Bottom-up modelling of the Belgian residential building stock: impact of building stock descriptions

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1. ABSTRACT

Building stock modelling is a key element for the analysis of energy policy scenarios at an aggregate level, such as the integration of buildings in smart grids. To analyse the impact of new technologies and evaluate the dynamic behaviour at an aggregate level, bottom-up dynamic models are a prerequisite. Nevertheless, data on the building stock characteristics is scarce and assumptions need to be made.

A comparison of two residential building stock typologies for Belgium is performed in this work with the aim of identifying their differences and investigating how variations in the representation of a building stock can influence the outcome of the model. For this purpose detailed models of the two typologies are implemented and simulated in Modelica using the IDEAS library. Qualitative and quantitative analysis of the heat demand and dynamic behaviour of the stock implementations showed that the inherent differences in the descriptions lead to strong differences in the results, especially when conclusions must be made for specific building cases. This study highlights the need for more reliable and comprehensive data for the building stock, which is a prerequisite for qualitative bottom-up modelling.

Keywords: bottom-up modelling, building stock description, residential, building simulation, Modelica

2. INTRODUCTION

Facing major energy challenges like the climate change, the depletion of natural resources and the energy dependence, the European regulations on energy consumption and energy efficiency become nowadays more and more stringent (European Parliament, 2012). Important focus is put on the building sector, which has a big share in the consumption but also great potential for improvement. More renewable energy and new technologies as well as application of demand side management (DSM) techniques and the integration in smart grids are some solutions towards reducing the energy consumption and increasing the efficiency of the sector (Xing, Hewitt, & Griffiths, 2011).

In order to evaluate the potential of a proposed measure, an accurate bottom-up model of the building stock is needed. Thereby these building stock models not only need to provide reliable results for the total energy demand on an aggregated level, but also have to capture the dynamic behaviour of buildings at high temporal resolutions. When the flexibility of the stock is studied for the implementation of DSM, then this dynamic behaviour of the buildings is also an important output of the model. Bottom-up engineering residential stock models are reviewed by Kavgic et al. (2010). Those models however don’t provide high resolution results that could be used for DSM. Further research has to be done on improving building stock models, making them suitable for such purposes. Regardless of the model, the focus should also be put on the input data, as it influences significantly the accuracy of the model.

In Belgium, several studies of the residential building stock have been published (Karen Allacker, 2010; Cyx, Renders, Van Holm, & Verbeke, 2011; Gendebien, Georges, Bertagnolio, & Lemort, 2014; Hens, Verbeeck, & Verdonck, 2001; Kints, 2008; Singh, Mahapatra, & Teller, 2013). Their scope and purpose may vary, but they all use building typologies to characterise the stock, which vary for the different studies. In this paper we compare two of the latest typologies, namely the TABULA typology (Cyx et al., 2011) and the ULg typology (Gendebien et al., 2014). As these two have the same structure and spatial and temporal resolution, they allow for good comparison. The purpose of the comparison is to analyse the differences in terms of geometry and thermal properties of the described buildings. Further, to assess the impact of these differences on the output of a building stock model that uses those typologies. In order to do so, both typologies are implemented as detailed building models in the same modelling environment with the same occupancy schedules (see paragraph 4). The resulting heating demand and dynamic behaviour of each building case as well as of the total stock are then examined and compared for the two typologies. The energy use is not evaluated since only the thermal behaviour of the buildings is studied and not of the installations.

For the purpose of this study the stock of 2012 is examined for both typologies. Only the single family buildings are considered, since the heating system and control in multi-family buildings often significantly differs from single-family dwellings and needs to be handled differently in studies on DSM. Furthermore, there is a debate on whether the multi-family buildings should be treated as whole buildings or as individual apartments. The typologies include three building types: detached (D), semi-detached (SD) and terraced (T) houses. Each type is further split into five construction periods: pre 1945 (A), 1945-1970 (B), 1971-1990 (C), 1991-2005 (1991-2007 for ULg) (D) and 2005-2012 (2007-2012 for ULg) (E). In the following each building case will have a name indicating the building type and the construction period (e.g. DA is the detached house constructed before 1945, SDC is the semi-detached house constructed between 1971 and 1990, etc.).

A verification of the resulting heat demand for either stock against real data is not possible. Only energy consumption data for the residential sector as a whole can be found in statistics, e.g. Eurostat (European Commission, 2014). Disaggregated data per building case and for specific end-uses is not available for validation of the models. In order to compare with overall residential energy consumption statistics, modelling of the multi-family buildings would be required. Furthermore the HVAC systems of all types of buildings (perhaps several HVAC cases per building) should be modelled as well. More heating schedules should be introduced to represent realistic users and the same would be needed for the internal gains. Domestic hot water (DHW) use should be also included in the model.

In the next paragraph the two typologies are introduced. First, in sections 3.1 and 3.2, the background of each typology is presented explaining the work done in the reference projects, followed by a description of the stocks as implemented in this paper. In section 3.3 a comparison of the main differences in geometry and thermal properties of the two implementations is performed. Paragraph 4 consists of a brief description of the model used for our implementation of the two typologies. In paragraph 5 the simulation results for each building case and for the total stock are presented and commented. The annual heating demand and the heat load and average daily temperature profiles are analysed in the respective sections. Overall conclusions and findings are discussed in the last paragraph.

3. BUILDING STOCK DESCRIPTION

3.1 TABULA

3.1.1 Background

The TABULA-project is a European project that focuses on the evolution of energy-related properties of buildings, regarding the energy performance of the particular building elements as well as the possibilities for improvement.

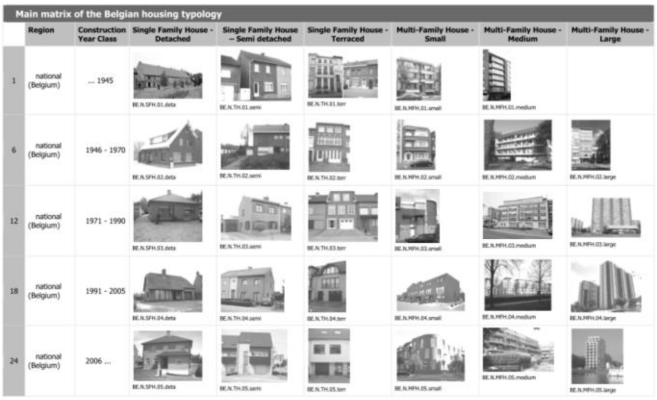

Figure 1: Main matrix of the Belgian housing typology following the harmonized TABULA approach (Cyx et al., 2011).

On the Belgian level two approaches have been implemented in the TABULA-project, referred to as (i) the Belgian housing typology or typical housing approach and (ii) the representative building stock approach. The representative building stock approach is a statistical bottom-up model used for scenario analysis on Belgian level. In this approach the characteristics of the building geometry, construction components and installations, cannot be directly mapped with a physical representation of a dwelling, but result from regression analysis. Moreover, the details are not available in the TABULA-report. In contrast, the typical housing approach implemented in TABULA provides a set of 29 typical dwellings grouped in 6 building types and 5 age classes as shown in Figure 1. This typical housing approach has been used to implement the dynamic bottom-up building stock model in this paper and will be further referred to as the TABULA building stock. The characteristics of the buildings are compiled from national building statistics. As such, they should be considered as average dwellings representing the building types of the typology and are closely linked to real dwellings.

In the TABULA-project, the geometry and U-values of the envelope components are specified for each typical dwelling together with a typical infiltration and ventilation rate. For the single-family dwelling cases, the geometry is derived from the Energy Advice Procedure (EAP) database (see Cyx et al., 2011) for Flanders and Wallonia. This database consists of dwellings that have voluntarily applied for an energy performance audit. Analysis of the data from approximately 11 000 EAP audits resulted in some 9 600 suitable datasets, which allowed deriving average geometrical characteristics for the 15 single-family dwelling cases in the typology (3 building types – detached, semi- detached, terraced – combined with 5 age classes). It has to be noted that the EAP audits are conducted on a voluntary basis. As such, the database might be biased due to a larger share of larger and less performant buildings, since building owners with a high energy bill are more likely to subscribe for an energy audit.

