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Abstract
This work presents the creation of a dynamic energy model able to simulate, with a reasonable workload, a very large number of integrated building-plant systems with different scales and resolutions, in order to have a design support for architects and designers, reducing their modeling effort and errors. The model includes the dynamic simulation of the building envelope, all the heating plant subsystems, and all the plant components relating to the production of domestic hot water, the latter with possible solar thermal integration.
Starting from a detailed model created with the calculation engine Trnsys, the paper explores simplifications that can considerably reduce the number of necessary inputs for the simulations, thus minimizing the modeling, implementation and simulation runtime of the model, while still maintaining an acceptable degree of accuracy with respect to the computational results and real energy consumptions. The model is benchmarked by means of a case study comprising three different residential apartments with very high thermal performances, subjected to a complete monitoring of all energy consumption. The results show that the accuracy of the integrated model is within 16% of the real monitored consumptions, even for extreme cases such as the one presented.

Keywords: dynamic energy simulation, building and plant energy performance, decision tool.

1 Introduction

The daily operation of commercial and residential buildings is responsible for roughly one-third of the world's primary energy consumption. Because buildings are typically operated for many years, there is great potential for reducing global energy needs through the design of more energy-efficient buildings (Urban et al., 2006).

Computer modeling and simulation is a powerful technology for addressing some of the many interacting architectural, mechanical, and civil engineering issues in buildings. Building Performance Simulation (BPS) can help in reducing greenhouse gas emissions and in making substantial improvements towards lower fuel consumption and higher comfort levels, by treating buildings and their thermal systems as optimized entities, and not as the sum of a number of separately designed and optimized sub-systems or components (Hensen, 2011). Experience with real buildings has shown that low-energy design is not intuitive and that simulations should therefore be an integral part of the design process (Hayter et al. 2001).

In fact, the efficiency of energy conservation measures cannot be studied in isolation because the interaction between components can have a substantial effect on the efficiency of each individual component. The impact of climate conditions and occupant behavior add to the complexity and make it almost impossible to predict performance without use of computational tools (de Wilde and Augenbroe, 2009).

However, architects and designers are still finding it difficult to use even basic tools (Punjabi et al., 2005). Findings confirm that most BPS tools are not compatible with architects' working methods and needs (Attia et al., 2009; Gratia et al., 2002), and even when simulation experts are part of the design team, modeling efforts and analysis of results typically are out of sync with the dynamics of the rest of the design process, leading to integration issues.

On a generic level, needs related to the design process can be easily identified as time and accuracy. Accuracy is an essential prerequisite for every analysis used for decision-making and becomes significantly more relevant during the design process of buildings, where decisions taken can have serious implications for future energy use and can affect building performance and operation for a large number of years. Accurate energy analysis requires time but this is in contrast with the necessity to minimize the time requirements to make it compatible with design times. A way to reduce time requirements could be the introduction of default values and databases for inputs, with the possible risk of reducing the model detail level and degree of freedom, themselves influencing the accuracy or relevance of the final result (Picco et al., 2013). In the context above, the research presented in this paper defines the creation of a configurable dynamic energy model able to simulate, with a reasonable workload, a very large number of integrated building-plant systems with different design scales and resolutions, including the dynamic simulation of the building envelope, all the heating plant subsystems, and all the plant components relating to the production of domestic hot water. This integrated and dynamic simulation model allows various simulations to be more easily initiated at various stages of design, instead of being used only in the final step of design validation, when most decisions concerning the building have already been made.

The objective of the work presented in this paper is to explore the main features of the model and to show its application to three different residential apartments characterized by very high energy performances and monitored energy consumptions, comparing the latter with the ones coming from the simulations.

2 Integrated and dynamic building – plant system model

The first step of the work has been the creation of an "adaptable and dimensionless" detailed and integrated dynamic building-plant system model.

The calculation engine used for this purpose is Trnsys (Trnsys version 17.00.0019). The model, as previously defined, allows the simultaneous simulation, for a maximum number of 15 different heated thermal zones, with detailed representation of the building envelope, heating plant (with all subsystems), and the hot domestic water systems. If needed, additional thermal zones can still be simulated with an "ideal load" approach.

