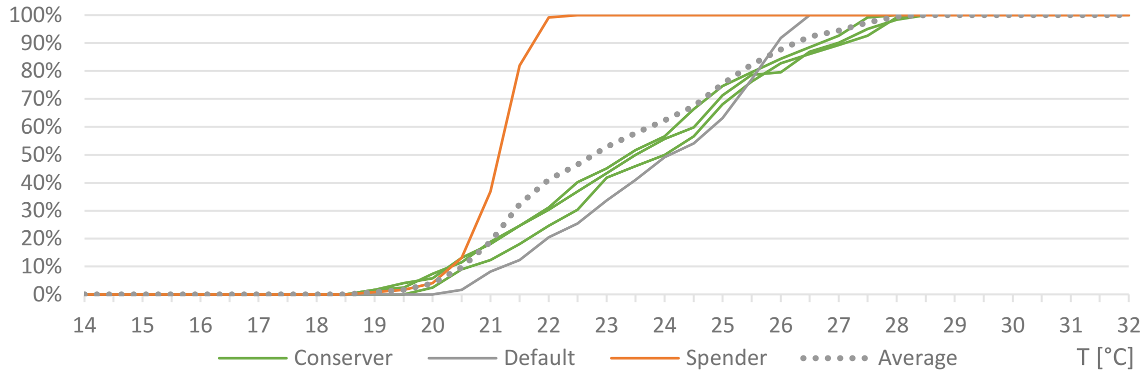


Figure 107: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey C, summer season

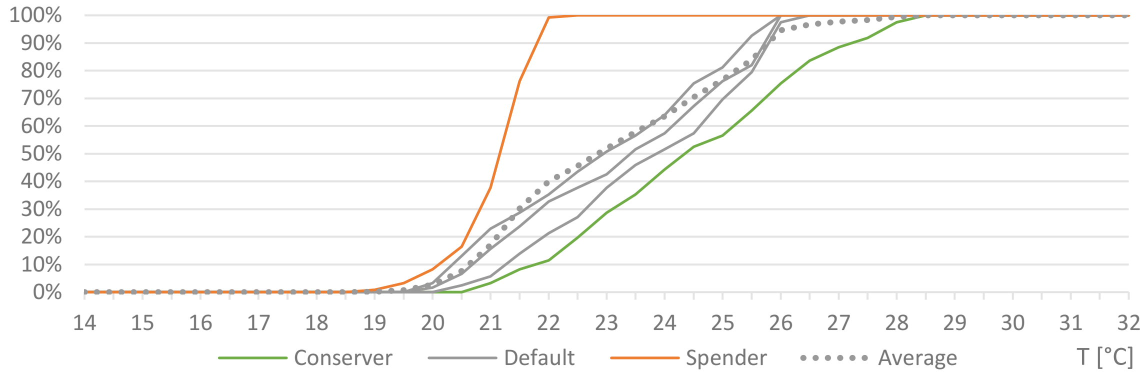


Figure 108: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey C, summer season

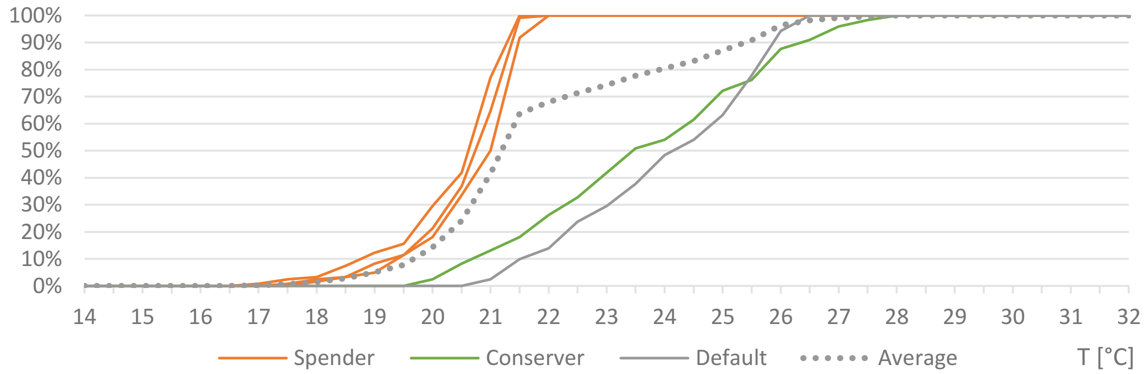


Figure 109: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey C, summer season

Building D

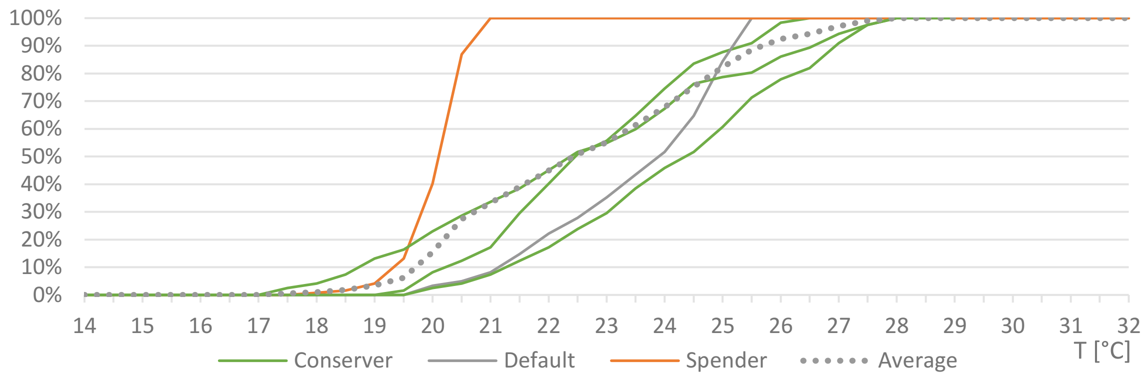


Figure 110: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey D, summer season

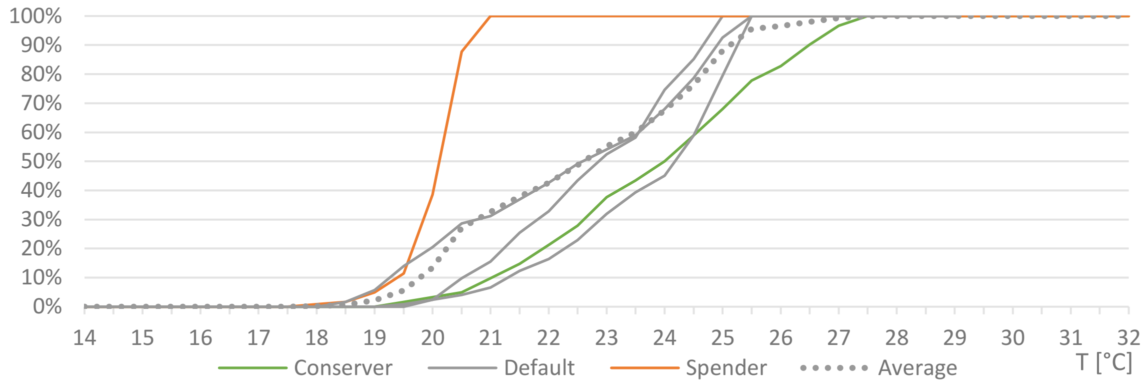


Figure 111: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey D, summer season

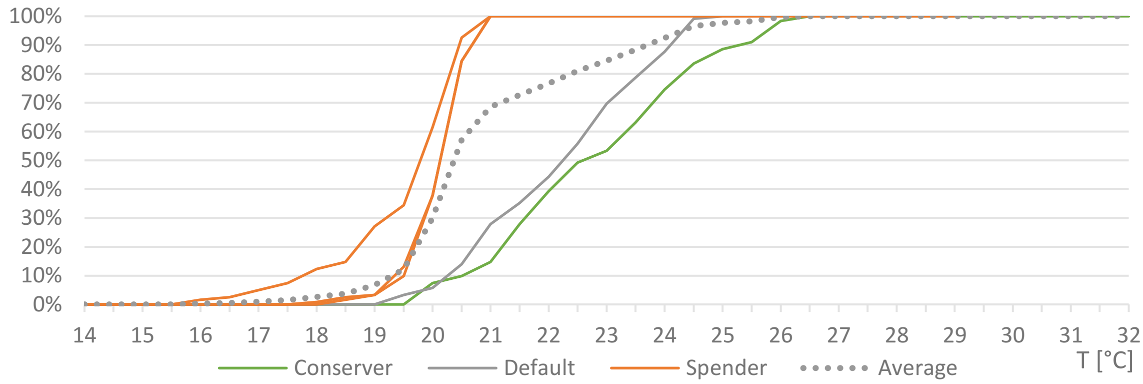


Figure 112: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey D, summer season

Building E

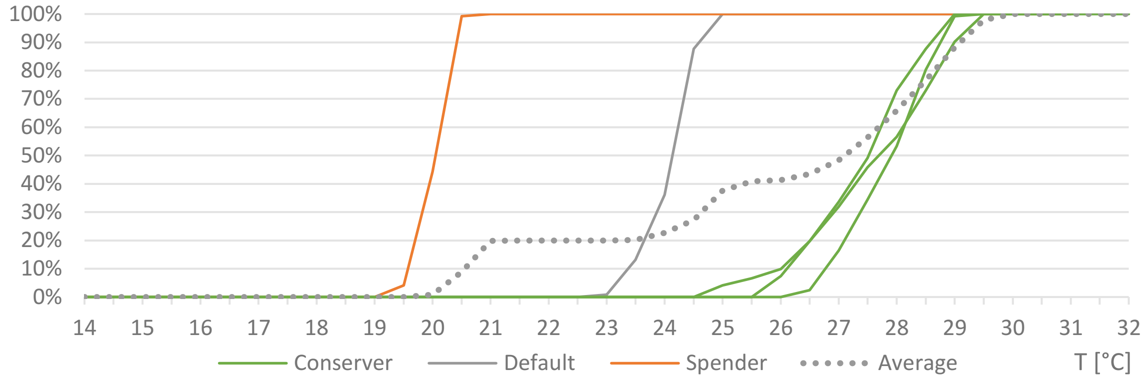


Figure 113: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey D, summer season

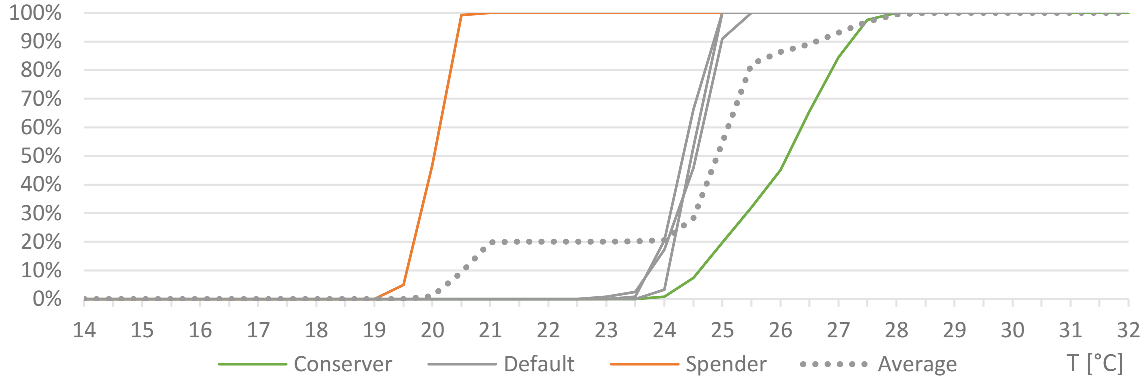


Figure 114: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey D, summer season

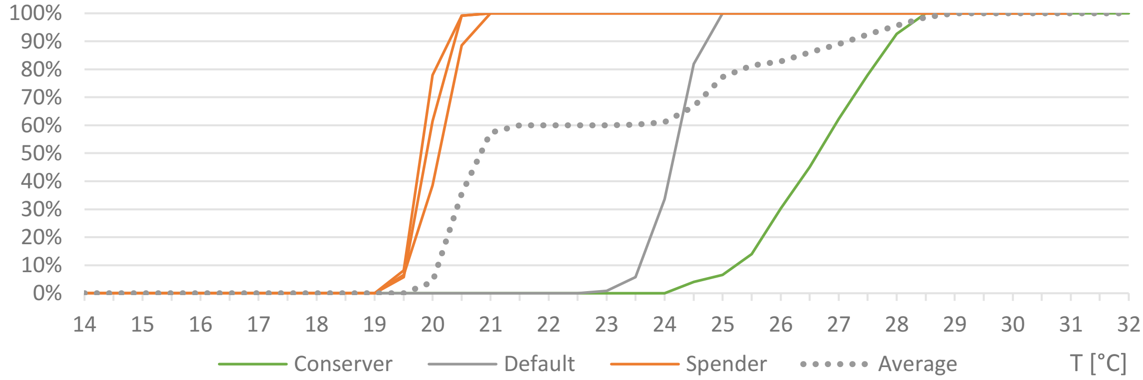


Figure 115: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey D, summer season

