

A dynamic model for district-scale building demand simulation

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ABSTRACT

A new dynamic building demand model was developed. The simulation process in which it is embodied makes it specially interesting for urban simulation as it allows the automation of the buildings definition and, therefore, urban scale demand simulation becomes feasible.

Both, the dynamic model and the simulation process are presented in this paper.

Furthermore, the validation of the model -conducted with a real building experiment- was successfully conducted. Some of the results and conclusions of this validation are also given.

1 Introduction

The world population has increased exponentially since the Industrial revolution and it has moved from rural to urban areas among others, due to the easy access to energy and other resources that the revolution brought with it. This increase of population in urban areas involved a complex resources supply system whose efficiency is not yet solved. With the growing concern over climate change and the end of fossil fuels of the last decades, many projects have focused on energy consumption in cities, trying to understand the complex system and reduce the impact of our energy use. Urban Energy System Models (UESM) can help in this task by giving scenarios with which to analyse the effect of different solutions.

Buildings can be considered the main components of the UESM as they provide the starting point for other analysis such as refurbishment purposes, system dimensioning or energy optimization.

This paper presents a dynamic building demand model that can be used in urban modelling thanks to the automation of data setting and its flexibility to adapt to different levels of data resolution.

The simulation process articulates in a linear work-flow (figure 1). Starting with the data acquisition and preprocessing, then the model definition, the simulation step and finally the presentation of results. Every work-flow step is susceptible to modifications and updates.

The workflow is implemented as an orchestration of Micro Web Services developed based using SimStadt workflow steps [1].

This paper gives an overview of the present status focusing on the simulation step, which uses INSEL as simulation engine. INSEL is a object-oriented, multi-domain modelling tool for component-oriented modelling of complex systems. It is a modular simulation tool to understand, plan, monitor, and visualize energy systems.

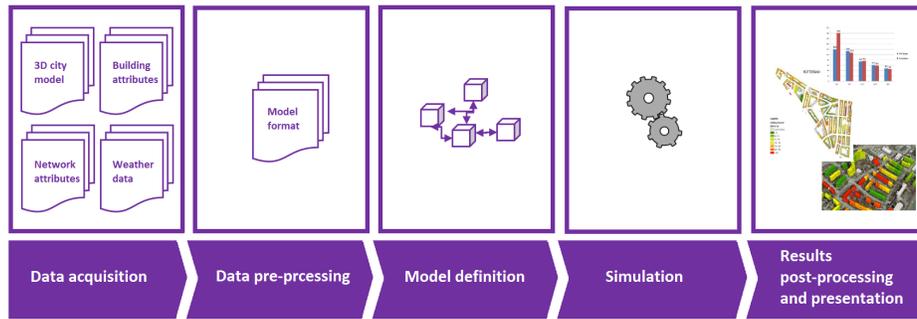


Fig. 1. Software work-flow.

2 3D City Data Models

3D city models come more and more available world wide [2, 3]. Usually, they are modelled following the international CityGML standard of the Open Geospatial consortium [4]. CityGML supports a multi-resolution modelling approach. A building can be represented in five Levels of Detail (LoD). Generally speaking, LoD 0 represents the building footprint as a polygon in 3D space. LoD 1 extrudes the building footprint to a given height (shoebox model). Semantic surfaces such as Wall- and Roofsurface as well as the roof structure itself is added in LoD 2. Windows, Doors, and more details on the facade are added in LoD 3, while LoD4 includes the interior of the building as well. The 3D building model of INSPIRE follows a similar approach, but is limited to LoD 1 and LoD 2. These 3D city models provide an excellent database for the simulation of urban energy systems on district and city level. However, they usually lack of specific semantics for energy specific purposes such as material/construction information. In order to close this gap, the CityGML Energy Application Domain Extension (ADE) has been developed as voluntary community work [5]. The main idea of the CityGML Energy ADE is to define a data model that is suited to create and manage an urban energy model base.

As an example, Bruse et al. [6] have used SimStadt to simulate the building energy heating demand using a monthly energy balance following the German DIN 18599 standard. This method has been applied to several European data sets [7, 8] to validate the interoperability of this approach within Europe.