3.1.2 Assumptions for implementation of dynamic model

To implement the dwellings of the TABULA building stock description as dynamic building models, assumptions have been made to extend the data provided by the TABULA report. These assumptions can be categorized in two groups. The first group completes the geometry specification needed for the dynamic building models. The implementation is based on a two-zone building model, taking into account the significant differences between day and night zones. Since this subdivision is not made in the TABULA project, most assumptions are related to subdividing the building in these two zones. In addition, assumptions were needed for the internal walls and floors, as they are not considered in the TABULA project. All assumptions used to complete the geometry specification are summarized in Table 1.

Table 1: Summary of the assumptions made to complete the geometry description of the TABULA building stock.

Aspect	Detached	Semi-detached	Terraced
Unheated spaces	All components except floors are assumed to be in contact with the outdoor environment. The whole ground floor is in contact with the ground.		
Floor area day-zone ($A_{fl,D}$)	The entire area of the ground floor is considered as day-zone		
Floor area night-zone ($A_{fl,N}$)	Calculated as: $A_{fl,use} - A_{fl,grd}$ (with $A_{fl,use}$ the usable floor area and $A_{fl,grd}$ the ground floor area)		
Volume day-zone (V_D)	Calculated as: $A_{fl,grd} h_{fl}$		
Volume night-zone (V_N)	Calculated as: $V_{prot} - V_D$ (with V_{prot} the protected volume)		
Floor height (h_{fl})	Calculated as: $V_{prot}/A_{fl,use}$		
Number of floors (n_{fl})	2	2	3
Area façades	55% of total wall area is oriented front-back; 45% is oriented left-right	The depth of the building is assumed 2 times the width. The dimensions are calculated assuming a rectangular ground floor.	The width (w) of the front and back façade is calculated as: $w = A_{ext}/(2h_{fl}n_{fl})$ (with A_{ext} the surface area of the external walls) The depth of the building (d_{gf}) is calculated as: $d_{gf} = A_{fl,D}/w$
Allocation of façade to day-zone	Front/back façade= 100% Left/right façade= 70%	For all façades factor is: $f_{day} = A_{fl,D}/A_{fl,use}$	
Allocation of windows to day-zone	70%	50%	50%
Orientation front façade	North		
Orientation windows	Window area is specified for each direction in TABULA specification		
Orientation roof	Pitched roof oriented to front and back		
Area of internal walls	Equal to outer wall area	Sum of outer wall area and half of the common wall area	
Area of floor between day- and night-zone	Equal to area of ground floor ($A_{fl,D}$)		
Area of internal floor night-zone	Calculated as: $A_{fl,N} - A_{fl,D}$		

The second set of assumptions concerns the thermal characteristics of the building (component characteristics, air tightness, ventilation rate…). For each envelope component (floor, walls, windows, roof) the composition and corresponding U- and g-values are specified within the TABULA project. Although the exact material properties and dimensions related to the U-values are not specified. Instead only a typical composition is provided. Based on these proposed compositions, the material properties used in this paper have been designed to match the U-values given in the TABULA specification. The thermal conductivity, specific heat capacity and density of the materials are based on the ISO 10456:2007 standard (ISO 10456, 2007). Note that an exception has been made for the U-values of the floor of period A (pre ’45) and B (’46-’70) as the value specified by TABULA was considered unrealistic for an uninsulated floor. The U-value is increased from 0.85 W/(m²K) as specified by TABULA to 2.82 W/(m²K).

The air tightness for each building type is specified in the TABULA project by the v_{50}-value. This value is translated to the n_{50}-value, used in the model, by taking into account the protected volume and total envelope area specified in the TABULA descriptions. Note that in the TABULA it is not specified if the volume is based on internal or external dimensions. Therefore, in this paper the same value is used to calculate the compactness as for the calculation of the ventilation rates. As specified in the TABULA report, the ventilation rate is zero for all cases before 2005. For the E (post '05) buildings, a mechanical ventilation system with a ventilation rate of 0.4 ACH and a heat recovery unit with an efficiency of 80% is considered.

Some of the main resulting properties of the stock (protected volume, heated floor area, overall UA- and gA-values, infiltration and ventilation rates, nominal heating power) for all buildings can be found in Table 5, together with those of the ULg typology.

3.1.3 Aggregation to national level

The aggregation of the heat demand of each building type to the demand of the entire stock is not explicitly carried out in the TABULA project for the typical housing approach. As stated in the introduction the typical housing approach merely presents a set of typical dwellings for each building type and age class. In order to get an estimate of the heat demand of the whole stock the heat demand of each dwelling is multiplied by the number of dwellings of each building case. The number of dwellings is obtained from the SuFiQuaD project (Allacker et al., 2011), which is also mentioned as a data source in the TABULA project and is in line with the Belgian land registry, though more detailed. However, there exist some discrepancies between the numbers shown in SuFiQuaD and our implementation for the TABULA building stock. The fourth period in the SuFiQuaD data ends in 2007 instead of 2005 in the Tabula project and there is no data for period E (2005-2012). The number of buildings as used for the ULg typology (see section 3.2.3) is therefore used for the period 2007-2012 and a linear interpolation is used to attribute the 2005-2007 buildings to period E instead of D. The results are summarized in Table 2.

Table 2: Number of buildings and correction factor used for the TABULA implementation.

	D: Detached		SD: Semi-Detached		T: Terraced	
	Number of dwellings	Correction factor	Number of dwellings	Correction factor	Number of dwellings	Correction factor
A:Pre-'45	269771	0.34	375000	0.41	766884	0.42
B:1946-1970	309263	0.38	275838	0.45	242952	0.45
C:1971-1990	446481	0.45	158123	0.50	87706	0.52
D:1991-2005	266050	0.60	81677	0.64	54519	0.67
E:Post '05	74135	1.00	29046	1.00	19388	1.00

Table 2 also shows the correction factors that have been suggested by the TABULA report. As stated in the TABULA report, the correction factors were introduced as the calculated energy use showed an overestimation compared to the energy use for heating specified in the EAP-database that was used to define the typology. According to the TABULA report the correction factors account mostly for the poor incorporation of the actual occupant behaviour especially in old buildings where an average indoor temperature of 18°C is seldom applicable. Although we have included an occupancy schedule and taken into account the differences in temperature between day- and night-zones, an analysis with and without correction factor is carried out in this paper.

Thereby we assumed that the same correction factor can be used to correct the heat demand that we calculate from our TABULA implementation.

3.2 ULG

3.2.1 Background

Within the framework of a bottom-up approach to simulate the domestic energy use in Belgium, Georges, Gendebien, Bertagnolio and Lemort (2013) (University of Liège [ULg]) have developed a tree structure to characterise the Belgian residential stock. They have used it in combination with a dynamic simulation tool (described in Georges et al., 2013) to assess the impact of different penetration scenarios of HVAC technologies on gas and electrical load profiles and on the annual consumption of the stock (Georges, Gendebien, Dechesne, Bertagnolio, & Lemort, 2013). Gendebien et al. (2014) presents the methodology used to create the tree structure and illustrates its potential by assessing different energy policy scenarios using a Heating Degree Day (HDD) calculation method.

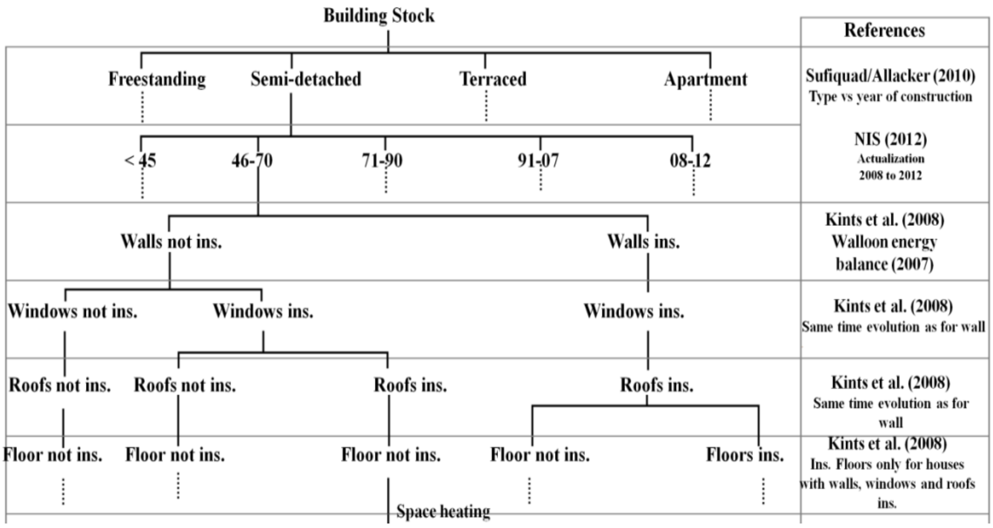

Figure 2: Belgian residential building stock tree structure developed by Gendebien et al. (2014).