Winter season by occupant type:

Building A

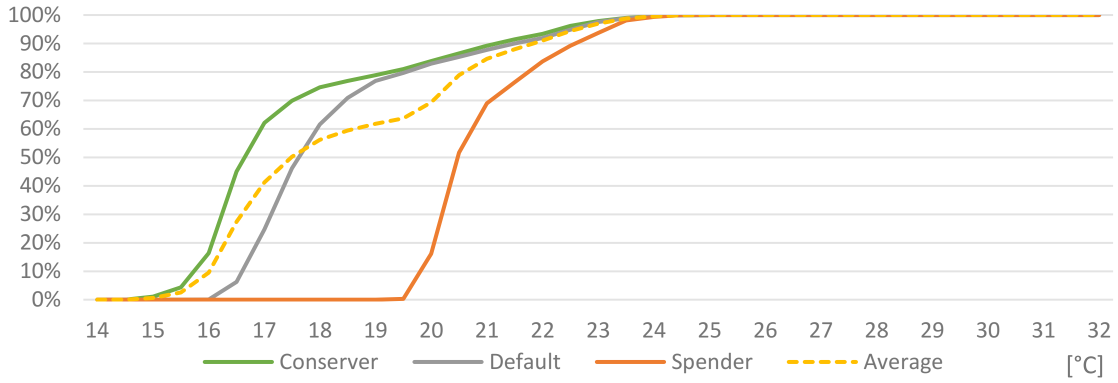


Figure 116: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey A, winter season

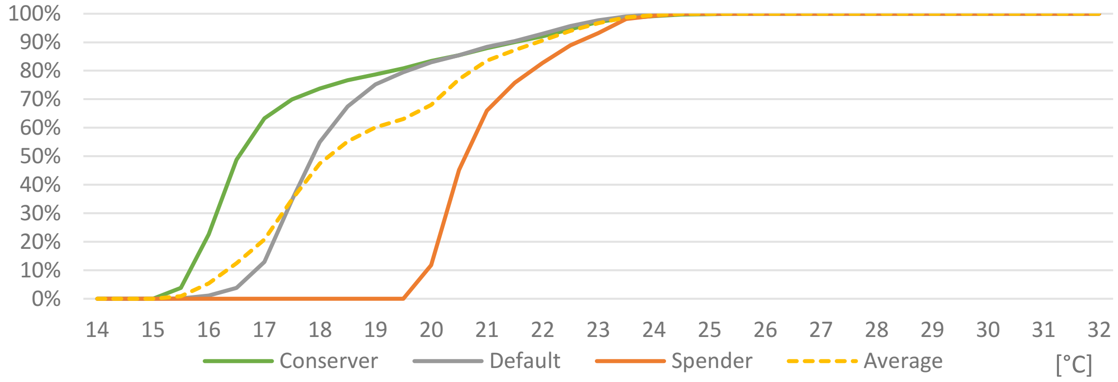


Figure 117: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey A, winter season

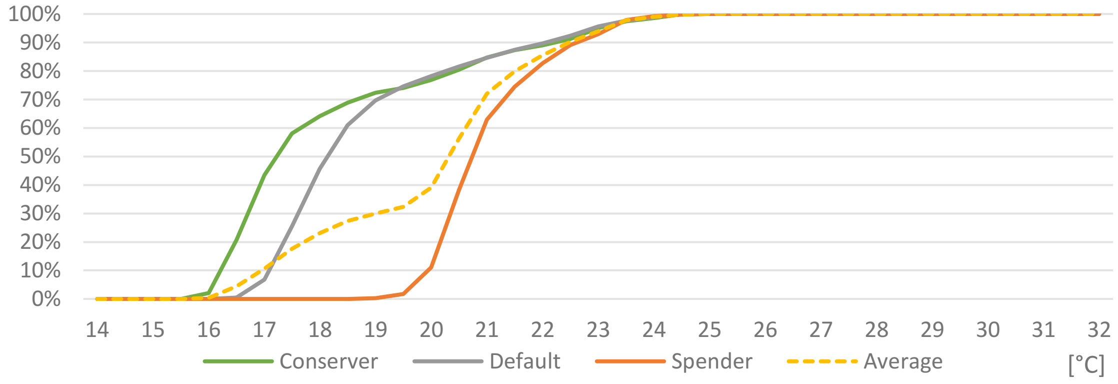


Figure 118: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey A, winter season

Building B

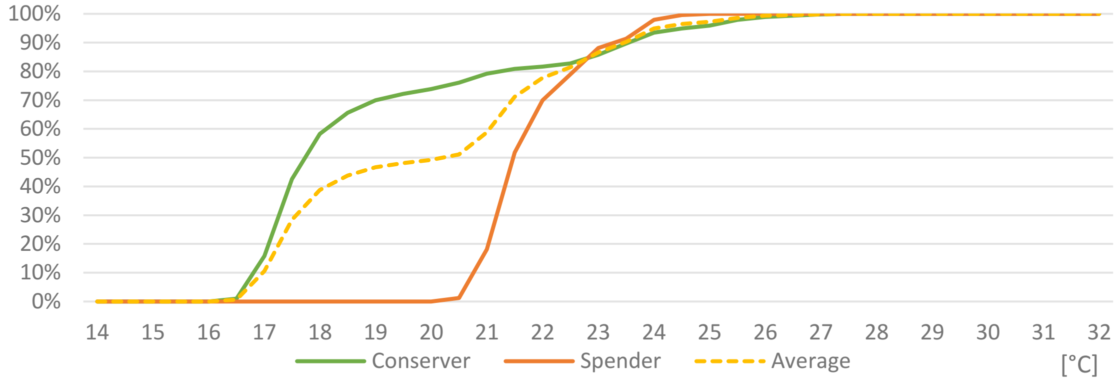


Figure 119: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey B, winter season

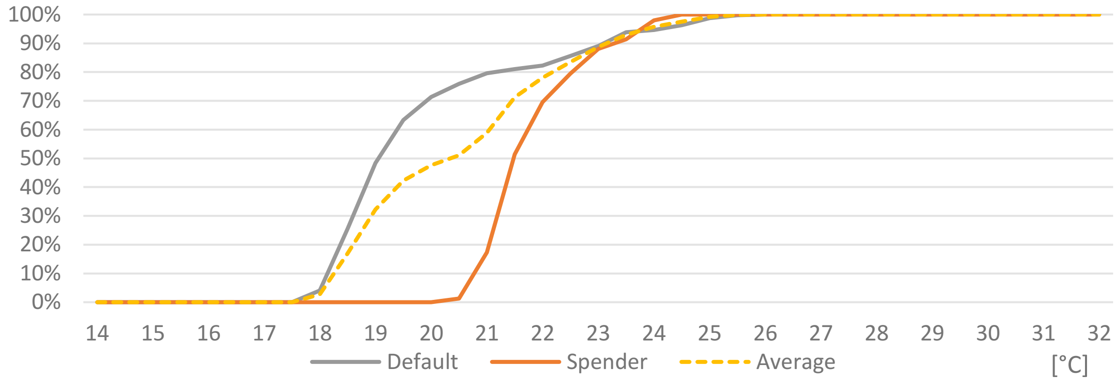


Figure 120: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey B, winter season

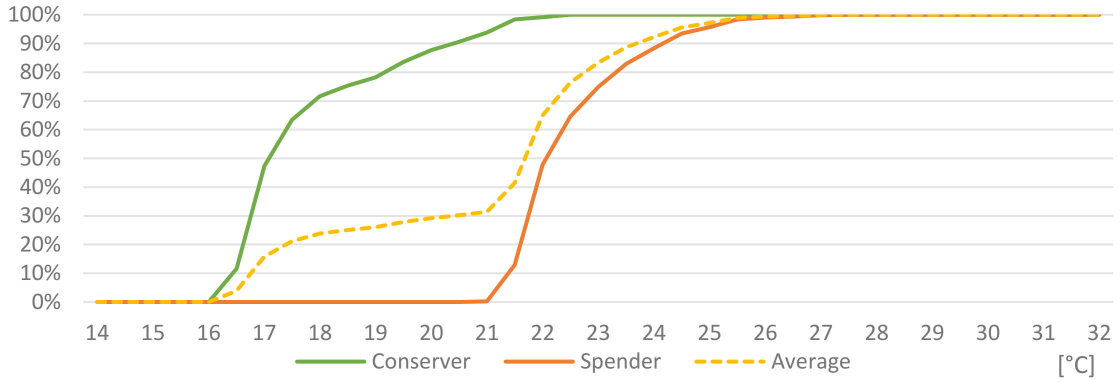


Figure 121: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey B, winter season

Building C

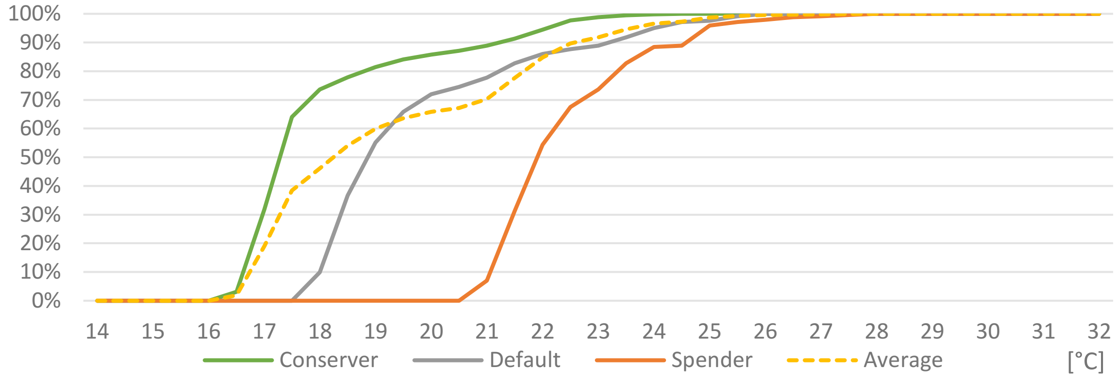


Figure 122: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey C, winter season

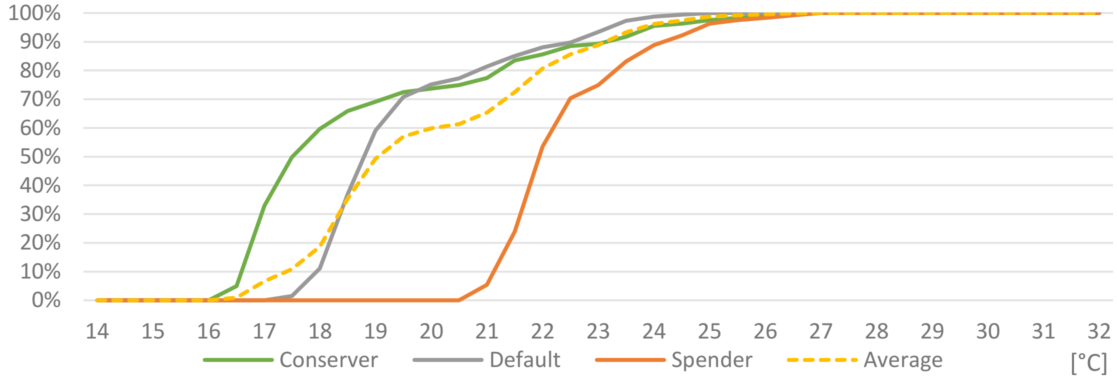


Figure 123: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey C, winter season

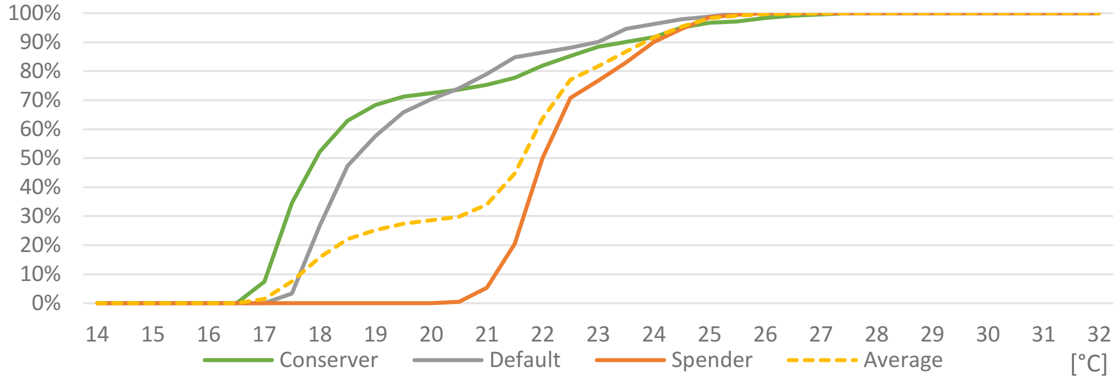


Figure 124: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey C, winter season

