ENRICHMENT OF SINGLE-ZONE EPB-DATA INTO MULTI-ZONE MODELS USING BIM-BASED PARAMETRIC TYPOLOGIES

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ABSTRACT

Bottom-up residential building stock models are often based on a limited number of reference buildings simulated using the same simplified, single-zone calculation methods as those used for regulatory energy performance assessments. Those methods have the advantage of requiring fewer inputs than multi-zone methods, but they do not allow simulating realistic heating and ventilation profiles as accurately as multi-zone methods and can thus result in inaccurate predictions. This paper presents an approach for using multi-zone calculation methods in building stock analyses that are based on statistical single-zone data collected in the framework of energy performance regulations. This is achieved by fitting more detailed BIM-models of parametric multi-zone typologies to the limited data available about large numbers of real houses.

INTRODUCTION

Reference buildings are used in bottom-up building stock models and in scenario-analyses on cost-effective solutions that support policy making (Allacker et al., 2011; Corgnati, Fabrizio, Filippi, & Monetti, 2013; Kavgic et al., 2010). Each reference building is considered to be representative for a specific subset of the whole building stock which is subdivided based e.g. on building typologies (e.g. single-family house, apartment buildings), the age of buildings, the construction method, the number of floors etc. The reference buildings can be real buildings or fictive buildings, respectively selected or defined based on statistical data or based on the knowledge of a panel of experts (Ballarini, Corgnati, & Corrado, 2014; Diefenbach et al., 2012). Any of these approaches results in a finite number of reference buildings that can be used for simulation studies. The validity of the simulation results for extrapolations to the whole building stock will depend on the representativeness of the considered set of reference buildings. This in turn will depend on the knowledge that was available for defining the set of reference buildings and on the typological variation included in the set of buildings. The smaller the number of considered reference buildings the more limited also the heterogeneity of the building stock that can be taken into account in the analysis. The accuracy of the predictions will also depend on the level of detail to which each reference building is modelled. This level of detail will also depend on the availability of statistical data.

A lot of technical information required for building these calculation models can be found in the energy performance of buildings (EPB) databases (Concerted Action EPBD, 2013; Diefenbach et al., 2012). By collecting data from the energy performance assessments of buildings, these governmental databases contain geometrical data, physical data, data on the building systems etc. However, because the assessment models are single-zone models, the granularity of the collected data does not give enough information to build detailed multi-zone models. As a result, many building stock models are based on data at the building level and not at the room level and use single-zone models, identical or quasi-identical to the models used in the regulatory framework (Ballarini et al., 2014; Diefenbach et al., 2012; Hens, Verbeeck, & Verdonck, 2001; Kavgic et al., 2010). While this allows better predictions of official performance levels depending on different design or policy strategies, this approach will result in the same modelling simplifications and prediction errors that are inherent to the regulatory assessment methods and that were revealed by comparisons between theoretical and real energy consumption figures (Magalhães & Leal, 2014; Sunikka-Blank & Galvin, 2012). It will thus not allow taking into account those parameters that are severely simplified or not considered in the official models, e.g. the zonal differentiation of heating and ventilation profiles and of the external building envelope or behavioural rebound resulting in different heating profiles at different performance levels. This can result in significant biases when comparing potential energy savings associated with different renovation strategies, with for example large overestimations of the energy savings associated with roof insulation because bedrooms commonly located under the roof or attic are rarely heated (Delghust, De Weerdt, & Janssens, 2015).

Still, it is possible to define the reference models to a more detailed, multi-zone level. When the reference buildings are real buildings, the necessary data can easily be collected. For fictive reference buildings, the solution resides in combining statistical data for defining the parameters at building level with knowledge and expertise for defining the internal lay-out of these fictive buildings at room level (Verbeeck, 2007). However, because of the lack of available statistical data at room level and because of the workload required for building each multi-zone model one by one, it is impossible to follow these approaches for very large numbers of reference buildings and warranting the statistical representativeness of the internal lay-outs.