In the tree structure representative buildings are identified for 4 building types (detached, semi-detached, terraced and apartment) and 5 construction periods, similar to TABULA. For each of these building cases a number of variations are applied concerning the insulation levels and the heating and DHW production systems, thus resulting in 992 cases in total, see Figure 2. Every end of the tree structure is accompanied by the percentage of occurrence in the total stock, in order to perform the aggregation of the results to the national level. Note that for the purpose of this paper, we do not take the discretization into different energy vectors and heating systems into account, as we only calculate the heat demand.

Various data sources were used for the development of the tree structure. The buildings were taken from the work of Karen Allacker (2010), where a set of existing buildings are chosen to represent the different building types and age classes. As a result, the geometry of the buildings is derived from the available plans. The share of each building type in the total stock is based on the SuFiQuaD project (Allacker et al., 2011), but is brought up to date using data from the Belgian National Institute of Statistics (NIS, 2011). The ratio of insulated to uninsulated building components (walls, windows, roofs and floors) is taken from Kints (2008). For the reconstruction of the envelope components the typical compositions proposed by the TABULA project (Cyx et al., 2011) were used combined with own assumptions for the conductivity, thicknesses, etc. A detailed description of the procedure and the assumptions used to create the tree structure can be found in the article of Gendebien et al. (2014).

3.2.2 Assumptions for implementation of dynamic model

In total 63 cases are realized for this paper, accounting for 3 building types, 5 construction periods and 5 insulation cases (only one case for each building of period E). It must be clarified that the typology used by Gendebien et al. (2014) differs from the reference typology (Allacker, 2010) with regard to the terraced houses built in the first two periods. Allacker specifies two types of terraced houses for period A and none for the next period, while Gendebien et al. considers the second type to be representative of period B. Here we follow the assumption of Gendebien et al. as well, although this leads to an abnormally large building representing the second period and a rather small one for the first period, see Table 5. The consequence of this is commented in the results section as well. Our implementation of the typology of Gendebien et al. will be further referred to as ULg typology or ULg stock.

Each building is modelled as a 3-zone model, except for the buildings DC and SDC which don’t have unheated spaces and therefore only have two zones:

- Day zone (includes living room, kitchen and “study” spaces, as well as adjacent corridors or small storage rooms; usually comprises the whole ground floor)
- Night zone (includes bedrooms and “dressing” rooms, but also the bathroom and corridors of the same floor; usually comprises the whole upper floor)
- Unheated spaces
  - Attic (in this case other unheated spaces are incorporated in the other zones)
  - Big storage rooms and the garage, if there is no attic

The surface areas of all the components are derived from the plans available from Allacker (2010). As those are given in rough detail, subjective judgment could have influenced the outcome. To make it more clear, all assumptions regarding the geometry are listed below.

- The height of the storeys is not specified in Allacker’s work. The heights chosen by S. Gendebien and E. Georges (personal communication, December 2013) are thus used, except for the one of the 2nd floor of the SDB building which was corrected to 4.2m instead of 6m.
- Allacker gives only the total area of windows for each façade of the buildings. Respecting the totals, each zone was allocated an area of windows per orientation based on interpretation of the plans.
- The orientation of the buildings is not provided with the plans either. In this paper a base case orientation is chosen but different cases are then investigated. As a start, the general rule is that the façades of the buildings point towards the cardinal directions and the living room is facing south.
- For buildings of period E (2007-2012) no building type is given by Allacker. The same geometry is used as for the buildings of the previous period, but with different construction elements. This is the same approach as that of Gendebien et al. (2014).

Regarding the thermal properties of the buildings, each building type is assumed to appear in the 2012 stock with 5 different insulation cases, as suggested by Gendebien et al. The frequency of each insulation case per type of building was provided by Gendebien (personal communication, March 2014) and results in the number of buildings shown in Table 3. The 5 cases are listed below:

- Insulation Case 1: original state when built
- Insulation Case 2: replacement of windows (also changes the infiltration rate)
- Insulation Case 3: new windows and insulation of roof
- Insulation Case 4: new windows, insulation of roof and walls
- Insulation Case 5: new windows, insulation of roof, walls and ground floor

To form these 5 cases, two states of each construction element are taken into account: original state and renovated state. Thus, in Insulation Case 1 all elements are in their original state whereas in Insulation Case 5 all elements are renovated. The exact composition of the construction elements – original state as well as renovated state – is the one described by Gendebien (personal communication, March 2014) with only few exceptions. In the following the differences and additions are discussed:

- The improvement of the air tightness was here attributed to the replacement of the windows rather than to the insulation of the walls (assumed by Gendebien et al.). In the opinion of the authors, infiltration losses are primarily linked to leaky windows and roofs. Instead of implementing the improvement in steps, which would reflect more the reality, the reduced infiltration rate was used as from Case 2 for simplicity.
- The composition of the floors has been corrected to resemble more the common practice in Belgium. Thus, instead of 3 cm reinforced concrete above 13 cm of light-weight concrete we implemented 3 cm of light-weight concrete on top of 13 cm of reinforced concrete (resulting in approx. 10% higher U-value).
- For our implementation, the composition of the flat roof was derived from the TABULA descriptions. For the renovation scenario the same average insulation thickness was used as for the pitched roofs, see (Gendebien et al., 2014).
- The composition of the internal walls and floors, since not described in the ULg model, are assumed to be the same as those created in this paper for the TABULA implementation.
- Windows: The U-values specified by Gendebien et al. are maintained choosing appropriate glazing and frame properties. The frame to window area fraction was assumed to be 0.25 for all windows.

Regarding the infiltration rates, the same v_{50}-values specified by the TABULA project were used for the air tightness (as used by Gendebien et al.), but here the conversion to air change rates is different. The v_{50}-values are converted to n_{50}-values, used in our models, by taking into account the protected volume and total envelope areas. The building plans provided by Allacker (2010) are not detailed enough to differentiate between internal and external dimensions, so the same dimensions are used to calculate volumes and areas for all cases. In this way the same approach is used in both our implementations (ULg and TABULA). The ventilation rate is zero for all cases except for the E buildings where a mechanical ventilation system with ventilation rate of 0.6 ACH and a heat recovery unit with an efficiency of 80% is considered, as done by Gendebien et al. (2014). The resulting properties for this model are summarized in Table 5, where a comparison is made with the TABULA model.

3.2.3 Aggregation to national level

As mentioned above, 63 different combinations of building type, age and thermal quality are modelled to represent the whole stock of single-family houses in Belgium for the ULg typology. In order to obtain results for the national level the results of the simulations of each case are aggregated in a simple way. Within the work of Gendebien (personal communication, March 2014) the occurrence of each of these combinations in the total stock of 2012 is specified, see Table 3. The total number of single family buildings results in 3 456 833 for that year (same as for the TABULA stock). Thus, the heating demand of the stock is derived by multiplying the demand of each studied case by the number of buildings it represents. When comparing building types, all insulation cases are included for the ULg buildings, unless it is differently specified.