Building D

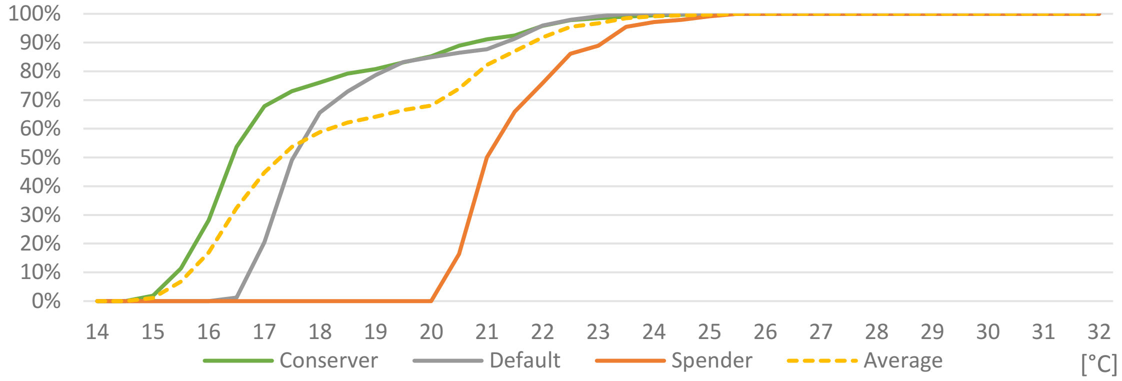


Figure 125: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey D, winter season

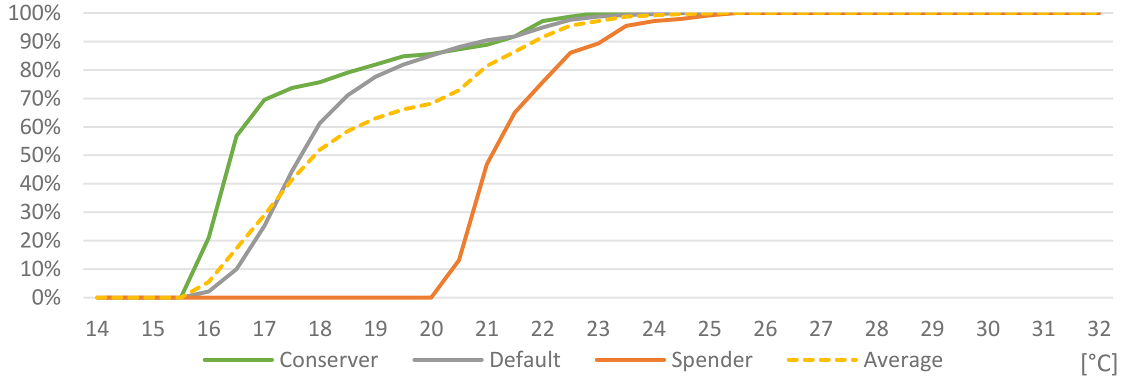


Figure 126: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey D, winter season

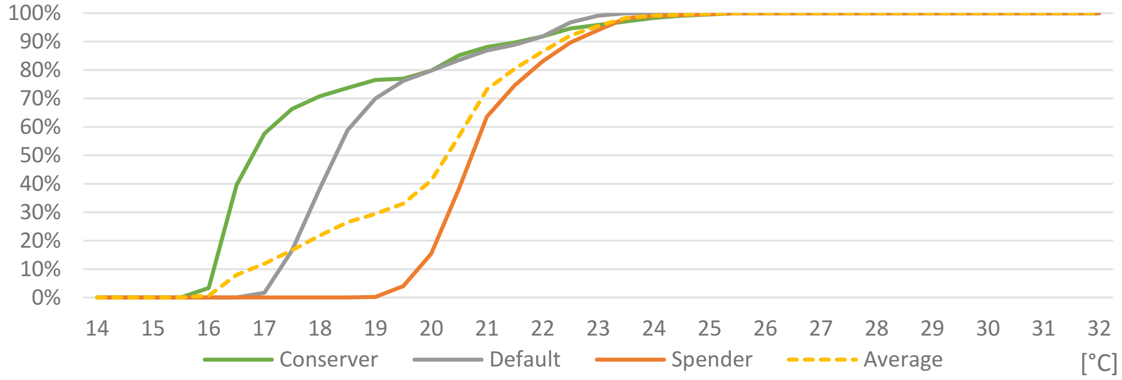


Figure 127: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey D, winter season

Building E

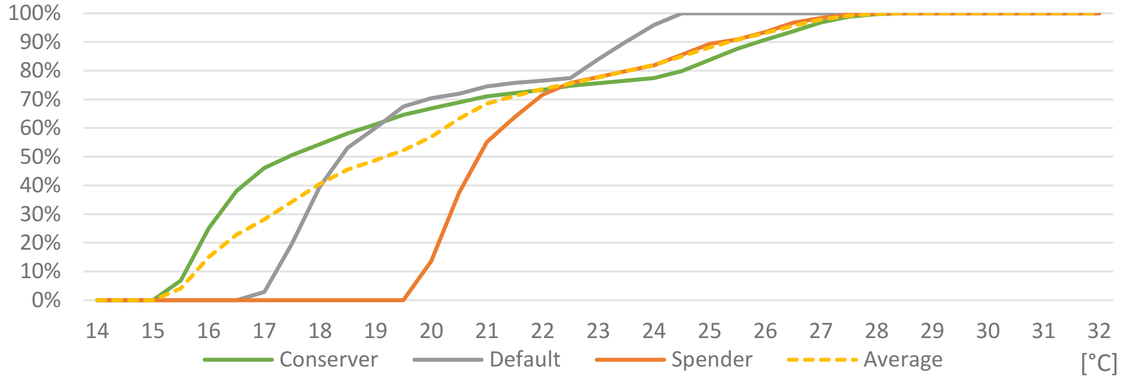


Figure 128: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey E, winter season

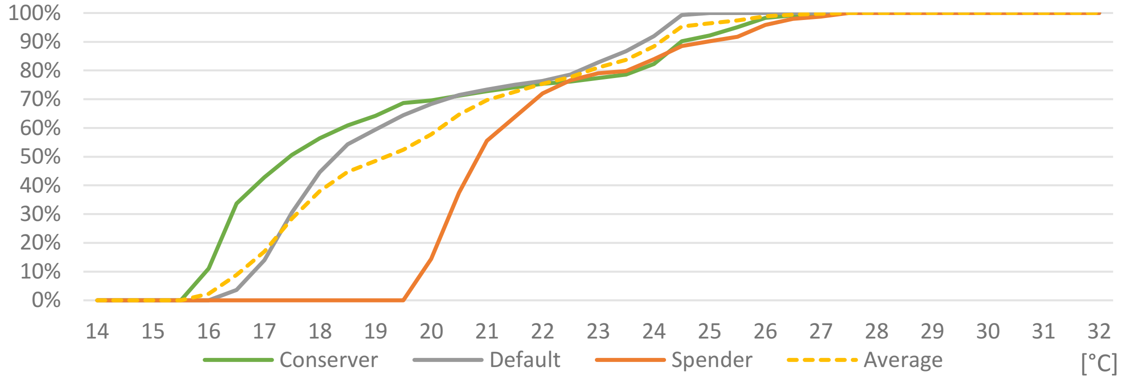


Figure 129: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey E, winter season

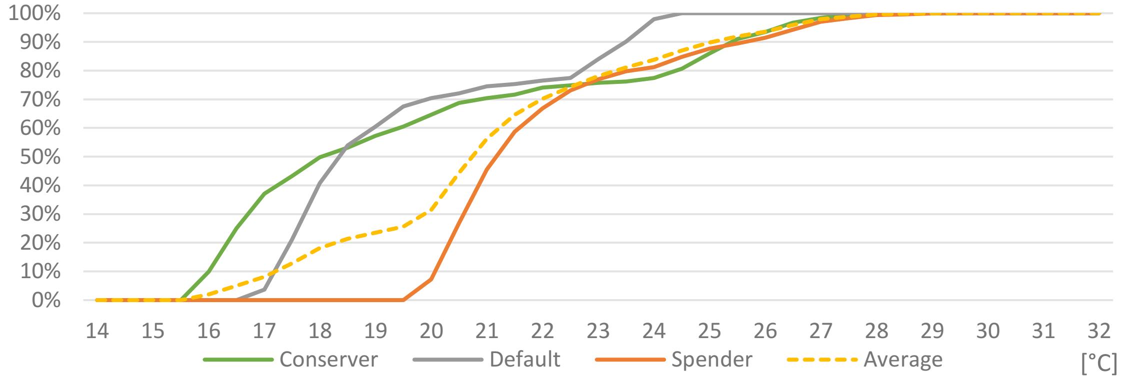


Figure 130: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey E, winter season

Winter season by apartment:

Building A

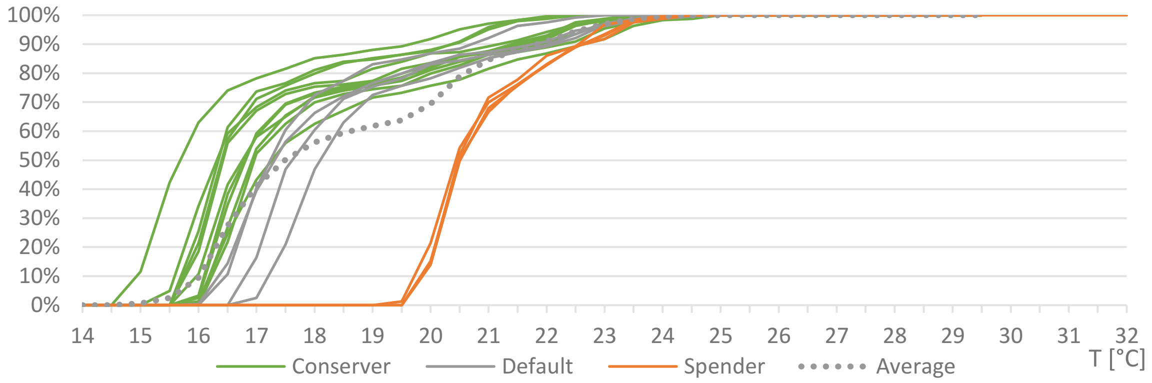


Figure 131: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey A, winter season

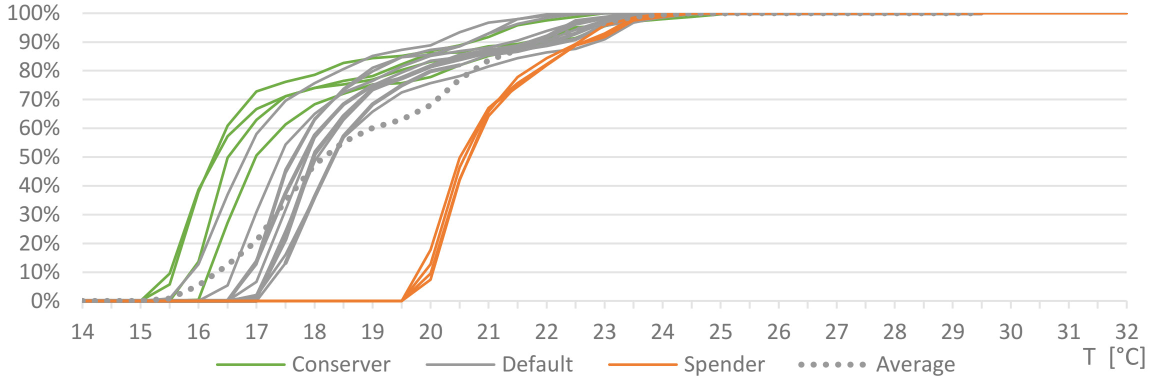


Figure 132: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey A, winter season

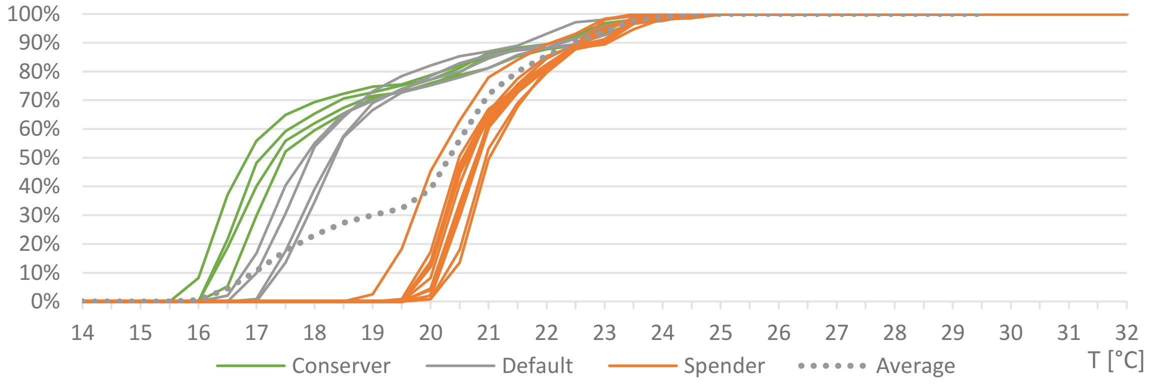


Figure 133: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey A, winter season