In the specific Trnsys3D tool, a three-dimensional representation of the entire building can be created, as well as all relevant shadowing objects comprising all the adjacent building structures and the specific solar obstructions.

To characterize the various zones, each one is defined in terms of materials and layers of walls and windows, thermal bridges, internal gains, temperature set-points, heating schedule, external and boundary conditions. To define these items, the TRNBuild tool is used, which is the Trnsys tool specifically dedicated to the characterization of the building envelope.

The dynamic operation of the heating plant and the domestic hot water system are modeled through the Trnsys components called "Types", all connected according to an input – output logic (Fig.1).

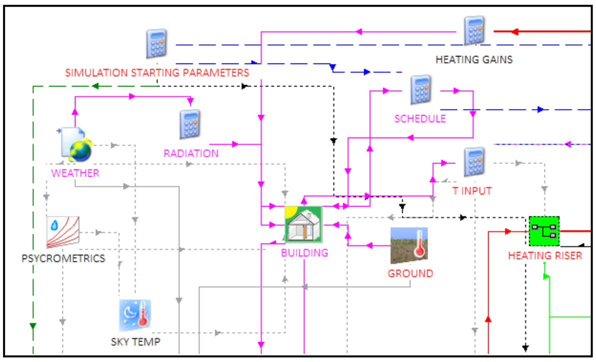

Figure 1 Extracted view of the Trnsys HVAC model

Within Trnsys each Type can be considered as a "black box", which processes input data as a function of defined algorithms, starting from user-defined parameters, and producing output data. The task of each Type is to solve simple problems, and their interconnection allows the user to study higher-level issues.

In the model described here, each Type corresponds to a single component of the building plant.

The hydraulic base system scheme that is simulated by the integrated model can be divided into two main different constituent parts or sub-systems:

- Sub-system A: this represents plant configurations composed of only one single generator with internal Domestic Hot Water (DHW) heat exchanger, for DHW and/or heating (H).

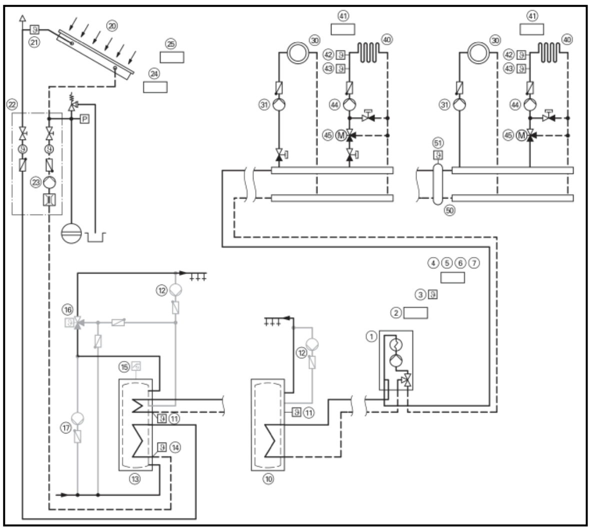

Figure 2 Sub-system A

- Sub-system B: this represents plant configurations composed of one or multiple generators with external DHW heat exchanger, for DHW and/or heating (H).