SimStadt supports several workflows to calculate heating demand for buildings and solar irradiance on roof surfaces, for example. A 3D building model of a city district is a required input for these workflows. This 3D building model has to be stored as a CityGML file. As SimStadt uses a generic CityGML parser, all valid CityGML files can be processed. However, not all CityGML input file result in useful output. For example, if ground surfaces are missing in the building model, the calculated volume of that building is obviously wrong. So the heating demand will be wrong as well, as it is based on a wrong volume. Obviously, there is a need for quality management. A test and validation plan has been developed to ensure that the 3D building models used as an input in the simulation system SimStadt fulfil certain requirements as explained in full detail by Coors et al [9].

In this paper, an extension of the SimStadt workflow is proposed to support a dynamic model for heating and cooling demand on district-scale.

3 Workflow Sequence

3.1 Step 1. Data acquisition

Four data families compose the required input data of the building model:

Weather data. It can be obtained either by using the models included in the INSEL [10] tool, or directly providing TYM3 data.¹

Geometry and location. CityGML [11] is a common semantic information model for the representation of 3D urban objects that can be shared over different applications. Due to its interesting methodology to create databases for urban modelling considering different levels of complexity of the data model, it is the perfect solution for the presented building model. The developer can have access to several levels of complexity of the urban model and select the right one according to his or her simulation tool. CityGML is thought to admit not only individual buildings but higher scale such as cities or even whole countries [4].

Construction data. The construction parameters can be stored in the CityGML Energy ADE, but this information is usually not available. In this case, it is extracted from a building topology database structured in a *Construction library*. This library is based on the German standard *Deutsche Gebaedetypologie, Institut Wohnen und Umwelt*² (2003 [12])

¹Typical Meteorological Year (TMY) data sets derived from the 1991-2005 National Solar Radiation Data Base (NSRDB) update.

²German Building Typologies, Institute for Housing and Environment

and 2011 [13]) including the *EnEV2014* [14] standards, and it has relevant information such as number of layers per wall, differentiating if it is external or internal wall, roof or ground; thickness, density, heat transfer coefficient and specific heat capacity of every layer; also construction of windows and window ratio, together with infiltration ratio or global thermal bridges U-value.

Human behaviour and internal loads data. This information is collected in a corresponding library as well, the *Usage library*. It handles two different levels of detail of deterministic values: fixed annual values or hourly values organized in five typical days. The data that can be found is related to occupancy, including convective and radiative internal gains due to presence, electrical appliances and lighting, together with set points and ventilation ratio. Two *Usage libraries* are already incorporated to the platforms: one is based on the Swiss norm *SIA380* [15] and the other from the German standards *DIN 18599-10* [16], *VDI 3807-2* [17] and *VDI 2089-1* [18].

3.2 Step 2. Data preprocessing

The process integrates systematic and automatic data preprocessing for different LoD and data availabilities of the building model separated in different preprocessor depending on the objective.

The *Geometrical preprocessor* defines the internal zoning in case it is not explicitly described in the CityGML model, and calculates:

- The thermal bridges, in case they are needed to be calculated (for LoD 3 or 4).
- As the windows geometry is usually not available (LoD 2 or lower don't provide this information), a window ratio is extracted from the Construction library depending on the YoC. With this value, virtual windows are created for the corresponding external walls.
- Some geometrical parameters of the internal rooms: the view factors for the long wave radiation exchange, and the internal solar fractions for the transmitted solar radiation distribution.

The *Ground preprocessor* calculates parameters of the virtual layer of the surfaces touching the ground using the definition of the construction of every surface, the ground characteristics and the mean value and variation of the external temperature calculated during the Weather preprocessing. The *Usage preprocessor* generates one year time series with a time step of one hour for human behaviour and internal loads. The data is extracted from the *Usage library* and its treatment depends on its LoD. The complete year is created depending on the usage of the building either from annual values or from typical days. Therefore, no external or internal dependencies (e.g. weather conditions or internal comfort) are considered.