Building B

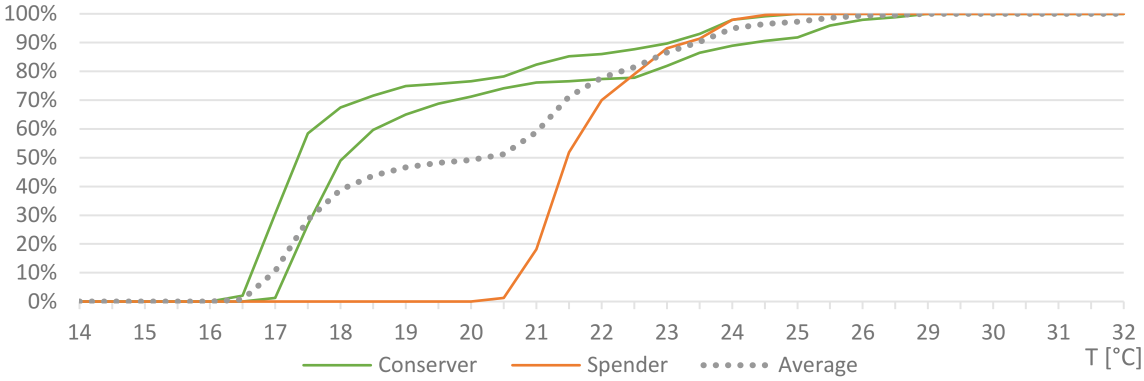


Figure 134: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey B, winter season

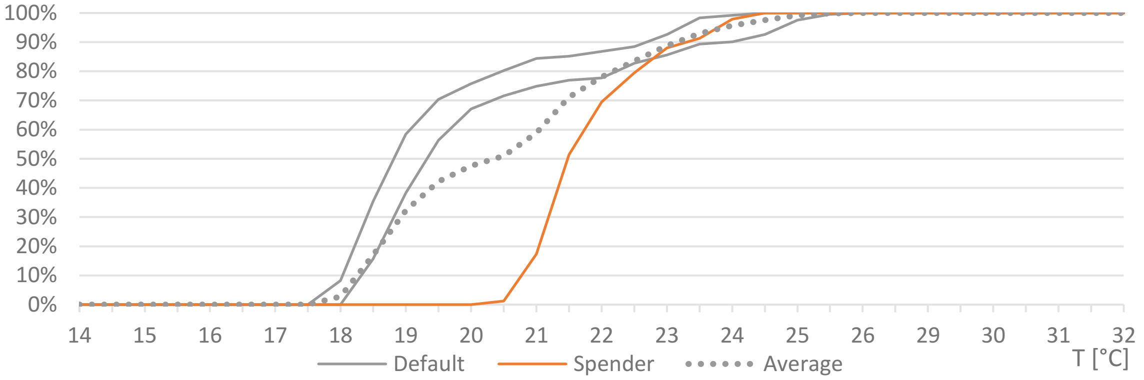


Figure 135: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey B, winter season

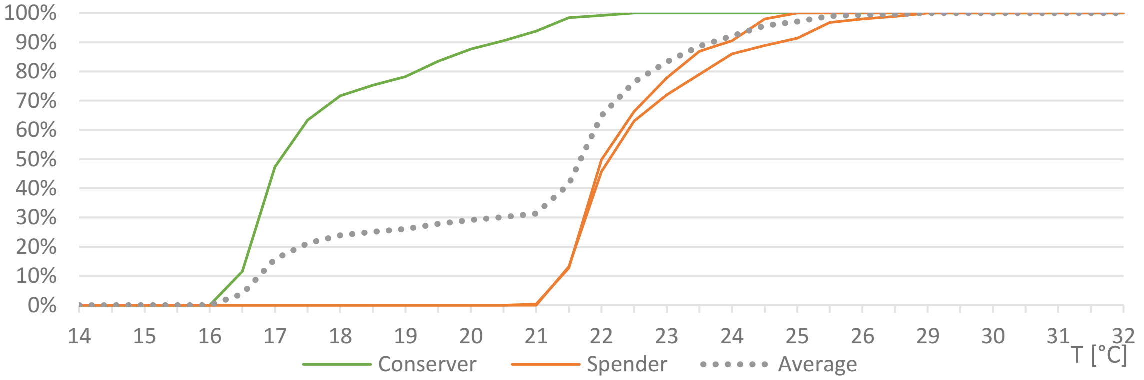


Figure 136: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey B, winter season

Building C

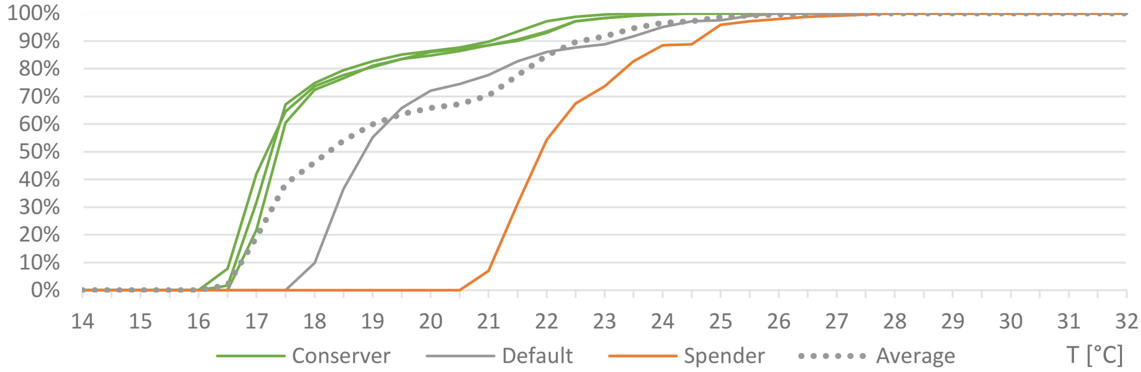


Figure 137: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey C, winter season

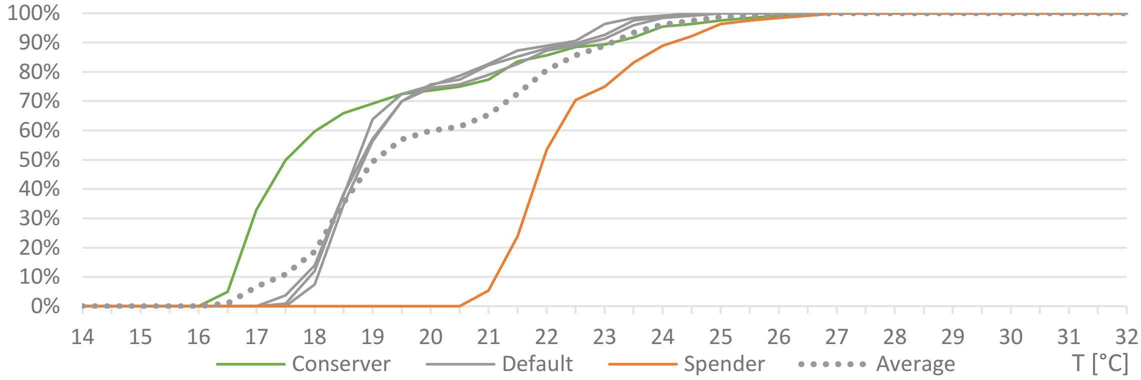


Figure 138: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey C, winter season

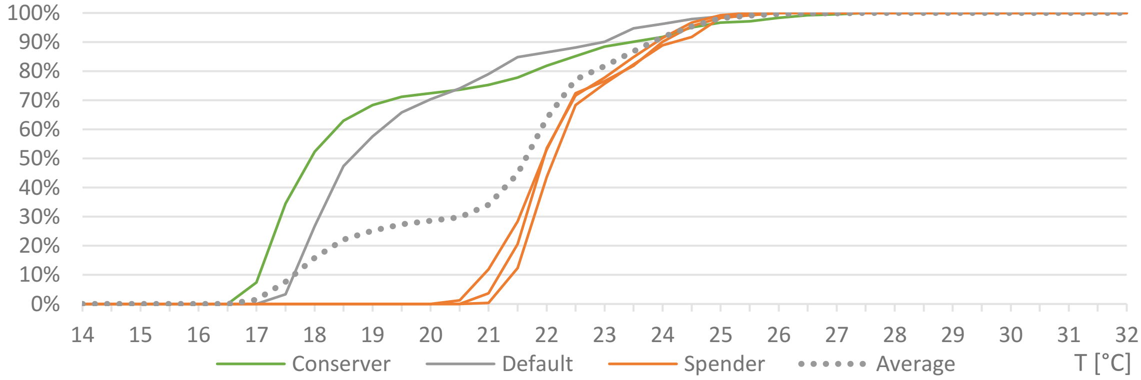


Figure 139: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey C, winter season

Building D

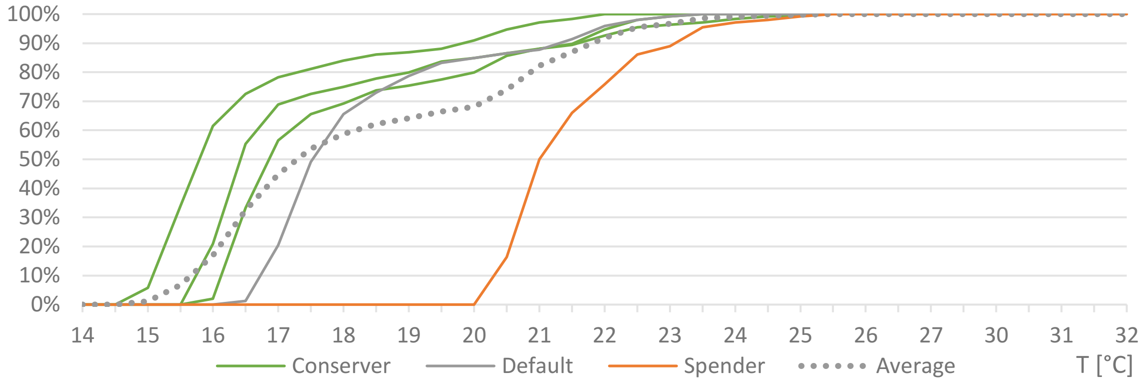


Figure 140: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey D, winter season

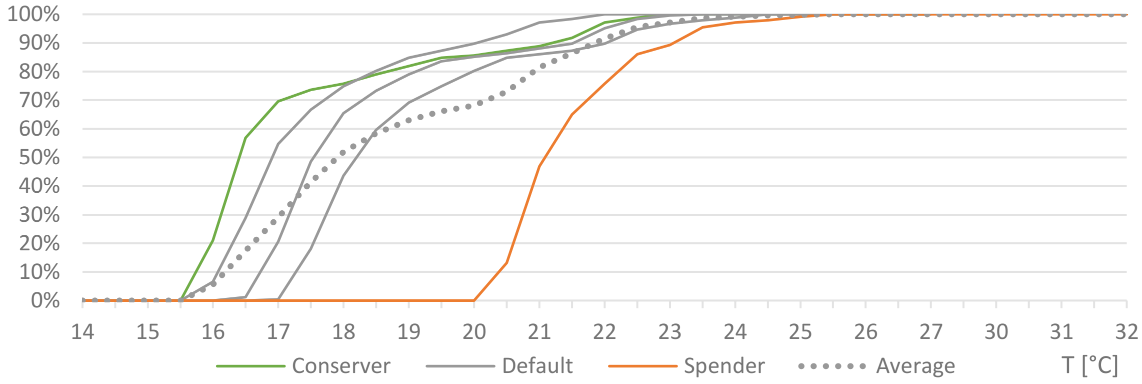


Figure 141: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey D, winter season

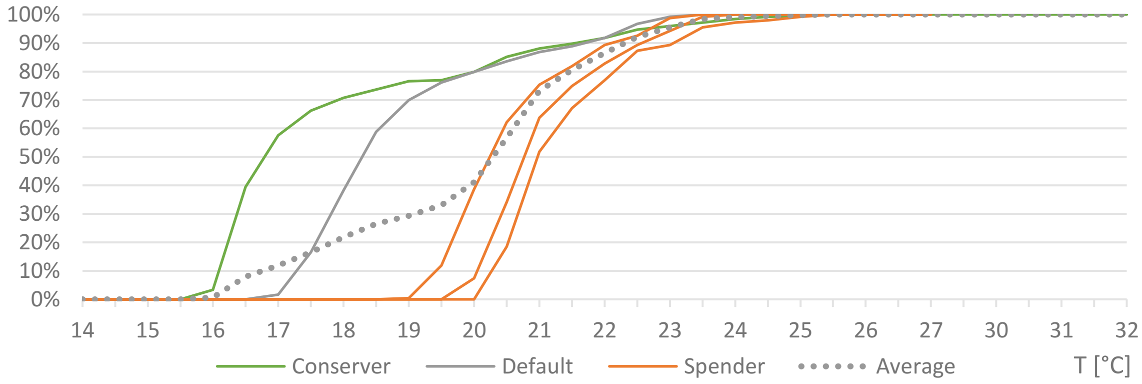


Figure 142: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey D, winter season