A balance between modelling accuracy and representativeness has thus to be found when making bottom-up building stock models: using more simplified calculation models that can be applied on a very large number of houses, directly using statistically representative inputs from the databases, or using more detailed and realistic multi-zone models of a more limited number of reference buildings. This paper presents an alternative approach for making large numbers of multi-zone simulations that also consider the large variation in building characteristics documented in official energy performance databases. The approach is based on parametric typologies that are fitted repeatedly to the available single-zone data of the different real houses documented in those databases.

MATERIALS AND METHODS

General concept of the parametric typology approach

The approach starts from a set of parametric, multi-zone models of predefined housing typologies, stored in Building Information Models (BIM) (Eastman, Teicholz, Sacks, & Liston, 2008). Each parametric typology corresponds to a subset of the database, differentiating e.g. detached, semi-detached and terraced houses. A copy of the parametric model is fitted to the available single-zone data of each separate real building in that subset (its total volume, floor area…). For each real building, an enriched, replacement model is thus created using a fictive parametric typology but considering the available data about that real building. These replacement models can than be used for multi-zone simulations considering varying user profiles and considering also the large documented variation across buildings present within each subset of the building stock.

Because the typologies used in this approach are parametric and will be fitted to the available single-zone data of each real house in the dataset (e.g. volume, area), it is not as important for them to have e.g. a representative size. It is more important for those parametric typologies to have a large 'elasticity': the extent to which they can be transformed in different directions and scaled. This requires mainly simple parametric models, without overly complex though still realistic geometries. Additionally, not only must the internal layout of the parametric typology be realistic to start with, it must also remain realistic after the typology is transformed to fit real houses that can be larger, smaller, more or less compact etc. This requires thoroughly defining the relationships between different internal and external walls, floor roofs, doors etc., in order to keep them in sensible absolute and relative positions compared to each other. In the end, the elasticity of any parametric typology will be limited and different typologies will be needed to cover the large geometrical variation found in a national or regional building stock.

Specific context: Flemish EPB-database

This paper further describes and illustrates the fitting procedure considering the data available in the Flemish EPB-database and focussing on the energy use for space heating. That database contains data on all new houses built in Flanders since 2006, but only to the level of their single-zone official energy performance assessment model. Furthermore, not all the data that was input by the EPB-assessor in the assessment software, commonly at the component level (e.g. the U-value of each window), is stored in the database. Instead, the database mainly contains data that is aggregated at the building level: the most important geometrical data (total external volume, floor area, heat loss area, total window area), the average U-value of all windows together, the average U-value of the total building envelope and the most important technical data about the ventilation and heating systems (the type and efficiency of the systems). The database also contains the results of the official energy performance calculations: the calculated yearly net energy demand and the monthly and yearly primary energy demand.

Fitting procedure

Fitting a parametric typology to the available geometrical data of each specific house of its corresponding subset of the database is done in different steps. The first fitting step targets the three main geometrical parameters that are documented in the database and that are important inputs for the heat-balance calculations: the total volume, heat loss area and floor area of the building. For each parametric typology, a set of three geometrical equations defines these three parameters in function of the length, width and height of the parametric typology. As the former three parameters are available for each case in the database, the set of equations can be inversely solved to determine the latter parameters and apply them on the parametric typology, e.g. making the parametric typology wider and taller to reach the same volume, heat loss area and floor area as the real house. The more simple the shape, the more simple the set of equations. However, a shape that is too close to a primary shape (e.g. a cube) cannot be fitted to the real variations occurring across buildings. Thus, a well-defined, realistic parametric typology is needed to be stretched and squeezed to fit to the required volumes and areas of the statistical data. Subsequently, all window areas of the transformed typology are scaled for their total area to match the total window area documented in the database. Once these geometrical fitting steps have been performed, the physical and technical system properties can be fitted. The efficiencies of the heating and ventilation systems are known and can thus be used directly as inputs for the new simulation models. Other parameters need a separate fitting procedure. All windows are labelled with the same average window U-value, because the database does not contain information on each individual window. While the database does not contain information about the insulation levels of floors, walls and roofs separately, such differentiation can be important in a multi-zone model and often exists in reality, with roofs being commonly better insulated than walls. In Flanders, the government also imposes different maximum U-values depending on the building component, with lower (better) values for roofs. Therefore, the following simplified approach is used. First, each separate part of the building envelope is labelled with the legally defined maximum U-value corresponding to the building period, asserting for the common differentiation between building components. Subsequently, all values are scaled up or down, respecting their mutual order of magnitude, in order for the average U-value of the transformed typology to fit with the average U-value of the house that is stored in the database. The multi-zone parametric typology is thus fitted in an algebraically defined way to as many available geometrical and physical parameters of the real building as possible. The resulting replacement model can then be used for multi-zone simulations.