Finally, the *Weather preprocessor* has two functions: first, to calculate the beam and diffuse radiations on the external surfaces (walls and roofs). These values are calculated from hourly global and diffuse horizontal radiations using a short wave radiation exchange model, the Simplified Radiosity Algorithm (SRA) [19]. Second, it calculates the virtual ground temperature as a function of the external temperature following the ISO 13370:2007 [20].

3.3 Step 3. Model definition

Every building in the region selected is individually modelled to be independently simulated.

At this point, depending on the information available, all or some of the following hypotheses are taken.

Building geometry and location. Shared walls³ are treated as adiabatic without windows. The model is ready to simulate a whole building with internal zone divisions. In this sense, if the data model is LoD2 or LoD3 (there is no information about internal structure of the building), it is assumed that the building has one thermal zone per storey, internal ceilings are added to the model and the air volume is reduced by the volume occupied by these surfaces. This assumption implies that only buildings with the same footprint at all storeys can be handled (figure 2). Information related to cellar can be externally provided: if the cellar exists and, in that case, if it is conditioned or not. If this information is not provided, it is assumed that there is no cellar and, therefore, the floor is in contact with the ground. The attic is assumed to be ventilated but not heated unless other information is externally provided. Finally, if the model doesn't include windows (LoD2), the window ratio extracted from the data base is assigned to all external walls (except for shared walls).

If the data model is LoD4, the thermal model is built with the information of the internal structure.

The location is a required data, provided within the CityGML file.

Human behaviour and internal loads data. The time series values prepared in the previous step are assigned to each thermal zone depending on its use, that must be specified in the CityGML file. If the LoD is lower than 4, it is assumed that the whole building has the same use, unless there is a mix use of the building ('sales + apartment building' or 'sales + office') and it has more than one storey. In this case, the use 'sales' is assigned to the base storey and all the rest have the other use ('office' or 'apartment building').

³If in the data models there are two walls closer than 0.25 meters, then they are considered adjacent and are treated in the simulation model as shared walls for both buildings

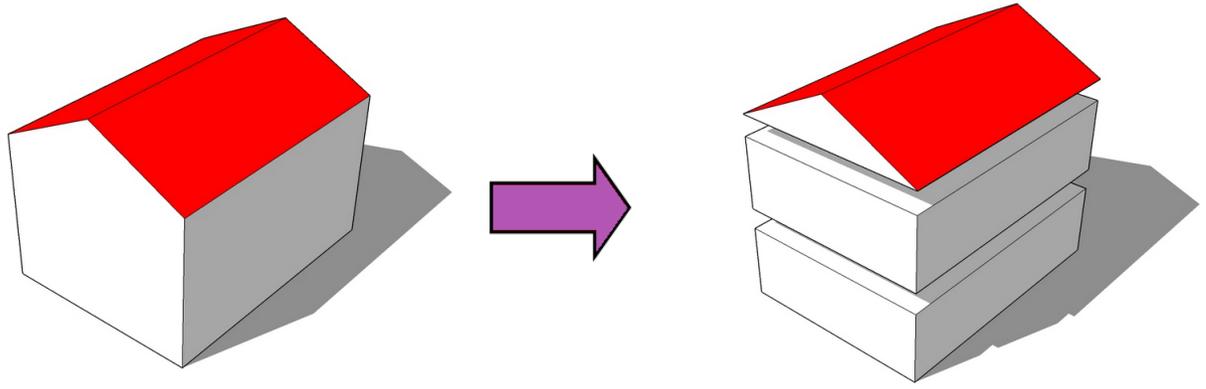


Fig. 2. Division of LoD2 and 3 building models by number of storeys.

3.4 Step 4. Simulation

Not only the workflow, but also the simulation model is very modular, as it will be seen in the next section. It is divided in five main components: walls (external, internal and those in contact with the ground), thermal zones air, long-wave exchange inside the thermal zones, short-wave exchange inside the thermal zones and windows.

Using *INSEL* each component is written in a different block to be later interconnected according to the building definition and simulated.

3.5 Step 5. Results postprocessing and presentation

The results obtained after the simulation -internal temperatures and heat demands (heating or cooling) in every separated thermal zone- are saved in csv files for further use. These values are provided with one hour time step.