Different orientations of the buildings are also taken into account for the ULg stock. As stated earlier, a base-orientation was chosen for each building, representing orientation 0° (either south or north). Then the buildings were rotated by 90°, 180° and 270°, resulting into 4 simulations for each building case. Figure 3 shows the deviation of the annual heat demand from the average value. The average results are derived from simply averaging the results from the four simulations, as no data was found to support a different distribution of the buildings to the various orientations. This figure shows the case with the highest deviation (for most buildings) which occurs for the insulation case 5 because the solar gains influence more the energy demand when the building is better insulated. The SDC and SDD buildings show a slightly different behaviour because they have the majority of their windows concentrated in two adjacent façades, whereas the other buildings have them in opposite façades. The difference is maintained within ±4% for most buildings, while SDC and SDD reach above 6% for two of the orientations. For the peak loads the difference is much smaller (no more than 0.33%) and therefore is not displayed here. This is explained by the fact that the peak load mainly depends on the nominal power of the heating system, which remains the same for all orientations.

Table 3. Number of buildings per building type, construction period and insulation case used for the ULg stock (Gendebien, personal communication, March 2014).

		InsCase1	InsCase2	InsCase3	InsCase4	InsCase5
D: Detached	**A:Pre 1945**	86824	106576	38564	18892	18869
	B:1946-1970	86953	106652	38393	38690	38643
	C:1971-1990	65258	79933	28923	136248	136085
	D:1991-2007	14812	18168	6540	132321	132163
	E:2008-2012	36191				
SD: Semi-Detached	**A:Pre 1945**	92127	112887	117447	13701	38793
	B:1946-1970	59100	72417	75343	17997	50956
	C:1971-1990	17615	21585	22457	25170	71267
	D:1991-2007	3467	4248	4420	21197	60016
	E:2008-2012	17474				
T: Terraced	**A:Pre 1945**	165264	202478	291732	1192	106165
	B:1946-1970	45664	55947	80608	674	60065
	C:1971-1990	8575	10506	15138	594	52928
	D:1991-2007	2030	2487	3584	602	53618
	E:2008-2012	11597				

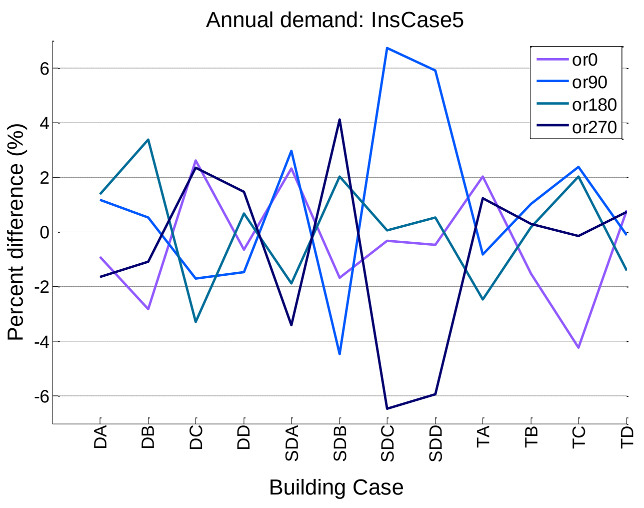

Figure 3: Percent difference of the 4 orientations compared to the average in total annual demand for the insulation case 5 for all building cases.

Note that the aggregation of many rooms into one thermal zone (like was done in our model) makes the influence of the orientation fade away as all rooms can share the solar gains reducing the heating (or cooling in other cases) demand. Therefore, although the differences appear to be small enough for this particular model, all orientations are taken into account and the average results of all four are further used in this paper.

3.3 Comparison of building stock descriptions

Both abovementioned typologies mean to represent the Belgian residential building stock and as such can be used in building stock modelling. The outcome of a building stock model depends on the modelling technique used but also on the typology itself. For this paper the same model is used for both implementations in order to compare the typologies. Significant dissimilarities can be identified regarding the stock descriptions, as presented in this paragraph.

3.3.1 Geometry

The main difference regarding the geometry of the buildings is that TABULA uses “average” buildings, derived from analysis of energy audit databases, while ULg uses existing buildings, chosen for their characteristics that are assumed to be representative. In the TABULA report it is stated that “considering that these audits were commissioned by owners or residents, we are aware of the fact that the EAP-databases do not contain a representative sample of the actual housing stock” (Cyx et al., 2011, p. 19). Recognising this fact, the thermal properties of these buildings were not used in the report. However the database was used for the calculation of the geometrical properties of the buildings. This must be taken into account for this comparison. On the other hand, the selection of the houses in the ULg typology is not clearly explained in the relevant reference (Allacker et al., 2011) and can be debated as well.

In Table 5 the main differences in size of the buildings can be observed. In general, TABULA buildings tend to be significantly larger. The heated volume for the total single family stock of Belgium is $2.2 \cdot 10^9$ m^3 according to the TABULA stock whereas for ULg it is only $1.2 \cdot 10^9$ m^3. It must be noted that TABULA does not specify which spaces are included in that volume, which can create a lot of confusion. For the ULg stock the unheated spaces (attics, big storage, garage) are not taken into account in the above calculation. Some unheated spaces indeed might have changed use over the years becoming heated spaces (e.g. attics become bedrooms) but these effects are not modelled. The inclusion of all unheated spaces in the total volume for ULg results in $1.45 \cdot 10^9$ m^3, which doesn’t explain the large difference between both stock descriptions.

A comparison can be made between the heated surface areas of the two typologies and the average values given by Kints (2008, p. 15). The latter refer to Wallonia and are based on the General Socio-economic survey of 2001 (Vanneste, Decker, & Laureyssen, 2007), however they can be used to evaluate the order of magnitude of the buildings’ size. In Table 4 the average areas of TABULA and ULg are calculated based on the contribution of the different age classes to the total number of buildings within one building category (see Table 2 and Table 3). It can be thereby deduced that the ULg areas appear to be much closer to the results of the General Socio-economic survey.

Table 4: Comparison of average heated surface area (m^2) per building type.

	Detached	Semi-detached	Terraced
Kints (2008)	146.6	128	116.1
TABULA	251.4	213.8	213.9
ULg	127.4	110.6	144.8

This large difference is expected to affect the outcome at the individual dwelling comparison but even more at the aggregate level.

Table 5: Summary of the properties of TABULA and ULg stock implementations.

		Detached					Semi-Detached					Terraced				
		A	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
Protected volume [m3]	**TABULA**	766	648.5	655.7	710.5	714.4	651.8	531.7	509.6	615.9	642.7	621.3	546.6	462.8	526.9	549.8
	ULg	335.5	250.5	423.2	293.2	293.2	192.2	331.1	442.5	382.2	382.2	215	970.5	686	402.2	402.2
Heated floor area [m2]	**TABULA**	279	235.8	238.4	258.4	269.6	237	193.4	185.3	224	233.7	225.9	198.8	168.3	191.6	199.9
	ULg	104.8	104.5	148.5	138.4	138.4	68.6	118.3	185.6	126.3	126.3	76.8	323.5	245	143.7	143.7
UA-value [W/K]	**TABULA**	1268	1031	628	462	313	945	741	466	458	262	713	599	324	247	190
	ULg InsCase1	961	716	571	252	186	409	585	355	244	177	345	1039	471	264	199
	ULg InsCase5	302	192	316	181	-	145	215	190	175	-	131	441	297	204	-
gA-value [m^2]	**TABULA**	35.8	36.2	31	26.8	20.7	25.9	26.6	24.9	20.1	21.7	27.4	25.9	18.8	20.6	21.6
	ULg InsCase1	12.2	15.7	39.3	18.5	11.3	6.1	10.9	19.3	13.9	8.5	6.1	53.9	32.3	13.9	8.5
	ULg InsCase5	6.6	8.5	24	11.3	-	3.3	5.9	11.8	8.5	-	3.3	29.1	19.7	8.5	-
Infiltration rate [1/h]	**TABULA**	0.7	0.75	0.715	0.47	0.23	0.6	0.6	0.6	0.4	0.2	0.4	0.405	0.39	0.25	0.145
	ULg InsCase1	0.8	0.8	0.9	0.5	0.3	0.7	0.6	0.6	0.4	0.2	0.4	0.27	0.265	0.26	0.155
	ULg InsCase5	0.3	0.27	0.315	0.26	-	0.2	0.2	0.2	0.2	-	0.2	0.11	0.11	0.155	-
Ventilation rate [1/h]	**TABULA**	0	0	0	0	0.4	0	0	0	0	0.4	0	0	0	0	0.4
	ULg InsCase1	0	0	0	0	0.6	0	0	0	0	0.6	0	0	0	0	0.6
	ULg InsCase5	0	0	0	0	-	0	0	0	0	-	0	0	0	0	-
Nominal heating power [kW] (sum of day and night zones)	**TABULA**	40.3	33.8	22.6	19.2	13.7	30.3	24.8	17	14.6	11.3	22.1	19.2	12.2	10.6	10.7
	ULg InsCase1	21.6	19	17.9	9.7	8.3	10.5	13.8	12.9	9.8	8.4	8.2	28.4	19.9	10.2	9
	ULg InsCase5	10.4	7.5	11.7	8.2	-	5.6	8.4	9.5	8.3	-	5.3	20.3	15.3	9.2	-