Practical implementation

The multi-zone geometrical data of each transformed typology is described in a platform neutral and open data scheme that can be generated by most BIM-software: the green building extensible mark-up language (gbXML). For this project, the BIM-models of the reference typologies were created in Autodesk Revit Architecture. A Revit add-in was developed to collect the parametrical inputs (e.g. parameters the model has to be fitted to), parametrize those base-models and generate a gbXML-file for each geometric variation. Subsequently, the models can be calculated directly using that same add-in or afterwards, using a separate standalone application. To do so, the data is processed and passed on to a calculation kernel. That calculation kernel contains the official single-zone monthly quasi-steady state calculation method used in Flanders (VEA, 2013) and based on ISO 13790 (ISO, 2007) as well as a custom multi-zone quasi-steady state algorithm. While less detailed than dynamic simulation software, this multi-zone algorithm allows taking into account different intermittent heating profiles in coupled zones while keeping the calculation times very low in order to run simulations on very large numbers of houses. Furthermore, it requires less data than dynamic models, e.g. regarding the exact layering of walls, thus making it more suited for situations with limited availability of data. The tool, including the calculation kernel, was programmed in .NET (VB.NET and C#) and reads the additional inputs from an Excel-template where to it also writes the simulation results. Creating the 3D-geometries starting from the reference-model takes the most amount of computer time (on average approximately 3 seconds per case on a standard personal computer, depending on the complexity of the geometry). Once the building geometries have been generated, varying the heating profiles, physical properties (e.g. U-values), orientations, and glazing areas and subsequently running the multi-zone simulations and exporting the results takes on average less than 0.3 seconds per case (approximately 5 minutes to run simulations on 1000 cases or variations), thus enabling scenario analyses on large sets of buildings.

Single-zone test set: EPB-database

Three parametric typologies are used to test the approach (left side of Figure 1): one detached, one semi-detached and one terraced house, each counting three bedrooms. First, data from the official Flemish EPB-database is used to illustrate the approach in the framework of building stock analyses, to test the elasticity of the parametric typologies compared to large numbers of real houses and to verify the quality of the fit on single-zone level. For each of the three typologies, 5000 cases were randomly extracted from the official EPB-database.

Multi-zone test set: three case-study houses

Because a good fit on single-zone level does not guarantee a good fit on multi-zone level, the approach is further tested considering three real houses for which the architects supplied the original as-build Revit-models. Again, one detached, one semi-detached and one terraced house are analysed (right side of Figure 1). Limited changes to the Revit models were needed for the simulation tool to process these models. Firstly, some complex joints between building components (walls, roofs, windows) were cleaned up in Revit or simplified to avoid junction-errors when generating the gbXML-model. Secondly, large openings between e.g. an open kitchen and the living room were closed using walls and doors to have distinct room types and because, in its current development stage, the tool does not yet process very large air openings and it thus cannot yet feed the data required for modelling these large air openings to the calculation kernel. No other changes were applied to the shape or the internal lay-out of the building. Still, one important modelling assumption was made. The attics were defined as adjacent unheated spaces outside the building envelope because this assumption was also made when defining the parametric typologies.