The cumulated results can be visualized in 2D or 3D GIS maps.

4 Dynamic Building Simulation Model

The dynamic building model aims to calculate the thermal energy demand for air conditioning of one building, based on the physical nodal method. This method is widely used for building simulation.

According to Foucquier et al. [21], the principal assumptions taken by this method are:

- Each thermal zone is an homogeneous volume characterised by uniform state variables.
- A node represents a thermal zone (also called 'room' in the simulation model), a wall, a window or else the exterior of the building.
- The thermal transfer equations are solved for each node of the system.
- The nodal method can be considered as a one-dimensional approach.

Figure 3 illustrates the energy flow paths considered for the building model. The traditional energy flow paths in buildings [22] also consider furniture and latent flows, which are not included here. However, the ground surface is explicitly studied, which is not done in the traditional model.

Starting from the energy balance in the air point node of every thermal zone, the energy flows are broken down step by step to explain the building model.

Note that airflow between different zones is not included in the models.

$$\frac{dU}{dt} = \dot{Q}_{conv} + \dot{Q}_{TB} + \dot{Q}_{vent} + \dot{Q}_{inf} + \dot{Q}_{IGconv} + \dot{Q}_{sys_conv} + \dot{Q}_{dem} \quad (1)$$

(2)

Where:

$$\frac{dU}{dt} = m \cdot Cp \frac{dT_{room}}{dt} \quad (3)$$

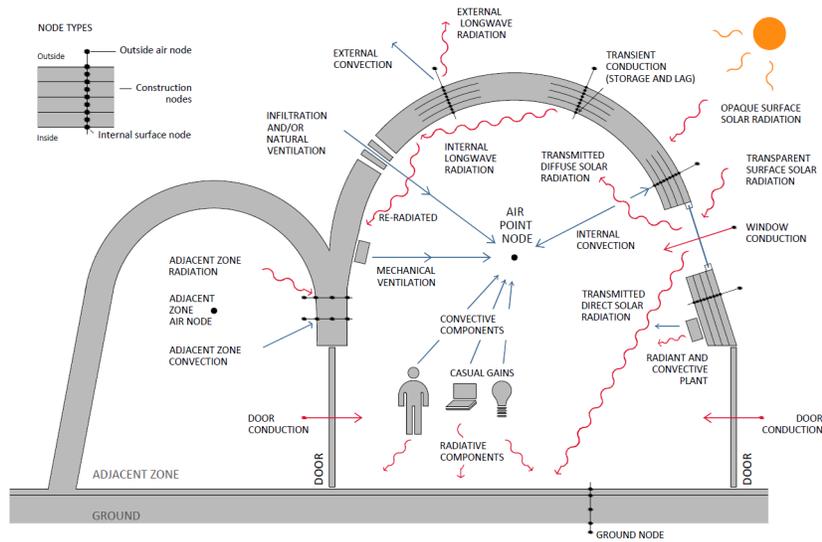


Fig. 3. Energy Flow Paths (Source: adapted by Alfonso García-Leyaristy from [22]).



Fig. 4. Ventilation and infiltration (By R. Monsalvete^a).

\dot{Q}_{vent} [W] and \dot{Q}_{inf} [W] are the mechanical ventilation (external air mass flow voluntary introduced to maintain good air quality) and infiltration (involuntary external air mass flow into the volume) heat inputs respectively (figure 4).

$$\dot{Q}_{vent} = \dot{m}_{vent} C_p (T_{vent} - T_{room}) \quad (4)$$

$$\dot{Q}_{inf} = \dot{m}_{inf} C_p (T_a - T_{room}) \quad (5)$$

All parameters of both equations (except T_{room} [°C]) are inputs for the model. \dot{Q}_{IGconv} [W] and \dot{Q}_{sys_conv} [W] (figure 5), which are the convective heat inputs due to casual gains (or internal gains) and convective fraction of the heat emitted by the thermal systems (plants), are also inputs for the model so, they don't need to be internally calculated.