3.3.2 Thermal properties

The U-values used for the envelope components of both stocks are summarized in Table 6. The windows have the same U-values for the original state, see Table 7, while the internal walls and floors are the same for both stocks. As can be seen here, a major mismatch exists in the thermal properties used for the roofs of the first two periods. This difference results from the discrepancy between the component description and the corresponding U-value that is presented in the TABULA project. In the ULg implementation the U-value is calculated based on the component description, as done by Gendebien et al. (2014), whereas for the TABULA implementation the value presented in the TABULA project is used.

Table 6: Comparison of U-values [W/(m^{2}K)] of the envelope components used in both stocks.

Component:	**Exterior walls**					**Pitched Roof**					**Floor on Ground**				
Period:	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
TABULA	2.2	1.7	0.99	0.6	0.4	1.71	1.66	0.85	0.6	0.3	2.82	2.82	0.84	0.67	0.53
ULg Org.	2.28	1.57	0.92	0.48	0.41	4.74	3.7	0.79	0.44	0.31	3.73	3.73	1.19	0.74	0.4
ULg Renov.	0.59	0.53	0.43	0.41	-	0.46	0.45	0.31	0.31	-	0.79	0.79	0.54	0.41	-

Table 7: Comparison of window properties

Property:	**U-value of window [W/(m^{2}K)]**					**g-value of glazing [-]**				
Period:	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
TABULA	5	5	3.5	3.5	2	0.87	0.87	0.77	0.77	0.47
ULg Org.	5	5	3.5	3.5	2	0.87	0.87	0.77	0.77	0.47
ULg Renov.	2.75	2.75	2.75	2	-	0.47	0.47	0.47	0.47	-

The infiltration rates were based for both stocks on the TABULA specifications for the v_{50}-values leading to similar results, as shown in Table 5. No ventilation is taken into account for the majority of the dwellings. However, different ventilation rates were assumed for the buildings of the last period: 0.4 ACH for TABULA and 0.6 ACH for ULg.

Taking into account the transmission and ventilation losses, as well as the intermittency of the heating, the nominal power needed for heating the dwellings was calculated in this paper based on the EN12831:2003 standard (EN 12831, 2003). Table 5 clearly demonstrates the higher needs of the TABULA buildings, mostly due to their bigger size.

4. MODEL

In order to compare the two building stock typologies the same model is used for the two implementations. A tool that can simulate dynamic physical phenomena is needed in order to be able to simulate demand profiles and peak loads for DSM and integration in smart grids. All parameters of the models that are not specific to one stock description are kept the same for the two implementations.

The detailed simulations of both stocks for this paper are carried out using the IDEAS library developed at the KU Leuven. The IDEAS library is implemented in Modelica (2014) and expresses transient thermal processes in detail based the control volume method (CVM) as described by Baetens et al. (2012). The buildings are modelled as 2- and 3-zone models, taking into account the different requirements of different rooms of a dwelling (day-zone, night-zone, unheated zone). Since the paper only aims at calculating the heat demand, ideal heating systems with maximum power input equal to the nominal power of each zone (day and night zones) obtained by the EN12831:2003 (EN 12831, 2003) standard were implemented.

Regarding the temperature requirements for the heating, a fixed schedule is used in order to make in inter-building comparison. The set-point for the operative room temperature is set to 21°C and 18°C for respectively the day and night zones in accordance to EN15251:2007 (EN 15251, 2007). A set-back temperature of 16°C is implemented. The day-zone is assumed to be heated between 07:00-22:00; the night-zone between 21:00-09:00 (Aerts, Minnen, Glorieux, Wouters, & Descamps, 2014). For the internal gains a model based on Markov-chains that is largely consistent with the model of Richardson, Thomson, Infield and Clifford (2010) but adapted to the Belgian case was used (Baetens et al., 2012). The outputs of the model are presence and activity of the occupants and the usage of electric appliances and lighting resulting in internal heat gains for the building. A random profile was chosen and used for all buildings of both stocks. It must be noted that although the deterministic approach used in this paper is acceptable for the inter-building and inter-model comparison, a stochastic representation of the occupant behaviour should be implemented for a bottom-up analysis of the energy use of the Belgian building stock.

For modelling purposes, the walls adjacent to neighbouring houses were considered to be adiabatic. Also the thermal capacity of the zone's air was estimated to be 5 times that of the air (Sourbron, 2012, p. 229). The air change rates were calculated using rule of thumb by dividing the n_{50} values by 20. Last, the simulations were performed for the moderate climate of Uccle (Belgium), for which climatic data is obtained by Meteonorm v6.1 (2009).

5. RESULTS

A comparison of the calculated heat demand is performed in order to evaluate the differences between the two stocks introduced in the previous paragraph. The annual demand as well as the dynamic heating load and temperature profiles are examined, since the latter are also important when DSM is to be studied.

5.1 Annual heat demand

Simulation of the heat demand for both building stock descriptions results in an annual use of 63 020 GWh and 51 275 GWh (or 79.7 kWh/m^2 and 115.5 kWh/m^2) for the corrected TABULA and ULG cases respectively. The aggregation of the results of individual building cases is done as explained in sections 3.1.3 and 3.2.3. The uncorrected TABULA demand was much higher (145 768 GWh), demonstrating the need for correction factors of the buildings in the TABULA project. These results cannot be compared to real data (as explained in the introduction), which doesn't allow for a conclusion on which typology gives more accurate results. However, the obtained difference (65% for uncorrected and 18.6% for the corrected TABULA results) indicates that none of the typologies can be accepted as reliable without validation. Nonetheless, verification of the simulation model based on a comparison of the results obtained by our simulations with those obtained in the reference studies is possible.

In the TABULA project the total annual demand for each building type was calculated using a monthly averaged method implemented in the EPB-software (EPB Besluit Bijlage V, 2013), the Flemish implementation of the EPBD. Multiplied by the number of dwellings for each case and taking into account the correction factors, this results in a reference value for the total annual demand of 86 154 GWh. As such the heating demand obtained by our dynamic model is 26.9 % lower than the value obtained by the static calculations in the TABULA project. This difference is mainly due to the fact that the EPB calculation, used in the TABULA project, assumes a default value for the ventilation loss, whereas in our dynamic model the ventilation rate is set to 0 ACH for all buildings before 1990, as described in the TABULA project. Moreover, the EPB software used in the TABULA project accounts for thermal bridges by increasing the average U-value of the components by $\Delta U_b = 0.1 * (C + 2)/3$, with C the compactness of the building. Implementing the ventilation according to the EPB-calculation into the dynamic model, resulted in an air change rate of approximately 0.4 ACH for each dwelling and an increased heat demand of 72 020 GWh, reducing the discrepancy with the TABULA project to 16.4 %. Since the current version of IDEAS does not support a detailed calculation of thermal bridging effects, an estimation of the impact is made by increasing the UA-value of the envelope by 10%. As such, the annual heat demand is further increased to 75 200 GWh, reducing the difference with the TABULA report to 12.7%. Note that both modifications are not maintained in the paper, as both aspects are not included in the specifications reported by the TABULA project.