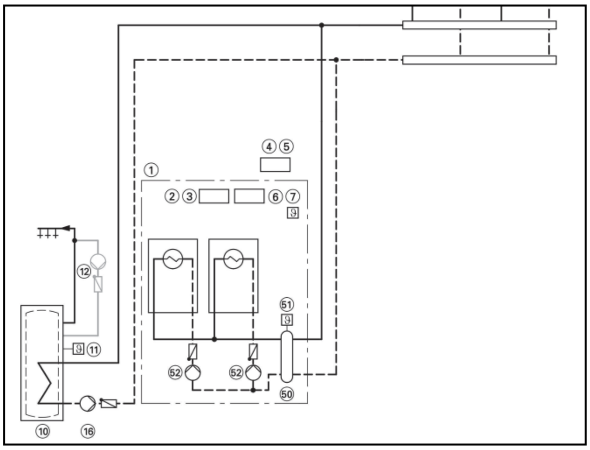

Figure 3 Sub-system B

Table 1 Hydraulic base system schemes

			DOMESTIC HOT WATER (DHW)					
		No HDW	Instantaneous production: No solar integr. – Priority	Instantaneous production: Solar integr. – Priority	Storage production: No solar integration – Priority	Storage production: No solar integration – No priority	Storage production: Solar integration – Priority	Storage production: Solar integration – No priority
	No HS	/	A1	A2	A3	/	A4	/
HEATING SYSTEM (HS)	Direct HS	A5	A8	A11	A14	/	A17	/
	Hydraulic separator HS	A6	A9	A12	A15	/	A18	/
	Storage HS	A7	A10	A13	A16	/	A19	/
	Direct HS & DHW	B1	/	/	B4	B7	B10	B13
	Hydraulic separator HS & DHW	B2	/	/	B5	B8	B11	B14
	Storage HS & DHW	B3	/	/	B6	B9	B12	B15

In the two schemes there can be, for the domestic hot water:
- Instantaneous production, with priority;
- Storage capacity, with or without priority;
- Solar integration;

For the Heating system, there can be a:
- Heating system without hydraulic separator, in other words: a direct loop from the generation;
- Heating system with hydraulic separator or storage (the heating storage can replace the hydraulic separator in Fig.2 and Fig.3);

All these possible simulation combinations are summarized in Table 1, generating an option space that consists of 34 different system schemes starting from only one dynamic and integrated Trnsys model.

As specified above, the model is highly “adaptable” because the 34 different base system schemes can be split into a lot of other different combinations. In fact each scheme is suitable to have the following variations:
- for the emission and internal control subsystems the base model still allows flexible simulation of the behavior of radiators, radiant panels, fan coils, district heating heat exchangers, and variation between On-off, P, PI or PID control;
- for the distribution subsystem there can be different pipe lengths, materials and insulations, with the fluid moved by pumps with fixed or variable speed, the latter with control at constant or proportional pressure;
- for the storage subsystem there is the possibility to change volumes, internal heat exchanger properties, and stratification effects;
- for the generation subsystem the simulation allows for variation of one or multiple cascade/ integrated generators, with different generator types, like boiler supplied with traditional or renewable fuels, heat pumps, cogeneration systems;

The model can also be defined as “dimensionless” due to its adaptability (thanks even to the sizing and simplification protocols described later) to three different design scales, each characterized by a different "resolution", intended as the ability of the model to group multiple components into a unique one, especially for the emission subsystem.

In fact it can be used in the following three design conditions:
- Small scale and high resolution design, for the simulation of an independent apartment, commercial unit or building floor, where each thermal zone is composed of only one room and where each real emission device is individually simulated;
- Medium scale, for the simulation of an apartment building or a multi-floor building, where each thermal zone is respectively equal to one apartment or one floor and where the real emission devices are summarized and simulated with only one emission device with equivalent features;
- Large scale, for the simulation of district heating, where one thermal zone is equal to one building and its emission device is the district heating heat exchanger;

In conclusion, the single detailed dynamic model provides a starting point for a range of simulations at different levels of scale and resolutions.

3 Sizing and simplification protocols

The model described above represents the highest degree of simulative details with a high number of outputs made available at each time-step (up to about 1700 outputs), from the operating temperatures in all components to the unsteady heat balance regulating each component and the cumulative efficiencies of the various sub-systems installations. It allows to check the actual operation of the entire dynamic building-plant system at any variation of all possible internal and external conditions, taking into account each instant the interaction of all the components.

On the other side a large number of parameters and inputs has to be set for the simulations. In fact, the most detailed model is composed by a total number of 221 types, with about 1400 parameters and 1150 inputs required to describe their features.

In order to reduce the number of necessary variables for the simulations (note that the input-output connections of the types reduce themselves the variables to be set roughly to the number of parameters only), to minimize the modeling, implementation and simulation runtime of the model and to extend it to all the design scales, a “sizing protocol” and a “simplification protocol” have been created.

The “sizing protocol” is composed of a spreadsheet able to do the complete sizing and characterization of all TRNSYS Types used for the plant components, starting from the user's loads (the "ideal" heating load can derive from a dynamic simulation carried out only for the building envelope), going through a stationary plant design and ending with the highlighting of all inputs and parameters required by the detailed and integrated dynamic model.