The term \dot{Q}_{TB} [W] appears due to the one-dimensional heat transfer model of the nodal method approach. The points (e.g. corners) and linear details (e.g. two walls intersection, window-wall junction) must be treated separately.

$$\dot{Q}_{TB} = H_{TB} (T_a - T_{room}) \quad (6)$$

T_a [°C] is the ambient temperature and H_{TB} [W/K] is the total heat transmittance due to thermal bridges. The last one may come as a fix value for the complete building from the *Construction library* or be calculated during the construction preprocessing as:

^aRocío Monsalvete Álvarez-Urbarri. Arquitectura e Interiorismo (rociomonsalvete.com).



Fig. 5. Convective loads (By R. Monsalvete).



Fig. 6. Thermal bridges (By R. Monsalvete).

$$H_{TB} = \sum(\Psi_i \cdot L_i) + \sum \chi_j \quad (7)$$

Where:

- Ψ_i is the linear heat transmittance value of detail "i" [W/mK].
- L_i is the total length of the linear detail "i" in the analysis zone [m].
- χ_j is the point heat transmittance value of detail "j" [W/K].

\dot{Q}_{conv} [W] is a function of T_{room} [°C] and its calculation is developed hereunder.

Note that in equation 2 two terms for convective supply systems appear: \dot{Q}_{sys_conv} and \dot{Q}_{dem} . The first one is an input of the model when the convective part of the heat delivered by supply systems is known. The radiative part of the heat delivered by the supply systems is also an input for the model but it is associated to the surfaces surrounding the zone (equation 9). The second term is an output and represents the needed convective heat flow to achieve the required set temperature, T_{room} [°C]. Equation 2 can be also used to calculate the temperature of the node if ($\dot{Q}_{dem} = 0$).

\dot{Q}_{conv} [W] is the sum of all internal convection flows. The internal convection is caused by the difference between the temperatures of the different enclosures (walls, windows, doors and ground) and the air node. It is obtained from 9 using inputs from 9) for every enclosing surface.

$$\dot{Q}_{conv} = - \sum_i (\dot{q}_{conv_i} A_{surf_i}) \quad (8)$$

$$\forall i, \quad \frac{du}{dt} = \dot{q}_{conv} + \dot{q}_{cond} + \dot{q}_{rad_lw} + \dot{q}_{rad_sw} + \dot{q}_{Igrad} + \dot{q}_{sys_rad} \quad (9)$$

Where:

$$\frac{du}{dt} = m \cdot Cp \frac{dT_i}{dt} = \rho \cdot x \cdot Cp \frac{dT_i}{dt} \quad (10)$$

$$\dot{q}_{conv} = h_{ci}(T_i - T_{room}) \quad (11)$$



Fig. 7. Radiative components of casual gains and radiant plants (By R. Monsalvete).



Fig. 8. Transmitted direct solar radiation (By R. Monsalvete).

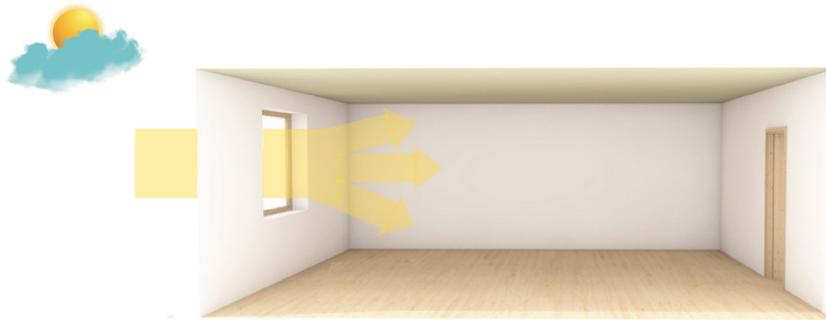


Fig. 9. Transmitted diffuse solar radiation (By R. Monsalvete).

x [m] is the virtual thickness of the surface where dT occurs.

\dot{q}_{IGrad} [W/m^2] and \dot{q}_{sys_rad} are the radiative component of casual gains and radiant plants respectively, and are inputs for the model (figure 7). The distribution of the radiative heat delivered by supply systems (plants) between the surrounded surfaces is not calculated in the model but in the *Geometrical Preprocessing* step.