For testing the approach, each model is simulated 320 times, considering different insulation levels, construction types (e.g. lightweight versus masonry) and heating profiles in order to assess the accuracy of the approach under different modelling assumptions. The building envelope was varied from an old, non-insulated state, via the different insulation requirements imposed over the years in Flanders, ending with a (quasi) passive house scenario. The eight different heating profiles vary from considering all rooms heated to the same temperature 24h/day, via intermittent heating profiles and different heating set points in the different rooms. These variations are further illustrated in the result section.

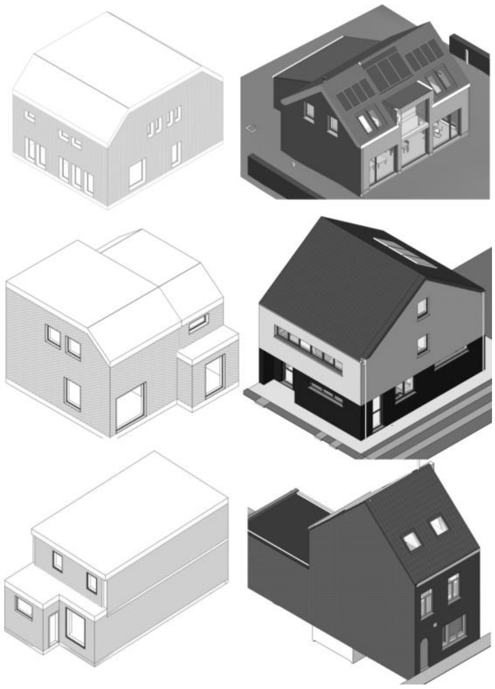

Figure 1 Left: parametrical typologies; Right: case-studies (copyright: BAST architects & engineers); Top to bottom: detached, semi-detached, terraced

RESULTS

Single-zone: EPB-database

A very good match was obtained between the geometrical and physical properties of the fitted parametric typologies and those of the original houses, documented in the official EPB-database. Over 90% of the fitted models had their volume, floor area and heat loss area being no more than +/-1% wrong and not a single error was larger than 2.5%. These small residual errors are caused mainly by the difficulty of taking into account the exact location of the reference planes of the different Revit components (e.g. walls, roofs, floors) defining the dimensions of the exported gbXML-model. This causes small errors especially when calculating the building volume. Figure 2 illustrates this fit as well as the large extent to which a parametric typology can be modified to fit to the houses of its subset. The figure compares the distribution of the floor area of the 5000 detached houses (‘stat,total’) with the floor areas of the houses that had a solution to the set of geometrical equations (‘stat,filtered’) and their respective replacement model (‘fitted’). The perfect fit in Figure 2 seems to suggest that all the 5000 cases were modelled. However this is not true. The set of equations relating the geometric characteristics of the parametrical typology has no solution for a case if its shape results in a combination of volume, heat loss area and floor area that cannot be matched by transforming the parametric typologies. As a result, the detached, semi-detached and terraced typologies proved to be useable only on 72%, 66% and 82% of the 5000 cases in their respective datasets. Figure 3 illustrates this limited elasticity by making a similar comparison as Figure 2, between data of the original and fitted models, but this time focussing on the compactness (volume divided by heat loss area). Once fitted, the accuracy is very high, but for the cases with very low or very high compactness it is more likely that there is no solution to the set of geometrical equations. Figure 4 shows that the error on the calculated space heating demand using the official single-zone calculation method is higher than the geometrical errors. This is caused by the fact that no data on the real orientation of the windows was available and that it was unknown if the EPB-assessors used detailed values for the shading angles from the surroundings or if, on the contrary, they used the conservative default approach authorized for the official assessment procedure. In the absence of information about the orientation, both underestimations and overestimations can occurr depending on the real orientation of each house. In the absence of the information regarding the shading angles, the conservative default approach was used for the energy simulations based on the replacement models. This option requires no detailed input on shading angles but results on average in lower solar heat gains. As a result, the error regarding the calculated heating demand of an individual case can be high, with the largest underestimation and overestimation being -10% and +77%, respectively. However, for 91% of the cases, the net space heating demand of the replacement model differed by no more than 10% from the official result stored in the database. Furthermore, the good agreement of the cumulated distributions of the original values on the one hand and the replacement models on the other hand indicates that the underestimated cases and the overestimated cases compensate each other to a large extent, resulting in a representative distribution on building stock level. The same findings apply to all three subsets. This is illustrated in Figure 5, showing the relative errors of the floor area (Sfl), the average U-value (Uav) and the net space heating demand (Qhnet) for the three test-sets extracted from the EPB-database.