Building E

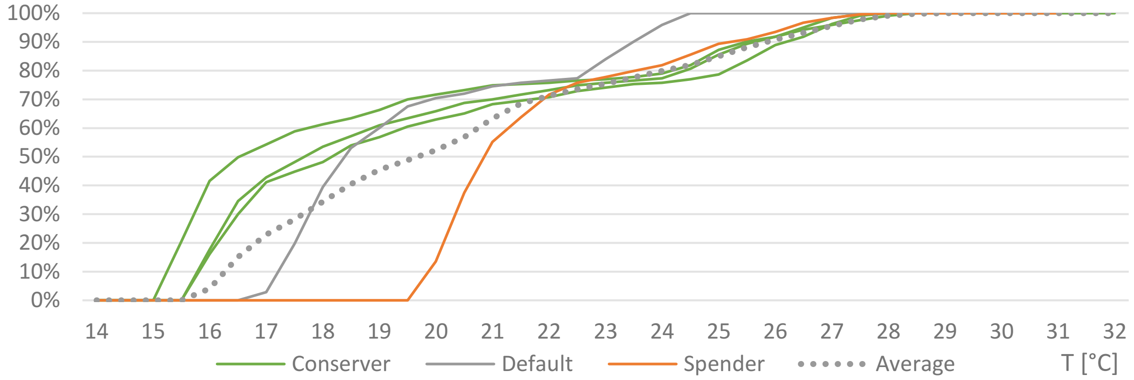


Figure 143: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey E, winter season

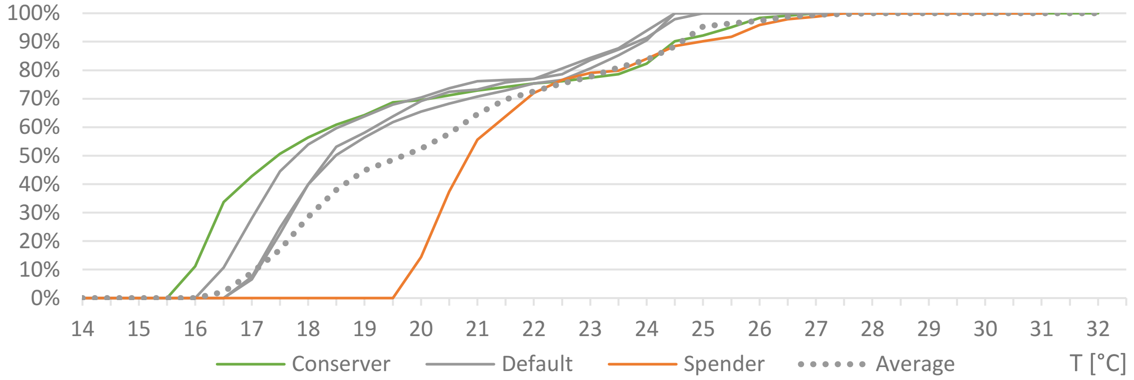


Figure 144: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey E, winter season

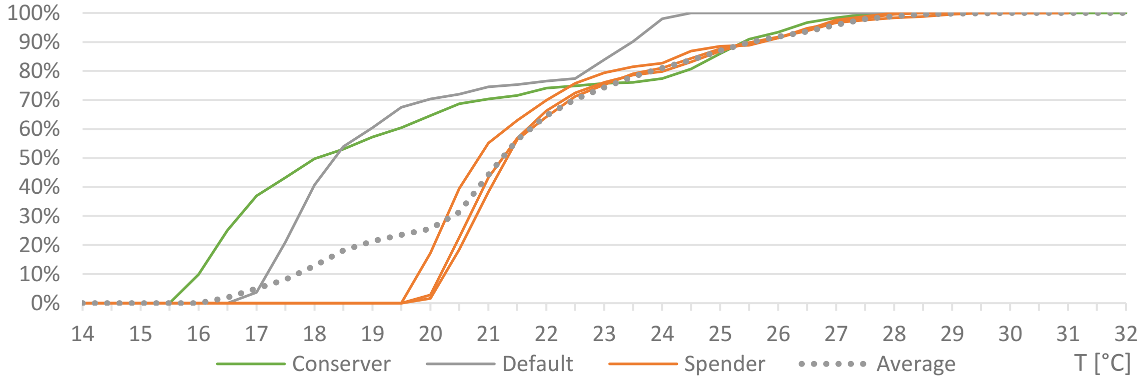


Figure 145: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey E, winter season

Whole year by occupant type:

Building A

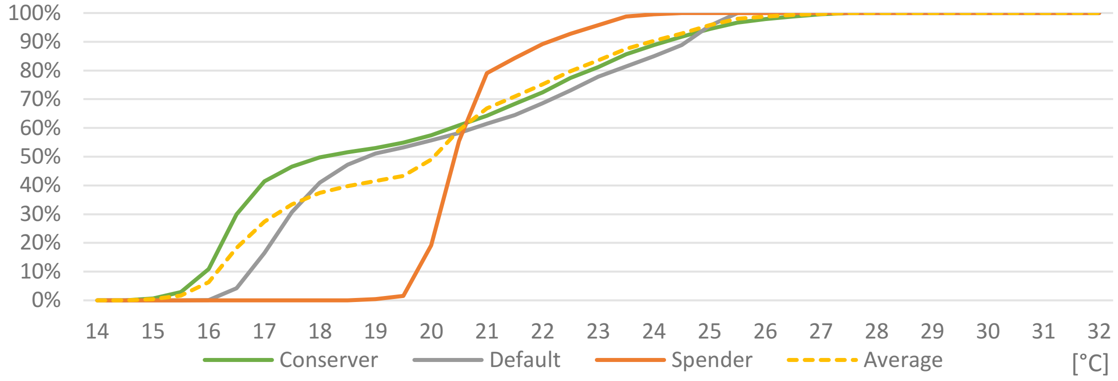


Figure 146: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey A, whole year

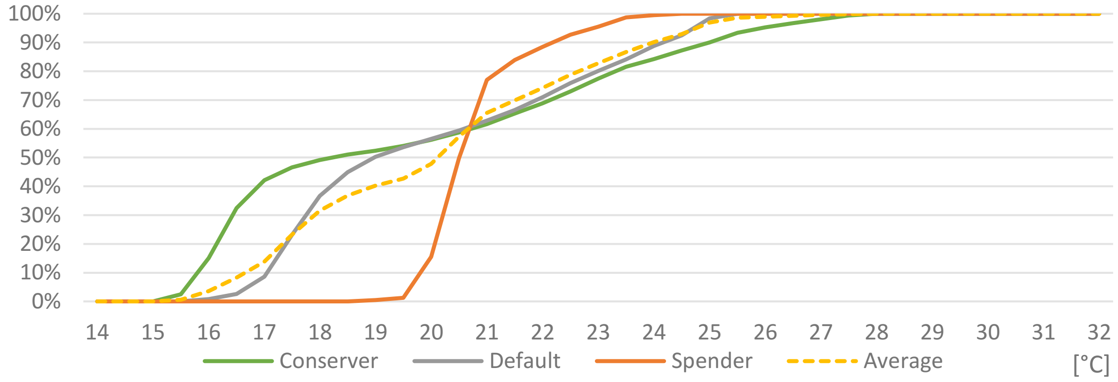


Figure 147: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey A, whole year

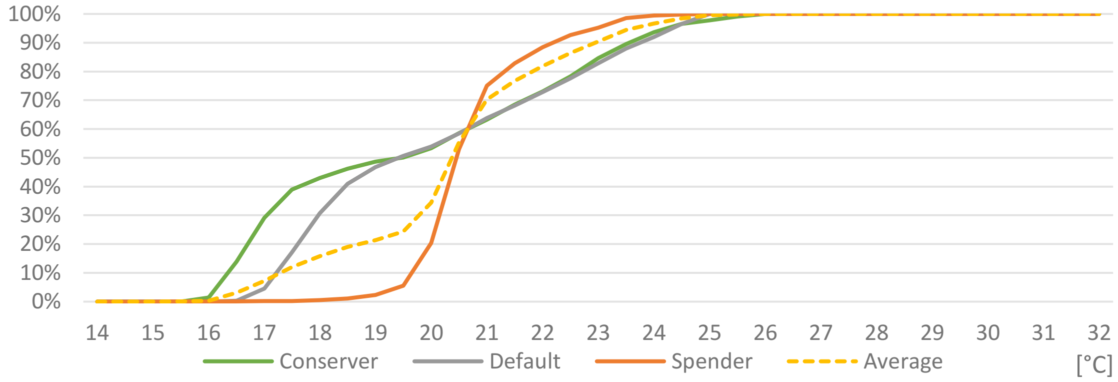


Figure 148: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey A, whole year

Building B

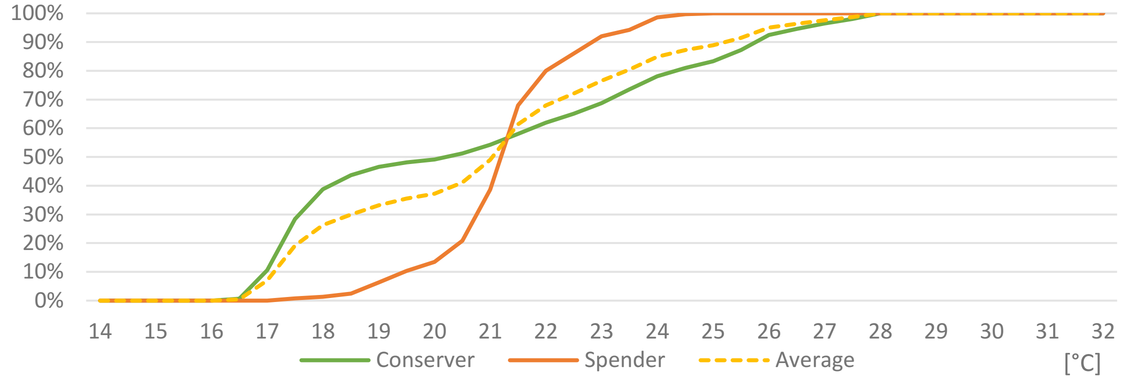


Figure 149: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey B, whole year

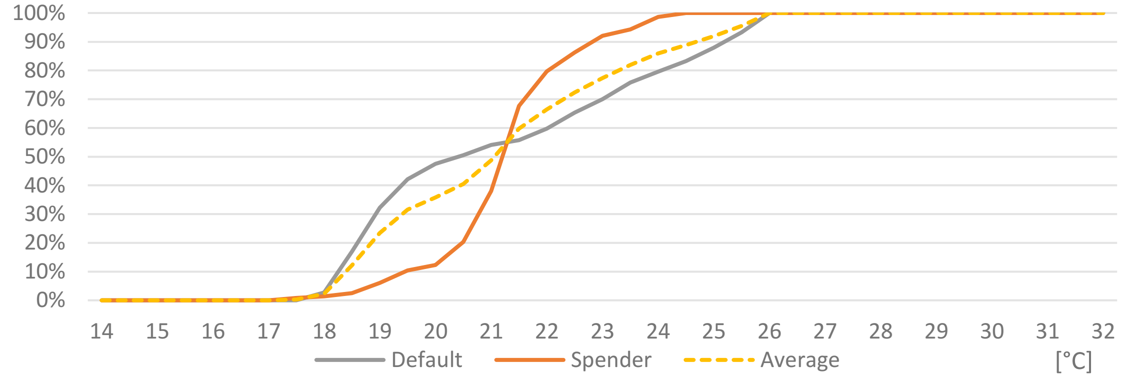


Figure 150: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey B, whole year

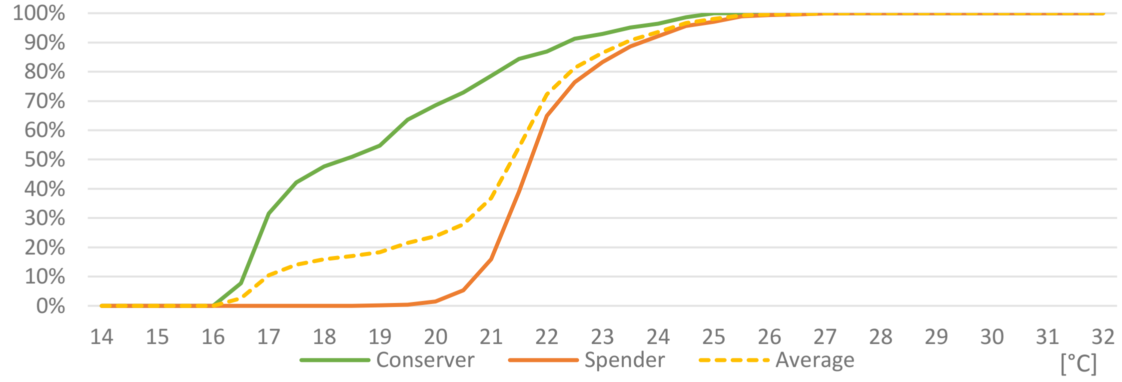


Figure 151: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey B, whole year

Building C

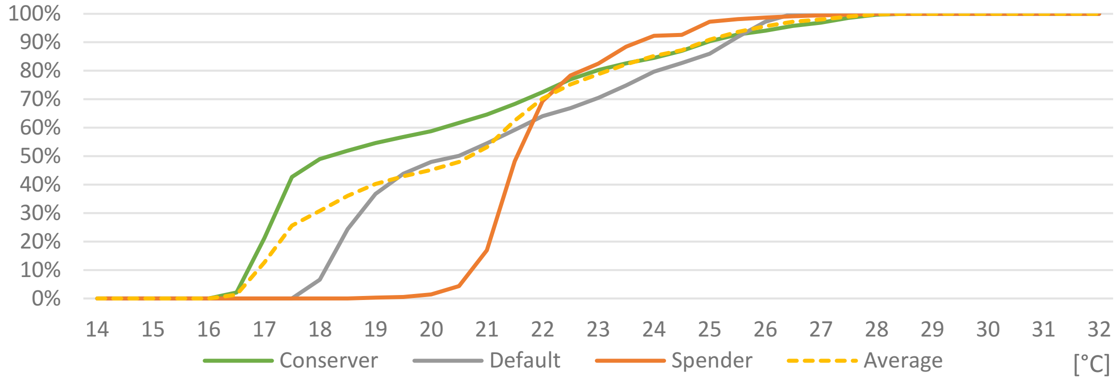


Figure 152: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey C, whole year

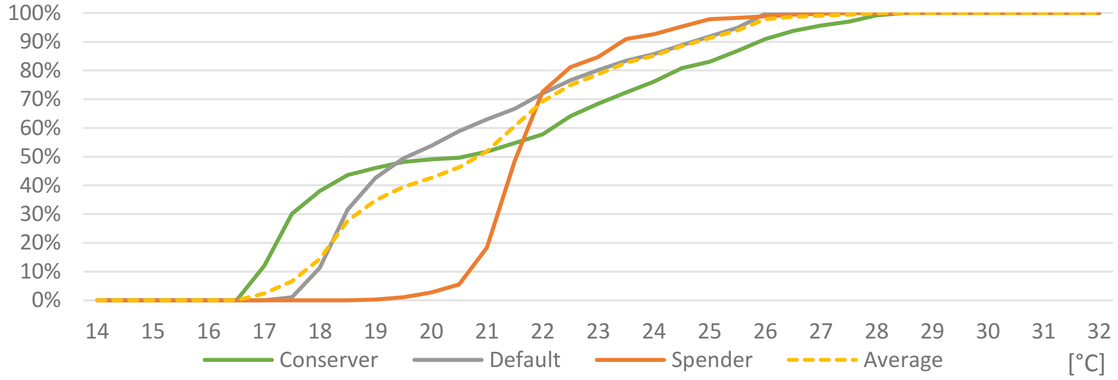


Figure 153: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey C, whole year

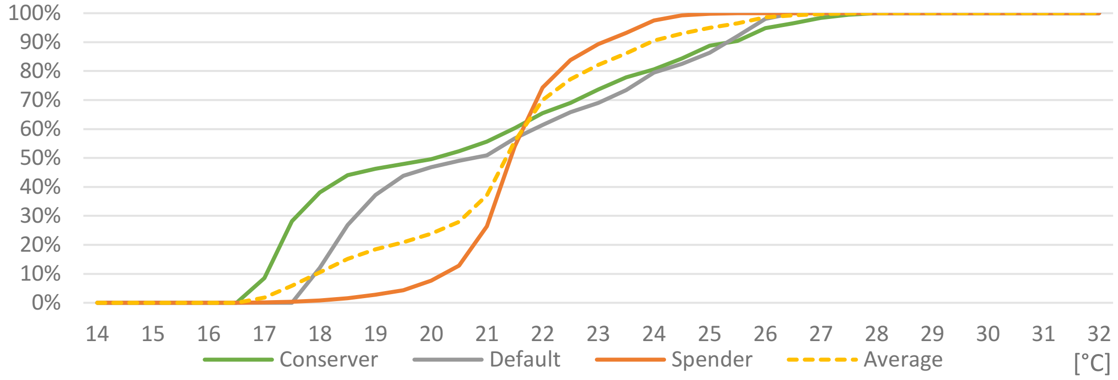


Figure 154: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey C, whole year

Building D

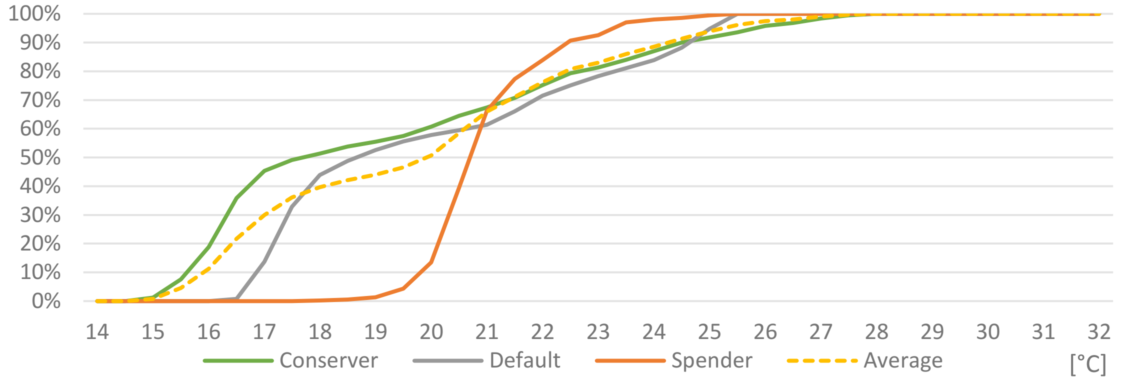


Figure 155: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey D, whole year

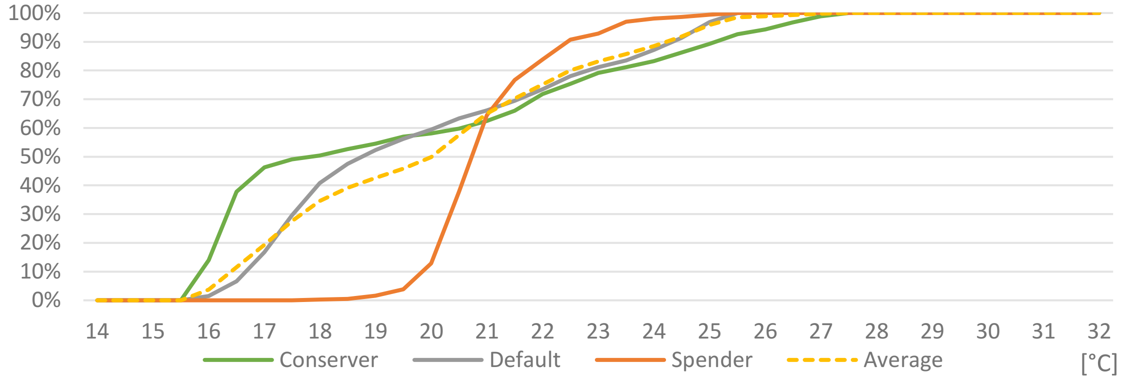


Figure 156: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey D, whole year

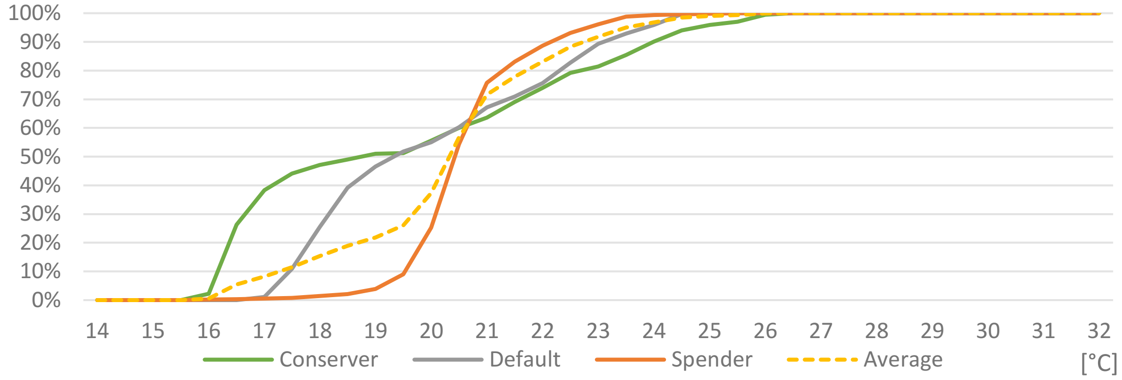


Figure 157: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey D, whole year

Building E

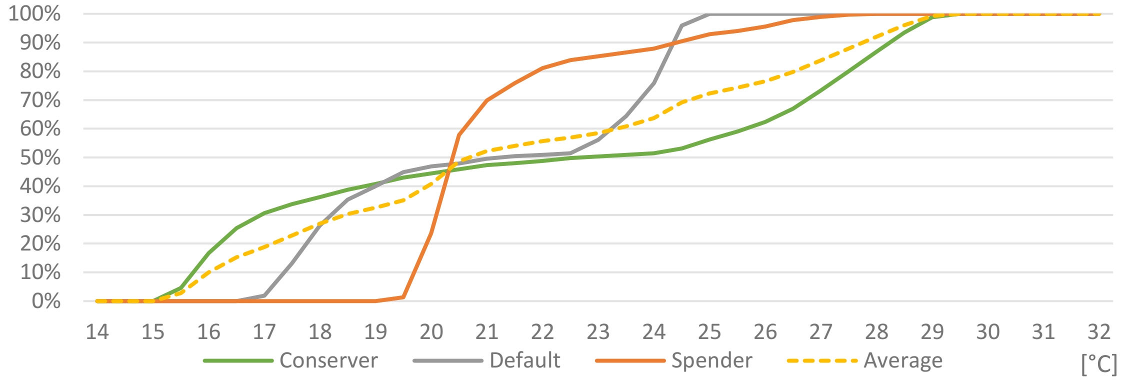


Figure 158: Dominant population: Conserver (c60:d20:s20), cumulative distribution by occupant type, building storey E*, whole year*

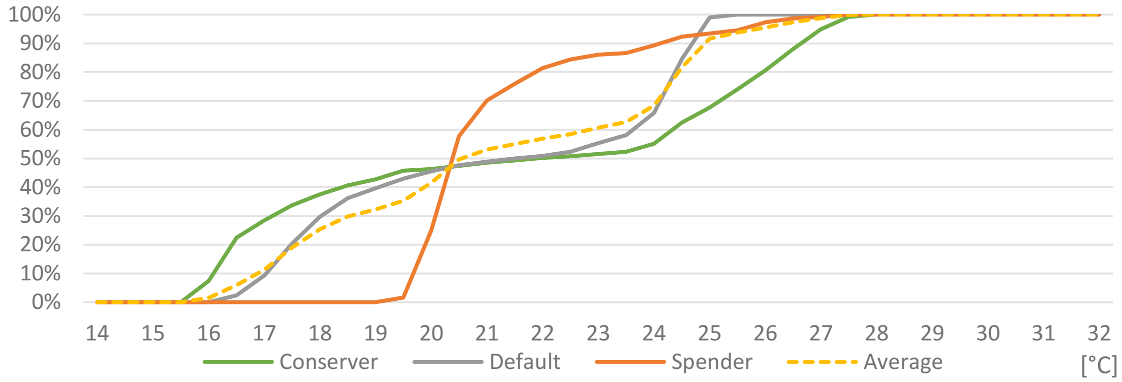


Figure 159: Dominant population: Default (d60:c20:s20), cumulative distribution by occupant type, building storey E*, whole year*

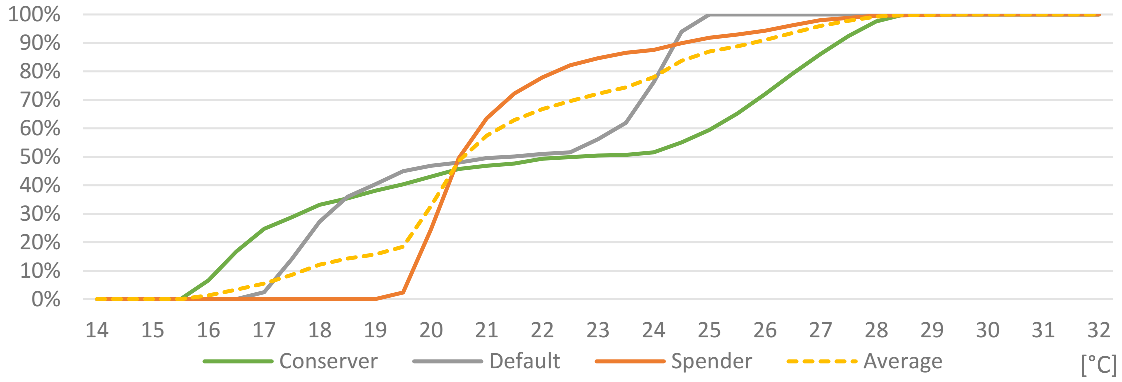


Figure 160: Dominant population: Spender (s60:c20:d20), cumulative distribution by occupant type, building storey E*, whole year*