\dot{q}_{cond} [W/m^2] is the conduction through room enclosures and is calculated using the one-dimensional heat transfer equation of the Finite-Difference Approximation Method.

\dot{q}_{rad_sw} [W/m^2] is the incident short wave radiation (equation 13). This is the fraction of the transmitted solar radiation that enters the room through the transparent enclosures (windows) which is absorbed by the room enclosure. It can be divided between direct (\dot{q}_{sw_b} [W/m^2]) and diffuse (\dot{q}_{sw_d} [W/m^2]) radiation (see figures 8 and 9).

Figure 8 shows how the direct radiation enters the room through the window and hits a small part of the floor. This solar spot moves along the day with the sun changing the temperature of the surfaces. Following this process has high computational costs, so one of these three approaches are usually taken to solve this problem [23].

- Predefined distribution (60% to the floor and the rest is divided per area between the rest of surfaces)
- Approximated distribution (using correlations)
- Backward-ray-tracing method⁴

⁴For a better understanding see [24]

The distribution of transmitted solar radiation is calculated during the *Geometrical Preprocessing* accounting with the walls' absorptivity and as a result, the simulation model receives the direct and diffuse solar fractions (SF_{sw} [-]) on every enclosing surface.

$$\dot{q}_{rad_sw} = \dot{q}_{sw_b} + \dot{q}_{sw_d} \quad (12)$$

$$\dot{q}_{sw_b} = SF_{sw}^b \frac{\sum_{wi} g_{wi} I_{bi} A_{wi} f_{wi} (1 - f_{bi})}{A_j} \quad (13)$$

$$\dot{q}_{sw_d} = SF_{sw}^d \frac{\sum_{wi} g_{wi} I_{di} A_{wi} f_{wi} (1 - f_{bi})}{A_j} \quad (14)$$

I_{bi} [W/m²] and I_{di} [W/m²] are the direct and diffuse solar radiation at the window's tilt respectively, and include the effect of external shadows and reflections. These values are inputs to the building model and are calculated in the *Weather Preprocessing* step.

A_{wi} [m²] is the area of each window, f_{wi} their glass-frame ratio ($f_{wi} = 1$ would mean only glass), g_{wi} [-] their direct-beam transmittance at normal incidence and f_{bi} [-] the darkness factor due to blind devices ($f_{bi} = 1$ is completely dark).

Back to equation 9, the last term to be defined, \dot{q}_{rad_lw} [W/m²], refers to the internal long wave radiation. This radiation is calculated as (i refers to the cited surface and j to the rest of them in a given enclosed volume):

$$\dot{q}_{rad_lw} = E_i - \varepsilon_i \frac{\sum_{j=1}^n (A_j F_{ij} (E_j + (1 - \varepsilon_j) \overline{q_{rad}}))}{A_i} \quad (15)$$

Where:

$$E_i = \sigma \varepsilon_i T_i^4 \quad (16)$$

$$\overline{q_{rad}} = \frac{\sum_{i=1}^n E_i A_i}{\sum_{i=1}^n \varepsilon_i A_i} \quad (17)$$

$\sigma = 5.67 \times 10^{-8}$ [W/m²K⁴] is the Stefan-Boltzmann's constant, ε_i [-] is the emissivity of surface i and E_i [W/m²] refers to the radiant energy emitted by surface i .

The view factor F_{ij} [-] is the proportion of the radiation which leaves surface i that strikes surface j . The view factors are also calculated during the *Geometrical Preprocessing*.

It is also contemplated the special case of low time constant of enclosures, such as very thin walls or, most commonly, windows (time constant for windows around one-two minutes, the environmental conditions can thus be considered constant over the time response [25]). In that case, the enclosure can be simulated in steady state conditions and, therefore equation 9 gets simplified and the conductive heat transfer through the enclosure is calculated with the Fourier equation for steady state:

$$\dot{q}_{cond} = U_{tot} (T_i - T_o) \quad (18)$$

$$\frac{du}{dt} = 0 \quad (19)$$

Where U_{tot} [W/m²K] is the overall heat transfer coefficient of the enclosure, and T_i [°C] and T_o are the temperatures of the internal and external surfaces (either outside or an adjacent zone).