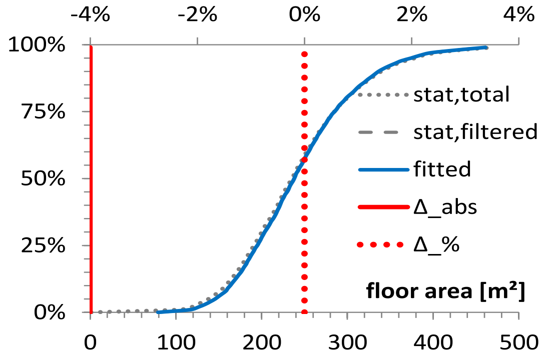

Figure 2 floor area: original detached cases versus their fitted typology

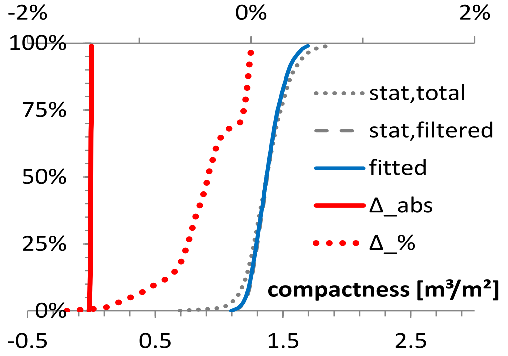

Figure 3 compactness: original detached cases versus fitted typology

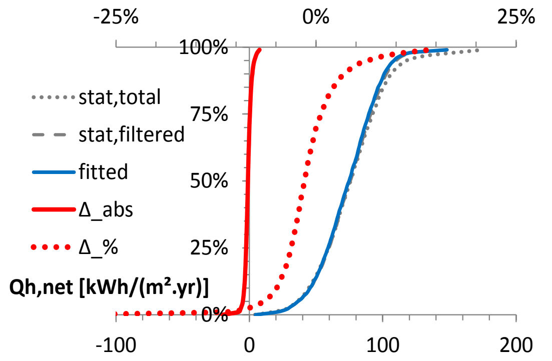

Figure 4 net space heating demand (single-zone): original detached cases versus fitted typology