Whole year by apartment

Building A

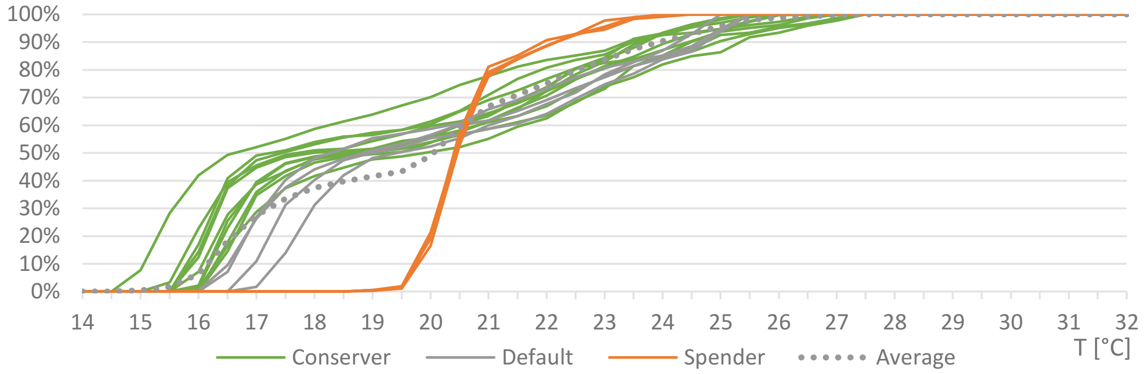


Figure 161: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey A, whole year

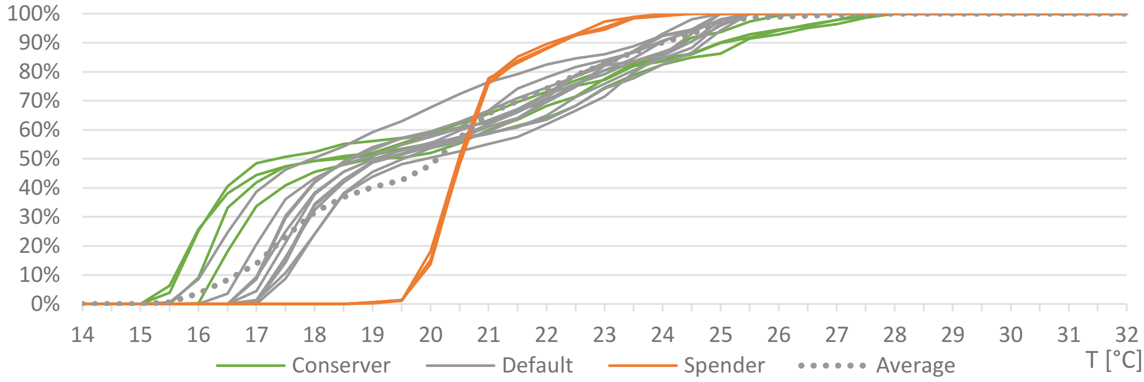


Figure 162: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey A, whole year

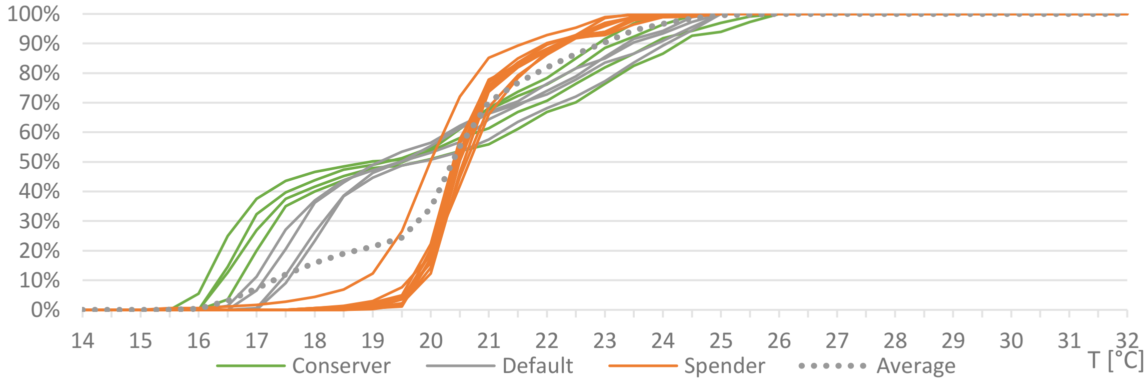


Figure 163: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey A, whole year

Building B

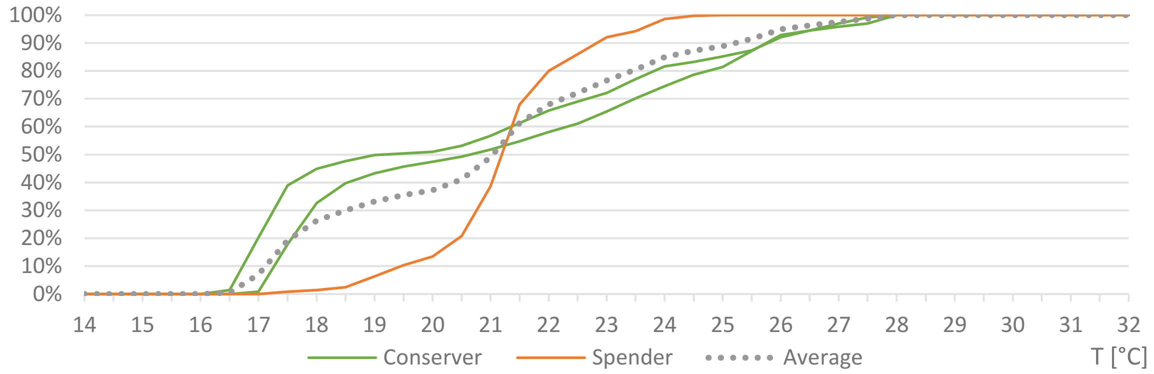


Figure 164: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey B, whole year

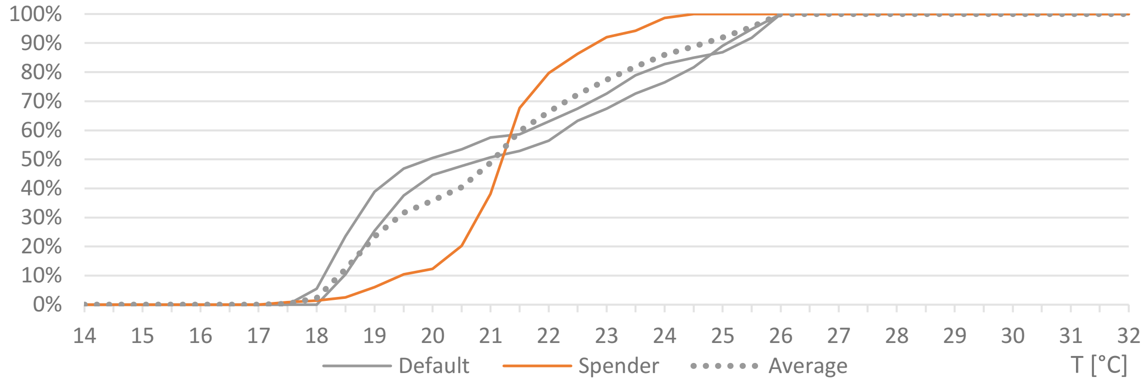


Figure 165: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey B, whole year

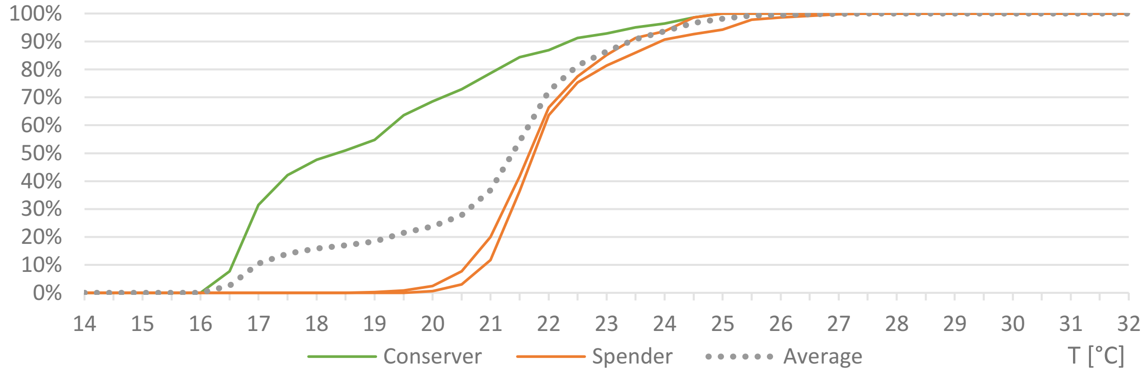


Figure 166: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey B, whole year

Building C

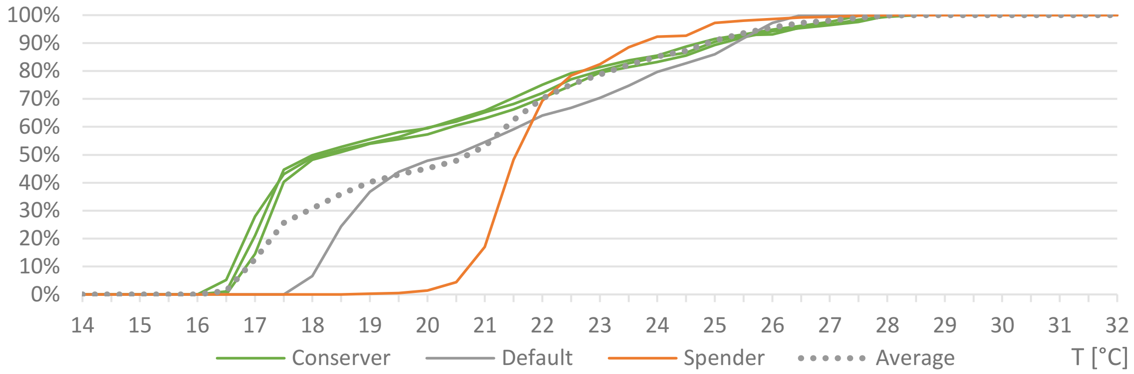


Figure 167: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey C, whole year

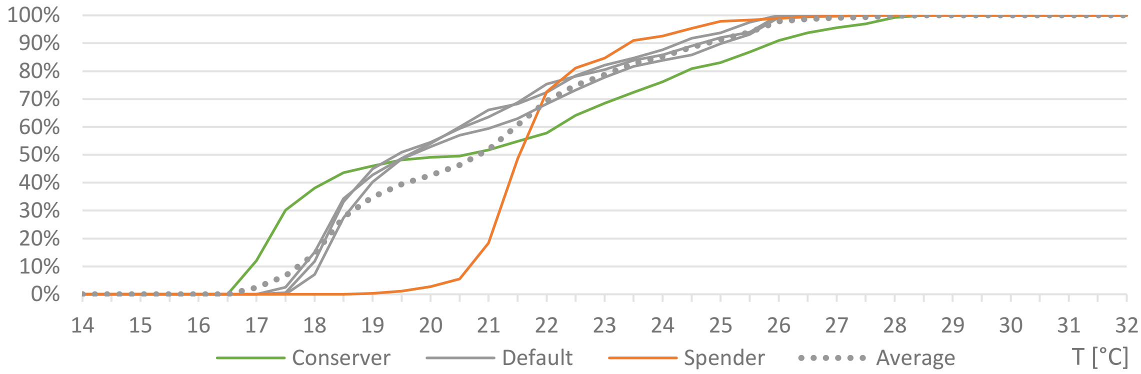


Figure 168: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey C, whole year

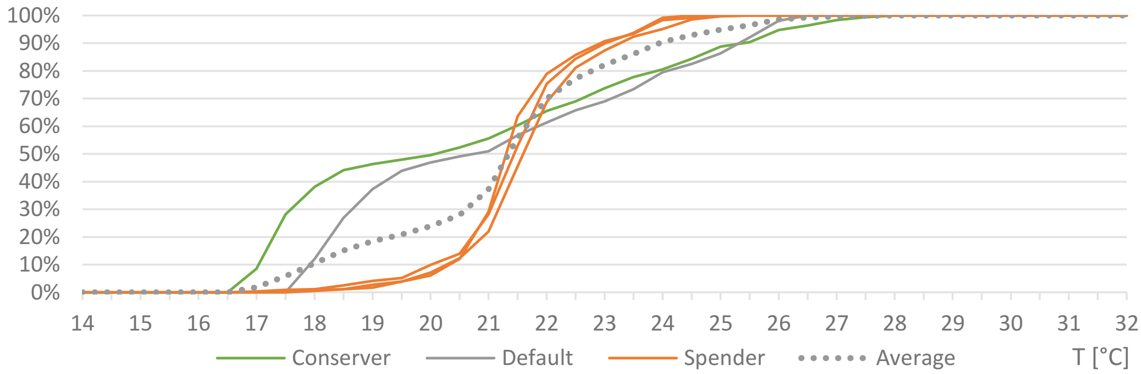


Figure 169: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey C, whole year

Building D

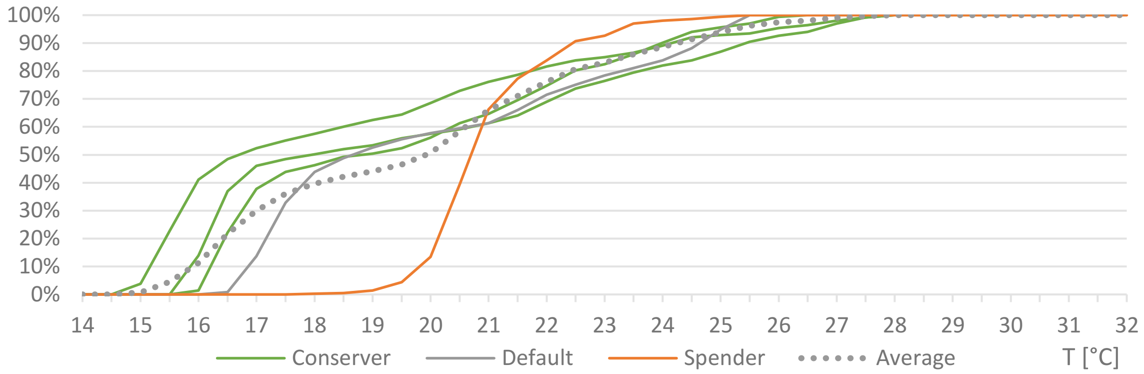


Figure 170: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey D, whole year

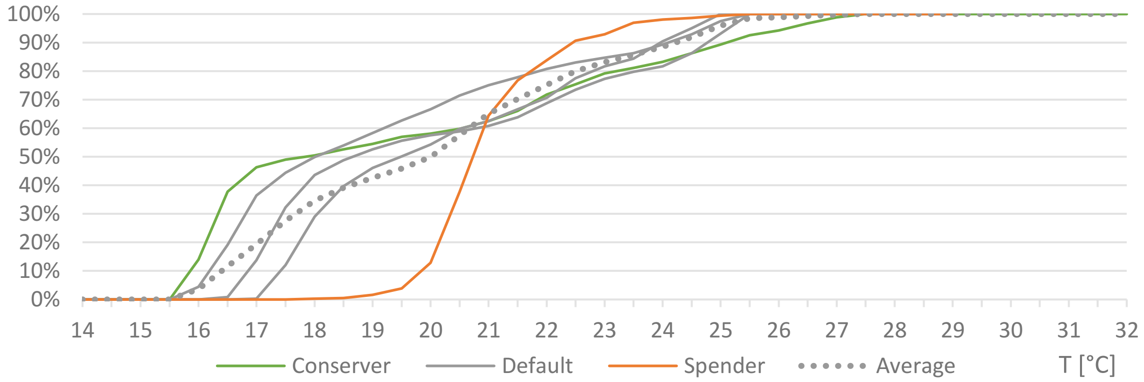


Figure 171: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey D, whole year

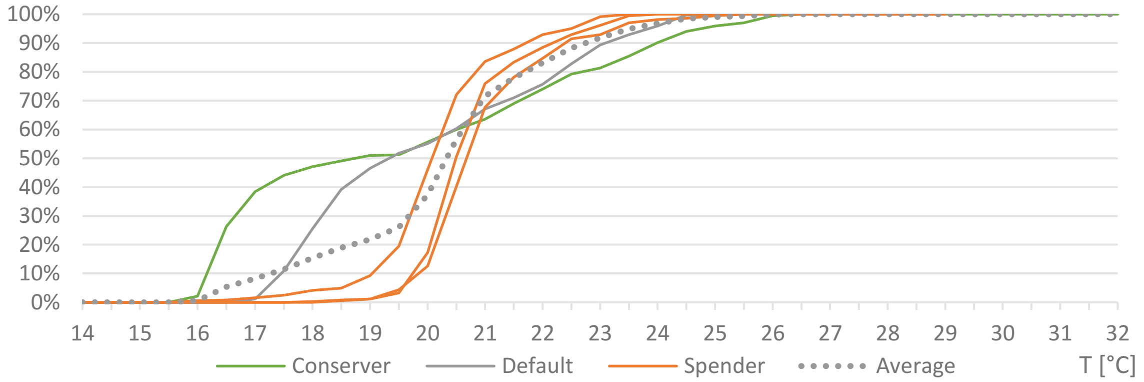