Therefore:

$$0 = \dot{q}_{conv} + U_{tot} (T_i - T_o) + \dot{q}_{rad_lw} + \dot{q}_{rad_sw} + \dot{q}_{IGrad} \quad (20)$$

5 Model validation

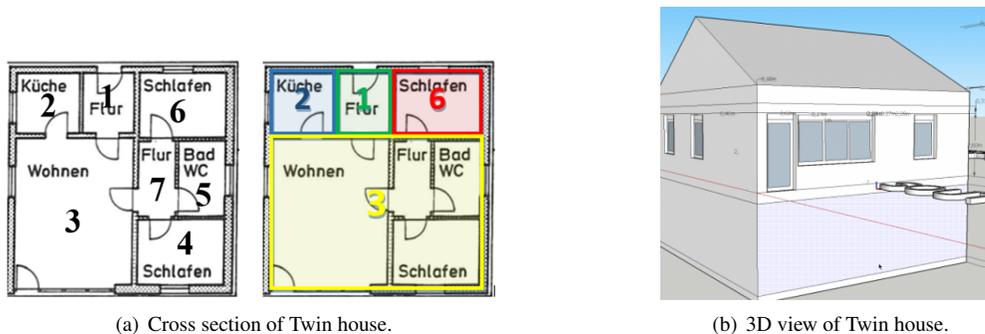
The dynamic building model has been validated using the a real full building scale experiment carried out within the scope of IEA Annex 58 subtask 4 "Reliable building energy performance characterisation based on full scale dynamic measurements", at the Fraunhofer test site (Holzkirchen, Germany). The experiment is fully explained in the Report of

Subtask 4a [26]. It provides also a collection of results from more than 20 modellers that used the experiments to compare with their predictions.

It was undertaken on two buildings with identical constructions, the so called Twin Houses N2 and O5 in Holzkirchen, Germany. The experiment, conducted in August and September 2013 was a side-by-side experiment, with external roller blinds down on the south facing windows of one building (N2) and fully up on the other (O5). A high mechanical ventilation rate was used. The heating system used was electric convector heaters.

Each twin houses have seven rooms. The three facing North (Küche –room 2–, Flur –room 1– and Schlafen –room 6–) are completely isolated from the others by sealing the doors. The Southern rooms (Wohnen –room 3–, Flur –room 7–, Bad WC –room 5– and Schlafen –room 4–) are connected through the doorway and a mechanical ventilation was installed with a supply point in the north-west corner of room 3 and two extract points in the south-east corners of the rooms 4 and 5 respectively. Therefore, they were modelled together as a single room.

Figure 5 shows the cross section of Twin houses and the simplification carried out in the model.



To compare the results of room 3 it has been used the mean temperature of rooms 3, 4, 5 and 7. [26] describes how the temperature sensors show an stratification of the temperatures inside the rooms of more than 2°C from floor to ceiling, considering then an error of $\pm 1^{\circ}\text{C}$ to show a good estimation of the mean temperatures.

The temperature and temperature errors measured in $^{\circ}\text{C}$ can be seen in figures 11, 12, 13 and 14, presenting a good agreement most of the time. A special moment must be commented, when around hour 580 the heaters turn on after a free-floating period, where the errors become much higher than expected. If zooming the experimental data at different heights a much bigger difference than the 1°C accepted can be observed. Therefore, the difference of around 3°C between measured and calculated temperatures at that specific point has also been considered success (see figure 10).

6 Conclusions

A dynamic building model was developed to be used for modelling large numbers of buildings in urban environments in a fully automated workflow.

The validation of the dynamic building using a real building scale experiment provided very good results in general, although during some periods the errors exceeded the maximum permitted.

Nevertheless, when comparing the results with the other simulation model results provided in the Report of the IEA task 58 Subtask 4a [26], the model presented in this paper seems to be amongst the best.