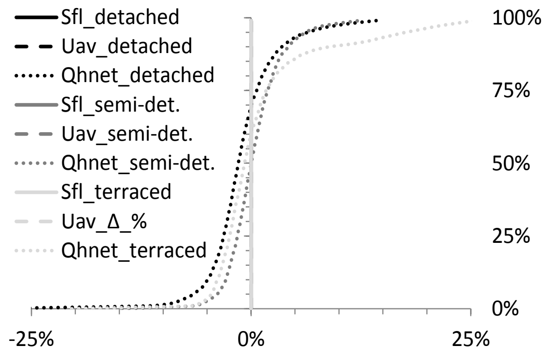

Figure 5 relative errors of the three fitted typologies

Multi-zone: selecting an appropriate typology

A good fit on single-zone level does not guarantee a good fit on multi-zone level. The selected parametric typology and its internal lay-out will influence the multi-zone results more than the single-zone results. This is illustrated by Figure 6. It compares for the detached case-study the net space heating demand of the 320 variations of the original multi-zone model with the results based on the fitted parametric typology. The same fitting approach was followed as for the cases from the EPB-data, except for one additional step: the parametric typology was rotated for its most glazed façade to have the same orientation as the most glazed, garden sided façade of the original house. Figure 6 shows a strong correlation between the replacement models and the original models, but large errors occur for the scenarios with a higher space heating demand. In fact, three clusters can be identified following three different regression lines. The best fit (slope=1.0092, R^2=0.999) is found for the scenarios with all the rooms being heated to the same temperature for 24 hours a day, thus being comparable to a single-zone situation. The intermediate cluster includes the scenarios where all rooms are heated, however to different set point temperatures and durations, with lower heating durations and set point temperatures in the bedrooms compared with the living area (living room and kitchen). The lowest cluster includes the results from the cases were only the living area is heated, to varying temperatures and durations, but with the sleeping area being only indirectly heated by the heat losses from the living area. On average, the latter cluster shows an underestimation by the replacement model of 22%. The underestimation in the latter two clusters is caused by the smaller heated living area of the fitted typology compared with the original model. In the former, the living area accounts for 25% of the total floor area while that number was 42% in the real house. This large difference is caused by the position of their garages. While the garage of the original model was located outside the insulated envelope, thus being excluded from the protected volume assessed in the official single-zone model, the garage of the parametric typology was located within the insulated envelope and is thus part of the considered total volume and area. As a result, fitting the typology based to the officially reported building volume results in a larger unheated part of the building, namely including the garage, and thus in a lower calculated energy demand. For further analysis, the living and circulation area of the detached parametric typology were extended to include their formerly adjacent garage, resulting in a typology that better corresponds to the case-study house. As a result, the living area accounts for 36% of the total floor area. This results in a much smaller prediction error, as illustrated in Figure 7.

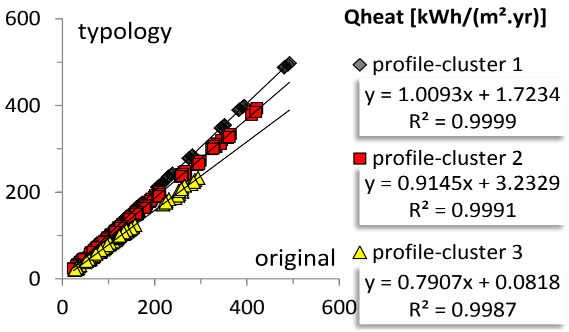

Figure 6 original versus replacement multi-zone models. Detached typology with included garage

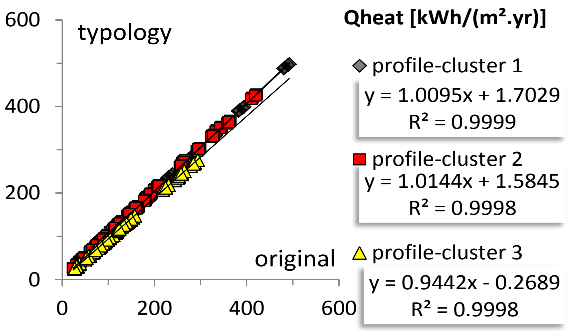

Figure 7 original versus replacement multi-zone models. Detached typology without garage