For the ULg stock a clear comparison cannot be made between our calculation and results from Gendebien et al. (2014). In their work the annual demand for heating per average dwelling is calculated (18.8 MWh/y/av. dwell), which however results from the inclusion of apartments in the stock and from different calculation method, heating schedules and climatic data. The calculated 14.8 MWh from our implementation is then 21.3% lower. This difference can additionally be attributed to the few different assumptions made regarding the stock, e.g. the infiltration rates of the insulation cases (see section 3.2.2). Indeed, the same dynamic simulation but following the assumption of Gendebien et al. for the improvement of the air tightness leads to a heating demand of 16.0 MWh per average dwelling, limiting the difference to 14.9%. This is an indication that such assumptions made out of lack of data can have a noticeable effect on the outcome. These results are nonetheless of the same order of magnitude, showing that the difference in the building characteristics, as found between the TABULA and ULg descriptions, is of greater importance.

A more elaborate examination of the results and inter-comparison between the two stocks will help revealing the causes of the differences. In Figure 4 the annual heat demand is presented for each building case. The results from the TABULA implementation without and with the use of the correction factor are compared to the results from the ULg implementation for the buildings at their original state (Insulation Case 1) and for the all-ins.-cases state. The latter is calculated as the weighted average of all insulation cases for each building (based on the number of buildings in each insulation case). Additionally the annual heat demand per “average dwelling” is shown for the two TABULA cases, for the ULg all-insulations case and for the reference projects (Cyx et al., 2011; Gendebien et al., 2014). Values for the “average dwelling” are obtained when dividing the stock’s demand by the total number of buildings. This figure demonstrates the impact of the correction factor in the TABULA approach, as well as the inherent differences of the two stocks. If one compares the original states for both stocks without taking into account correction factors it becomes obvious that the larger TABULA dwellings result in much higher needs (around 86% higher in average, but with values ranging from -5% up to 260% for the TB and TA buildings respectively), although the U-values are similar or even larger for ULg in a few cases.

The corrected TABULA demand is substantially lower and much closer to the ULg-all-ins.-cases outcome, especially for the older buildings. It appears then that the correction factor could account not only for the occupant behaviour and rebound effects as stated by Cyx et al. (2011), but also for the possible renovations that have occurred to the buildings and are not modelled explicitly. This interpretation cannot be verified for the TABULA buildings, however a closer look to the ULg stock reveals that the inclusion of 5 insulation levels for each building type reduced the annual demand of a building by 34% in average (range: 17-46% for the DA and SDC buildings respectively) compared to the original state alone.

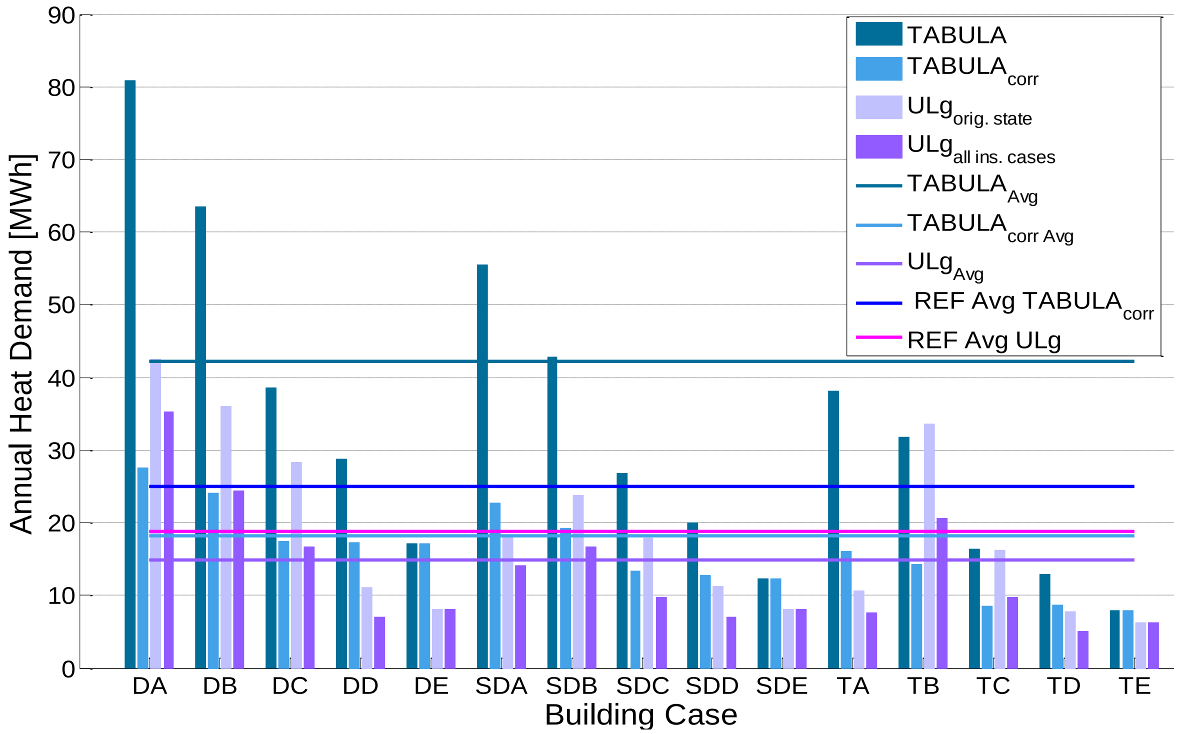

Figure 4: Annual heat demand [MWh] of all building cases for the two stocks. For TABULA: with and without correction. For ULg: original building state and with all insulation cases considered. Average dwelling annual demand for the above and additionally for the reference studies (Cyx et al., 2011; Gendebien et al., 2014).

For certain buildings, i.e. the DD, DE and SDA the larger dimensions of the TABULA buildings cannot be compensated by larger U-values or the correction factor, which explains the still smaller needs of the ULg dwellings. The strange behaviour of the TA and TB buildings is further commented for Figure 6.

Figure 5 shows the annual heat demand per m^2 of heated area for each building type, for the same cases as mentioned for Figure 4. When the difference in size is filtered out by analysing the heat demand per m² of heated floor area, a strong similarity is shown between the stock implementations without application of the correction factors. For both implementations the heat demand clearly decreases for newer buildings. In line with the expectations, terraced houses have a lower heat demand compared to semi-detached and detached houses. This figure demonstrates that the difference in heat demand between the TABULA and ULg buildings is mainly due to size effects. The application of the reduction factors for the TABULA dwellings results in a significant underestimation of the heat demand per m² compared to the ULg dwellings. This suggests that the correction factors possibly also account for the fact that the heated surface area of the TABULA dwellings is much higher than that of ULg and might therefore be overestimated. Nevertheless, the absence of reliable validation data does not permit to prove this hypothesis.

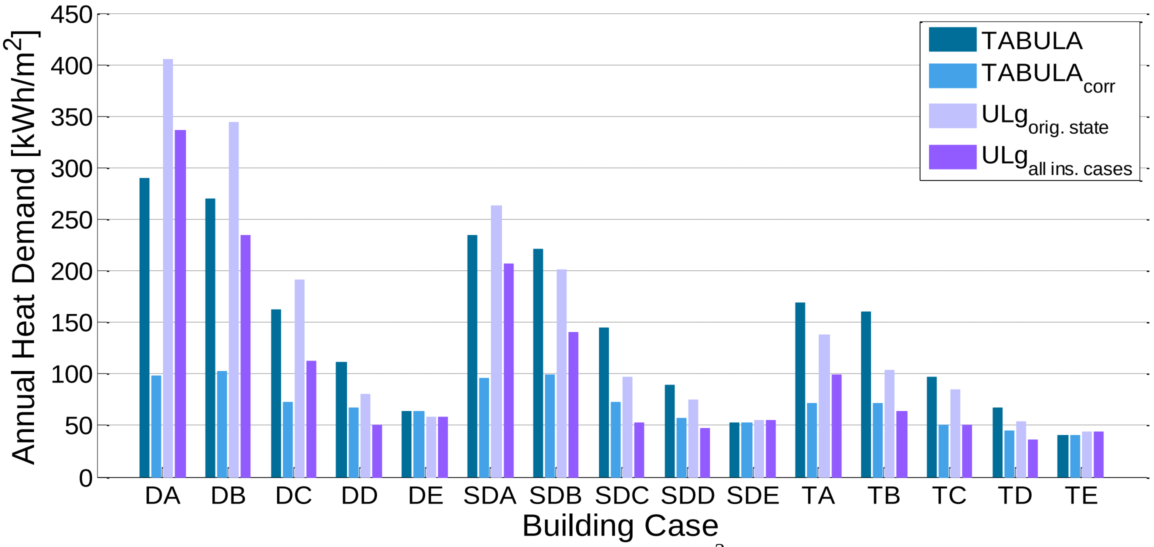

Figure 5: Annual heat demand per heated area [kWh/m^2] of all building cases for the two stocks. For TABULA: with and without correction. For ULg: original building state and with all insulation cases considered.