Figure 172: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey D, whole year

Building E

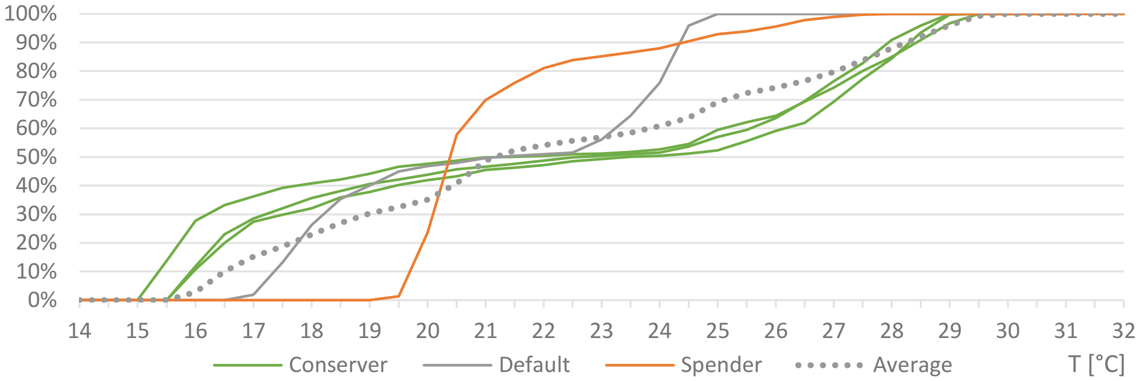


Figure 173: Dominant population: Conserver (c60:d20:s20), cumulative distribution by apartment, building storey E, whole year

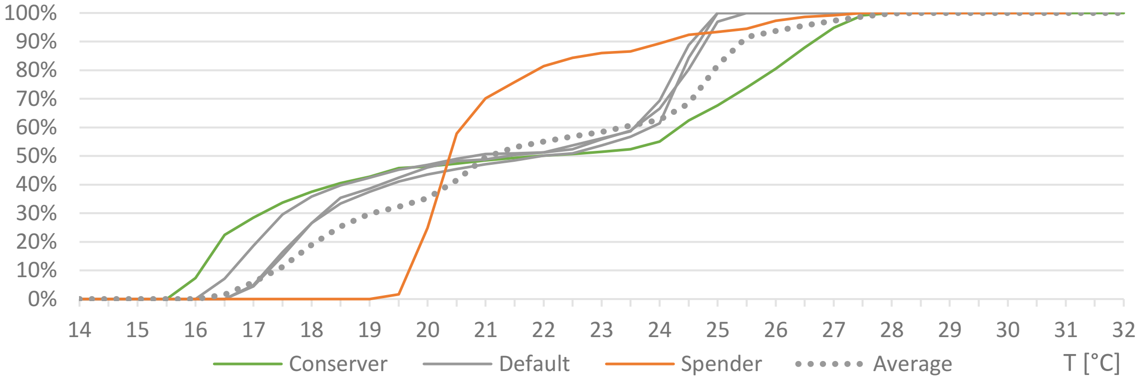


Figure 174: Dominant population: Default (d60:c20:s20), cumulative distribution by apartment, building storey E, whole year

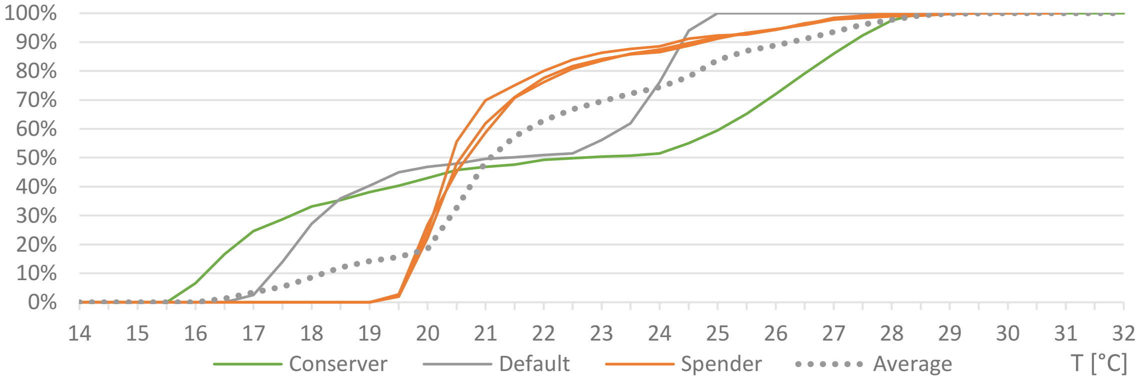


Figure 175: Dominant population: Spender (s60:c20:d20), cumulative distribution by apartment, building storey E, whole year

Figures A 176-178 exemplarily show the hourly temperatures for all living rooms (averaged) in building storey C and the hourly heating loads for these living rooms during a day in January. The effect of natural ventilation on indoor temperature and in further consequence on heating loads can be deduced from the graphs.

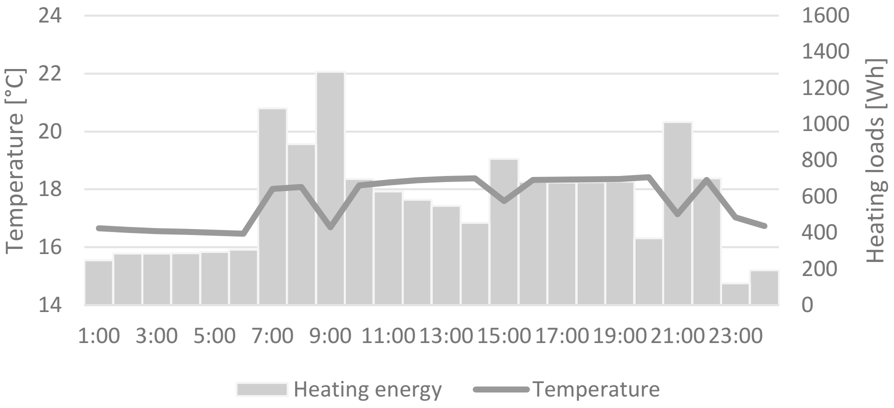


Figure 176: Dominant population: Conserver (c60:d20:s20), hourly temperatures and heating energy loads for all living rooms averaged on one day in January

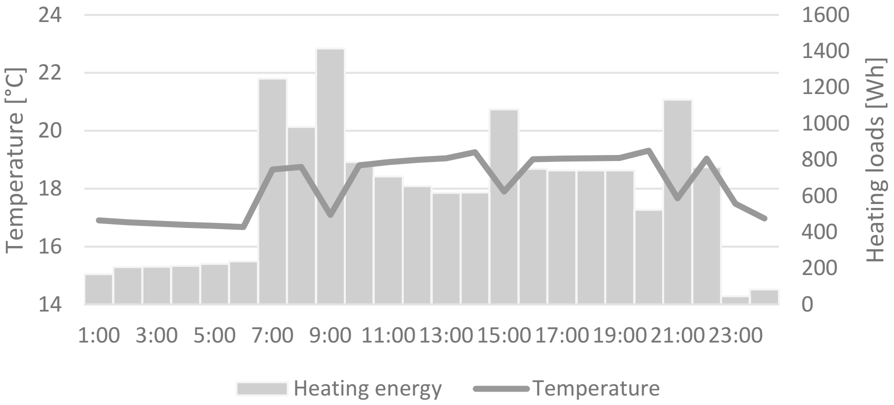


Figure 177: Dominant population: Default (d60:c20:s20), hourly temperatures and heating energy loads for all living rooms averaged on one day in January

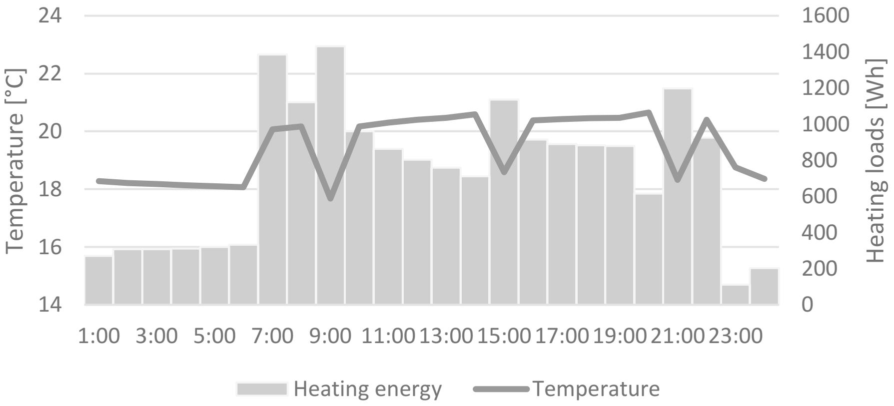


Figure 178: Dominant population: Spender (s60:c20:d20), hourly temperatures and heating energy loads for all living rooms averaged on one day in January