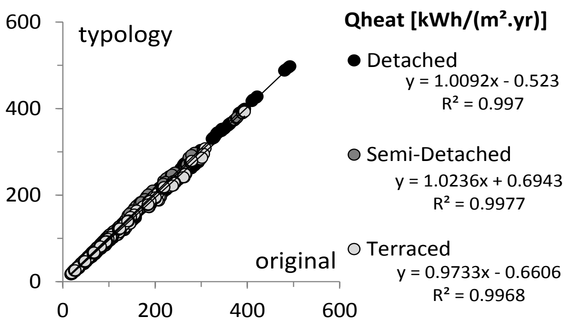

Figure 8 original versus replacement multi-zone models

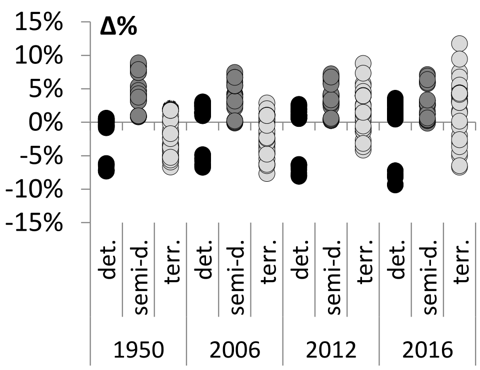

Figure 9 relative error of the space heating demand from the fitted typology

Figure 8 extends the analysis by including the other two case-studies and their replacement models. While the fitted typology of the semi-detached case has, on average, a small overestimation of the space heating demand, the opposite is true for the detached and terraced case-studies. Again, this proved to be correlated with differences between -7 to +4 percent point between the floor area fraction attributed to the most heated living area in the original and in the replacement model. While Figure 8 shows a very good correlation between the results of the original multi-zone models and the results from the replacement models, the errors can be relatively large when looking at individual scenarios within the set 320 scenarios considered for each house. Figure 9 shows, for the levels of insulation corresponding to four different building periods, that the space heating demand calculated using the replacement model can be wrong by up to 10%, with an overestimating or an underestimating bias depending on the typology. Those systematic biases result from the differences in shape and internal lay-out between the case-study houses and their respective typologies, resulting e.g. in heated areas that are more enclosed in the building or, on the contrary, located at a corner of the houses or protruding further outside the main volume.

DISCUSSION

Single zone

The parametric typology approach proved to reach very good results on the single-zone level. The fit between the real houses documented in the official EPB-database and the fitted typologies was quasi perfect with regard to the main geometrical properties (the building volume, floor area, heat loss area and glazed area) and the average U-value. The error on the calculated space heating demand was limited. Furthermore, small biases could easily be tackled by some minor tuning of e.g. the building orientation.

Therefore, the approach shows great potential for scenario analyses on building stock level. It enables making new calculations based on large numbers of real house, assuming e.g. different insulation levels, glazing types etc. This is possible notwithstanding important modelling data is often missing in official databases, e.g. regarding window orientations or the ratios of the total building envelope that are made out of walls versus roofs versus floors. Related assumptions made on the parametric typology will be projected on the results. Therefore, it is important for the parametric typologies to follow realistic assumptions, but variations can easily be included in the process and studied by means of sensitivity analyses, e.g. changing the orientation of the fitted typologies. In the end, compared to the common use of fixed, non-parametric reference buildings, the new approach will still enable simulating larger realistic variations present in the building stock with fewer, though parametric typologies. This approach can thus support governments in defining what future official performance levels (e.g. regarding space heating) can be reached with specific sets of measures (e.g. insulation thicknesses and glazing types) if applied to the heterogeneous building stock.

Over the years, building characteristics are not the only parameters evolving and changing the officially assessed building performance levels. The calculation methods are also regularly updated. With each change to the calculation method, the question rises to what extent the changes to the method will change the calculation results and for what type of houses. This is an important question, because some continuity within the regulation framework is needed to enable stakeholders, building professionals and buyers, to anticipate on future evolutions and to compare performance levels of different buildings. I.e. not only comparing houses built during the same year and evaluated using the same version of the calculation software. The presented simulation approach could also prove useful in those situations, allowing recalculating a very large number of houses from the database using a new calculation method and subsequently comparing results, before officially launching the new calculation method.