Figure 6 shows the demand aggregated for the total number of buildings for each building case. The importance of the age of the Belgian stock can be noticed. The new dwellings built after 1990 represent only 15.2 % of the single family houses and account for 12.6% of the total heating demand for the TABULA stock (only 7% for ULg). This fact indicates that energy efficiency policies targeting old buildings would have a higher impact on the stock's efficiency.

The evident trend of the heat demand decreasing from detached to terraced houses observed in Figure 5 is no longer obvious in the demand of the total stock. The relative contribution of each building case in the overall heat demand of the Belgian housing stock differs between the two typologies, although the same total number of buildings is used for the two descriptions. For the TABULA and ULg typologies, the dominant building types are respectively the terraced (TA) and detached (DA) buildings from before 1945.

This figure demonstrates the problematic behaviour of the TA and TB buildings for the ULg typology, where the small size of the TA building results in a much smaller share of those buildings in the total stock heat demand compared to the TABULA typology. The important contribution of the TA buildings in the Belgian stock was already noticed by Allacker (2010) who specified two types of terraced buildings for that period (but unjustifiably none for the next period). These two types were, in the opinion of the authors, mistakenly assigned by Gendebien et al. (2014) to the two periods (A and B) respectively. To test this, a simulation of the ULg stock was performed using the so far TB building as a TA-type2 building (keeping TA as TA-type1), as suggests Allacker. The number of buildings for the new TA-type1 and TA-type2 were adjusted and are both equal to the average of the previous TA and TB buildings. This was done for each insulation case separately. There was no TB building in this simulation. The result is an annual demand of the new TA (type1+type2) building of 16.7 (3.8+12.9) GWh, much closer to the corrected TABULA 16.0 GWh. Furthermore, the stock's demand is increased to 57 115 GWh, 11.4% higher than before. This reduces also the difference of the two stocks from 18.6% to 9.4% (for the corrected TABULA). It is therefore the authors' suggestion that for future use of the ULg typology both types of buildings should be used for the terraced houses of the period A, but also a building type (other than the oversized TA-type2 one) should be implemented for period B. For the remaining part in this paper the original approach is still used.

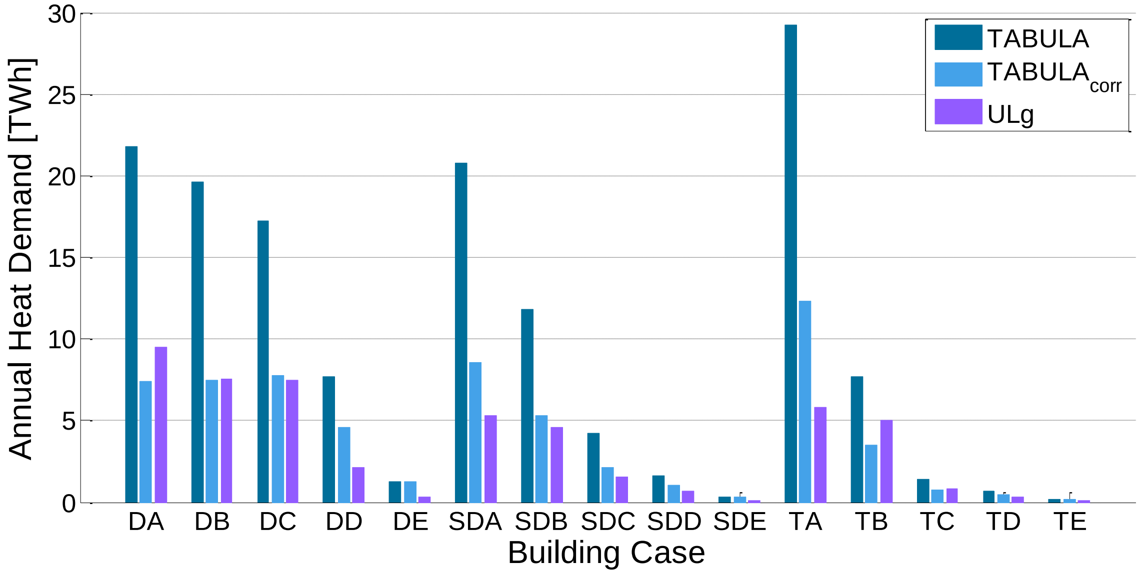

Figure 6: Annual heat demand aggregated for the total stock [TWh] of all building cases for the two stocks. For TABULA: with and without correction. For ULg: all insulation cases considered.

The analysis of the heat demand calculated by modelling the two stock typologies helped in identifying the main causes for the observed discrepancies. The high overestimation of the size of the TABULA buildings compared to the ULg ones appears to be the main influencing factor. A misuse of the TA-TB ULg building types was revealed to be of significant importance. Furthermore, possible interpretations of the purpose of the correction factor of the TABULA stock have been suggested. However, due to lack of validation data it is not possible to draw conclusions on the correctness of either typology. Moreover, it is the authors' opinion that the use of correction factors is not desired in a bottom-up model, since this would reduce the usability towards the assessment of new technologies.

5.2 Dynamic temperature and load profiles

In this section an analysis of the dynamic behaviour of the buildings is performed. Knowledge of the temperature profiles and peak loads is important for the implementation of DSM, where loads have to be shifted while maintaining the comfort levels.

Figure 8a and b shows the operative temperature profiles of an average day in January (average of 31 days). The day and night zone profiles are shown for the three building types of construction periods A (a) and D (b). In those graphs one can notice the fixed heating schedules of the day and night zones. For both stocks it can be observed that the older buildings cool down much faster, which is expected, due to higher infiltration rates and U-values. The TABULA buildings tend to have shorter cool-down and longer heat-up periods and reach lower temperatures than the ULg ones. In order to explain the observed divergence in behaviour a study of the heat balance of both stocks must be done.

The TABULA buildings have much bigger size as pointed out in the previous paragraph. This leads to larger transmission losses (U-values are comparable) and to larger infiltration losses, since infiltration rates are similar for both stocks (see Table 5). The proportionally larger solar gains of the TABULA buildings (average gA-value of dwellings for original state: TABULA=25.6m^2, ULg=18m^2) compensate for the higher losses at a certain extent, but this effect is limited in January, due to less solar radiation. In addition, because of the assumption of same occupancy and thus same amount of internal gains in both stocks, the gains per heated area are much smaller for the TABULA buildings, as shown in Figure 7. The thermal mass of the buildings in both stocks is of the same order, as the same element compositions were used and the area of internal walls was found comparable. Taking the above into account the dissimilarities on the temperature profiles can be better understood.

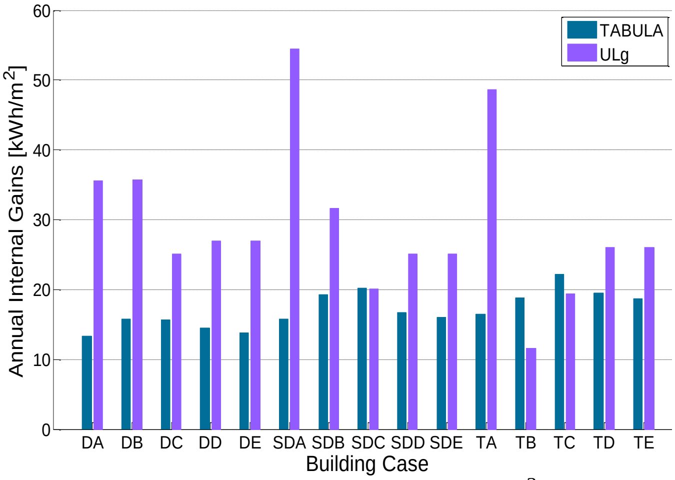

Figure 7: Annual internal gains per m^2 of heated area for all building cases and both stocks.