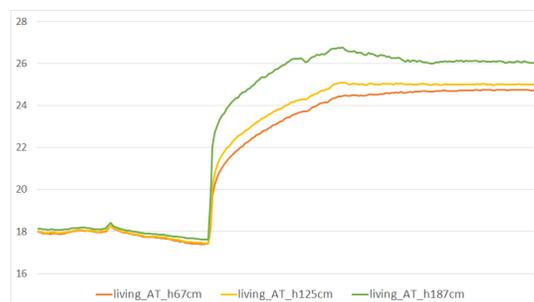


Fig. 10. Temperatures at different heights in the living room.

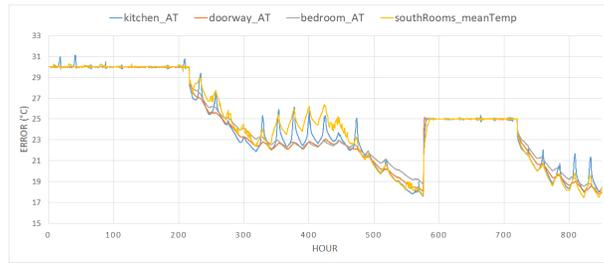


Fig. 11. Temperature blinds down.

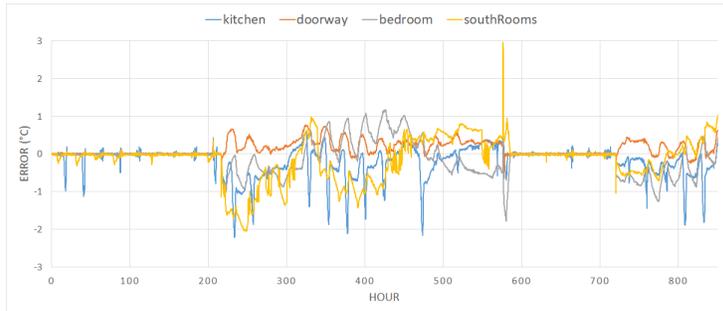


Fig. 12. Temperature errors blinds down.

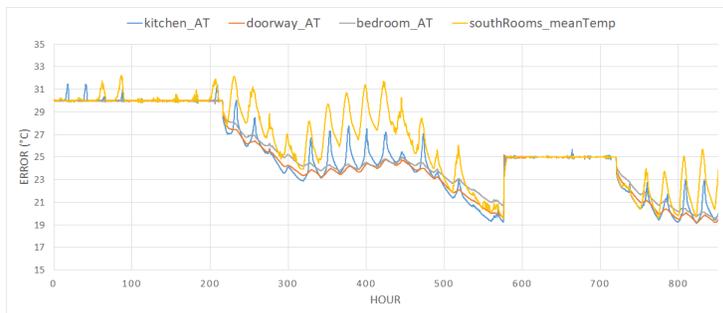


Fig. 13. Temperature blinds up.

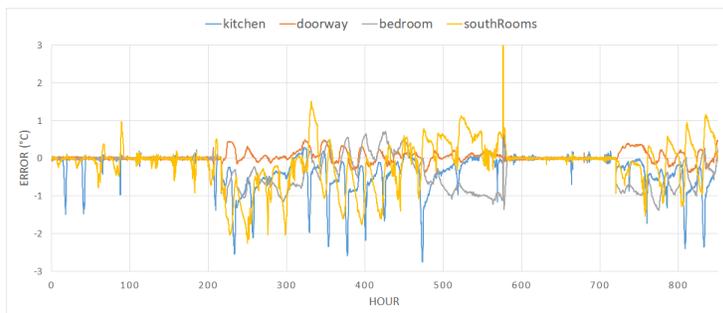


Fig. 14. Temperature errors blinds up.

The experience in urban energy modelling using 3D city models will be feed back into the CityGML standardization. Some missing concepts in CityGML for urban energy simulation such as storey height and number of storeys will be part of CityGML 3.0 (under development). Also the concept of Level of Detail will change in CityGML 3.0 to allow indoor modelling of a building in LoD 1, LoD 2, and LoD 3, which will allow a more flexible modelling approach. For instance, a LoD 2 building model may have rooms modelled as simple boxes.

The validated dynamic building model can be used for urban neighbourhood load modelling, allowing to analyse the potentials of demand response and passive storage activation.

Acknowledgements

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