In fact, the developed approach and the tool presented in this paper have been used in a project commissioned by the Flemish Energy Agency. The aim of that project was to develop a new way of labelling the performance of the building envelope and to propose what the tightening requirements could be for the following years. The approach had to be scientifically sound, but it also had to take into account the building realm, with large variations in types of buildings resulting from different ambitions of design teams, from different building requirements (e.g. for different sizes of households) and from different building sites. Indeed, it was important to know in advance what type of houses and how large a percentage of typically built houses would face more or less difficult challenges for reaching the newly developed criteria. Answering these questions required testing the proposed evaluation methods and imposed values on a representative set of houses instead of on a limited number of test cases, varying also the technical performance of the different envelope components and services. Therefore, the method presented in this paper was used, based on similar statistical data from the same database used for the presented analysis: the official Flemish EPB-database, containing data on all the new houses that have been built since 2006 and thus guaranteeing a large representativeness of the calculated results.

Multi-zone

Compensating for the lack of original multi-zone models by using the presented approach proved possible, but it can result in lesser relative accuracy than when aiming only at a single-zone replacement model. For multi-zone simulations, the results of the parametric typology approach are more sensitive to the selection of an appropriate typology and to additional parameters such as the distribution of the insulation across the building envelope and different heating profiles in different rooms. The errors will decrease with increasing homogeneity of the insulating envelope and of the heating profiles across rooms, approximating further the single-zone assumptions of the official assessment methods. However, the error associated with a replacement model compared to the original model could increase when using dynamic simulation algorithms, because they depend on more detailed information on building characteristics and user profiles than the quasi-steady-state algorithms used in this study.

While only tested on a limited number of geometries, the results support the potential of the approach, on the condition of a sound selection procedure for the typology. Important typology selection criteria should include the presence or absence of large unheated areas (e.g. garages and attics) or other non-standard rooms that could influence the internal ratio of heated and unheated rooms and thus cause a lesser fit at multi-zone level. While the availability of such information on building stock level will vary from one country to another, depending on their databases, collecting that information on a specific house requires only few questions to the inhabitant. Therefore, the approach also has potential for use in fast decision support tools giving tailored energy renovation advice to house owners, e.g. through a web platform, taking both the building and the users better into account than by using single-zone models of fixed building typologies.

Further research

The results presented in this paper were based on a bottom-up fitting procedure based on modelling inputs that are available in the EPB-database. Further research should focus on additional model calibration based not only on the inputs, but also on the outputs, comparing e.g. the results from the single-zone replacement models with the calculation results stored in the database to tune the replacement model, more specifically the missing inputs (e.g. the window orientations), before performing the multi-zone simulation. For that aim, Bayesian calibration methods might result in interesting approaches, because they enable taking uncertainties stochastically into account in simulation studies (Heo, Choudhary, & Augenbroe, 2012). Combining the parametric typology approach with stochastic approaches would be a sound research path, especially in combination with fast calculation algorithms similar to the simplified multi-zone model used in this study. Further research should also focus on improving the fitting procedure at the multi-zone level by taking not only the external geometry into account, but also basic information about the internal geometry, e.g. the approximate size of the living room and kitchen.

CONCLUSION

This paper showed how parametric typologies can be used for making multi-zone building models of specific houses when only single-zone data is available. The approach makes it possible for building stock analyses to consider variations of user profiles at room level while being based on statistical data about large numbers of houses documented at the single-zone level in official EPB-databases. It also enables making scenario analyses that have a higher degree of representativeness than when using a smaller number of fixed reference buildings. However, a word of caution is needed when using results not only from the single-zone models, but also from the multi-zone models. While very large correlations were found between the original multi-zone models and the multi-zone replacement models, large errors can result from selecting an inappropriate typology. To reach sufficient accuracy, more data is needed than purely about the building shape and size. Additional parameters should be considered such as the occurence of garages, attics and other large unheated or differently heated rooms that are not present in every house.

NOMENCLATURE

Δabs = fitting error
$\Delta\%$ = relative fitting error

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the Agency for Innovation by Science and Technology in Flanders (IWT). The development of the multi-zone calculation kernel used in the tool was supported in part by the Research Foundation Flanders (FWO) and the Flemish Institute for Technological Research (VITO). The authors also thank the Flemish Energy-Agency (VEA) and BAST architects & engineers for supplying the test data.

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