Figure 8c and d shows the corresponding average daily heating demand in January for the buildings of periods A and D respectively. Immediately one can see that in order to achieve the same thermal comfort the older buildings need much more energy. Also it is clear once again that the TABULA buildings have higher heating demand. Further, the peak demand period is slightly longer for the TABULA buildings, which corresponds to the slower temperature rise in Figure 8a and b. The trend that was observed in Figure 4, with the highest heat demand for the oldest detached dwellings is also clearly demonstrated in these graphs. Two peaks can be observed corresponding to the times when the day and night zones start to be heated. Of course this is only the result of the selected heating schedule (see paragraph 4). In reality the schedules (and temperature set-points) highly depend on the occupant's presence and preferences. The stochastic nature of these factors must be taken into account not only for the calculation of the total demand but more importantly for the study of DSM. For this purpose more reliable data is needed describing user behaviour.

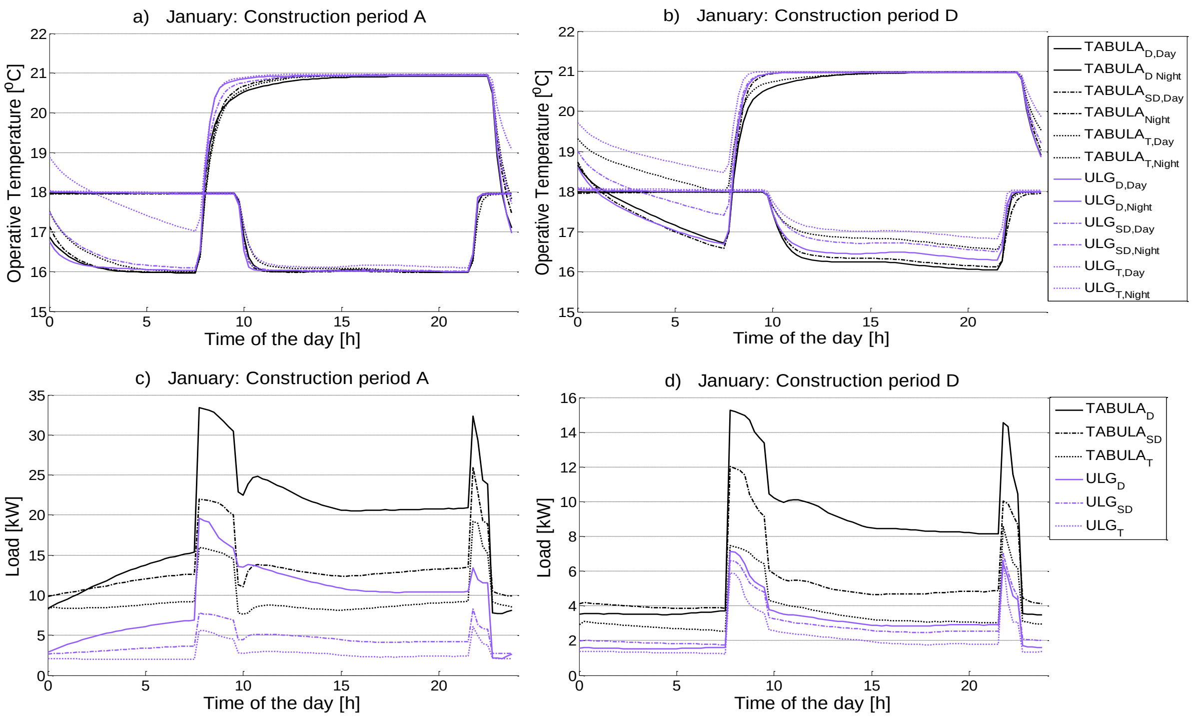

Figure 8: Average daily temperature profiles for January of the day and night zones of the three building types of the age classes A (a) and D (b). For both stocks the original insulation state is presented. Corresponding average daily heat demand (c and d respectively).No correction factor is used for TABULA.

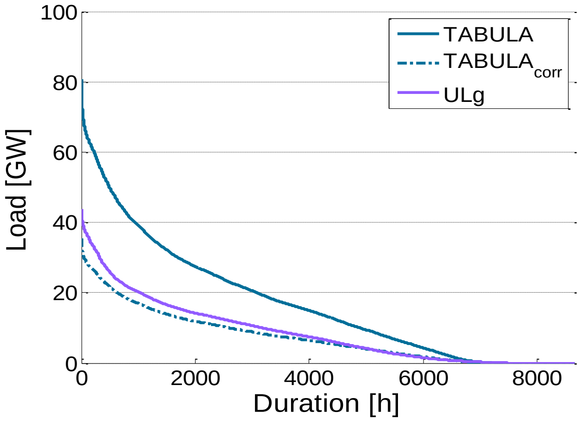

Figure 9: Load duration curves aggregated for the stock for the two implementations.

On building stock level, the peak load demand (translated to electricity load) is a useful metric to define the generation, transmission and distribution capacity of an electricity system. This aspect can be evaluated by examining the load-duration curve of the stock, shown in Figure 9 for the TABULA and ULg implementations. Each curve is the result of aggregation of the instantaneous heating demand of all the buildings of the stock, for one implementation. One can conclude that the TABULA and ULg stocks have similar behaviour and comparable peak loads (TABULA: 35GW, ULg: 44GW) only when the correction factor is used. However, the correction factor is meant to be used for the annual demand and its use cannot be justified for correcting the dynamic behaviour of the buildings.

The comparison of the dynamic behaviour of individual buildings and of the entire stock indicated that the two typologies give much different results and would lead to different conclusions if used to evaluate energy saving measures. The need for validation data at a disaggregated level is again highlighted by these results.

6. CONCLUSION

In this paper two different single-family residential building stock typologies for Belgium were compared, namely the TABULA and ULg typologies. For this purpose detailed simulations of both stocks were performed using the IDEAS library implemented in Modelica. For the sake of the comparison the buildings were equipped with ideal heating systems where deterministic schedules were applied. Furthermore, the same occupant profile (defining the internal gains) was used for all buildings. The results were evaluated in terms of annual heating demand and dynamic heating load and temperature profiles.

The examination of the descriptions and the analysis of the results showed that the two typologies differ significantly, resulting in large disagreement when comparing individual dwellings and the stocks. The TABULA buildings had an average annual heating demand 86% higher than the ULg dwellings. At an aggregate level the difference in annual demand was found to be 65%. Such large discrepancies indicate that at least one of the typologies is far from representing accurately the Belgian single-family residential stock. However, due to lack of validation data, it is not possible to conclude on which of the two performs better. The large discrepancies were primarily attributed to the differences in the size of the buildings and to the fact that the ULg typology considers five quality levels for each building case. The latter approach is thought as more appropriate in the sense that more cases represent better the heterogeneity of the stock, provided that there is enough data to support the additional discretization.

The use of correction factors to account for occupant behaviour and rebound effects, as proposed by the TABULA project for the Belgian stock, reduced the difference in annual demand between the two stocks to 18.6%. However, the use of correction factors is no valid part of a bottom-up approach as their value cannot be explained based on known parameters. As was shown by the analysis of the results, the correction probably accounts for more effects than just the ones specified by the TABULA project. Additionally, the scope of these factors is only limited to the purpose for which they were introduced. This reveals the weakness of the TABULA typology, which relies on correction factors to model the energy demand.

The comparison performed in this paper also emphasized the lack of reliable and comprehensive data for the building stock of Belgium. The existing typologies differ in such an extent that a question rises whether any of them is reliable enough. As the need for better and more detailed models increases to cover the requirements of the new technologies, the quality of the input data should follow. Therefore, a more systematic effort should be put on collecting and processing building related data. Further, relevant information on the energy use, e.g. obtained by smart meter readings, could support the validation of these building stock models, which is currently not possible. As soon as this data becomes available, future work could focus on setting up a validated residential stock typology that can be used for bottom-up modelling and analysis of the energy efficiency of the national stock.

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