The "simplification protocol" is composed of the following two possible simplifications:

- S1: Building envelope simplification;
- S2: Heating plant simplification;

Starting from the first (S1), the whole simplification process is composed by eight consecutive steps to generate a simplified model from a detailed model (Fig.4), where each step tackles one major aspect of the building model description.

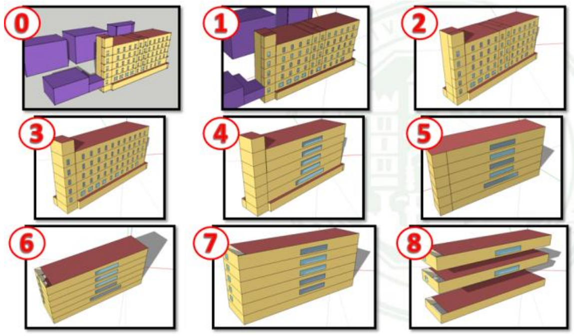

Figure 4 Building envelope simplification

It is divided into the following steps:

- Step 1- Simplified construction: reduction of the number of constructions to only 6 archetypes reflecting the average transmittance of each type of dispersant surface considered for the whole building
- Step 2- Removal of external obstructions: elimination of all the external shading elements modeled;
- Step 3- Zone lumping: characterization of each floor of the building with one single thermal zone.
- Step 4- Simplified transparent surfaces: modeling, for each floor, only one window for each cardinal direction that considers all of the windows present in that direction;
- Step 5- Single floor standardization: elimination of all accessory areas and defining of all zones (floors) with a single geometry. Zone parameters and internal gains are also made constant with the exception of underground and under-roof floors, if present.
- Step 6- Squaring zone: definition of each zone as an element composed of only six surfaces, making up a box (the main information to maintain as close as possible to the full model are the dispersant surfaces).
- Step 7- Standardization of fenestrations: characterization of all the windows facing one direction by the same parameters regardless of the floor, always considering all of the windows present in that direction.
- Step 8- Number of modeled floors: Reduction of the model to a minimum number of floors by allowing the creation of 3 zones only for any type of building (with the exception of the unheated underground and under-roof floors, if present), simulating the remaining as a multiplier of the above.

This first simplification process has been already tested and validated by Picco et al (2013) for different kinds of buildings, featuring differences always within the margin of 20% between the most detailed model and the most simplified model and a large decrease of the work load related to the building modelling (from days to hours).

About the heating plant simplification, three different simplifications has been identified:

- S2.1- Internal control with external energy input: this simplification involves the replacement, in the detailed model, of the component related to the simulation of the building behavior with a type constituted by an external data file that gives, at each time-step, the ideal thermal useful energy demand of each zone considered.

The latter, coming from a dynamic simulation carried out only for the building envelope, represents the new external input of the environmental control subsystem, no longer based on the internal temperature of the zone, assumed equal to the set point temperature as boundary condition for the emission subsystem.

- S2.2- External efficiency for emission and control subsystems: this simplification allow to characterize all the different kinds of emission and control subsystems only with their constant or variable efficiency, derived from standard values universally adopted.
- S2.3- Heating plant resizing: the reduction of a certain number of real zones to a single thermal zone coming out from the first simplification process S1 is necessarily accompanied by a new sizing of the plant, in particular of the emission and distribution

subsystems, now sized starting from the sum of the loads related to the real zones.

The whole simplification process has been already tested for a small scale design consisting of a residential unit located in a semi-detached existing house, subjected to a renovation design (Beltrami et al. 2015).

The model, composed of seven different thermal zones or rooms and the base system scheme A7, has been used for the development of the most detailed model and for the application of the simplification protocols to a small scale case study with common concrete structure and medium energy performances.

The results indicate the accuracy of the most simplified model in terms of energy needs, power curves and subsystem efficiencies is very high, with a difference from the most complete analysis always below the 12% for all the output parameters and with a workload for the preparation of the model and the simulation reduced to one half (from six days to three days) and equal or even less than the time necessary to perform a complete traditional stationary simulation.

4 Case study

This paper applies the generic model to a specific, challenging case study: a recently built apartment building in the UK which has been designed to high energy efficiency standards, and which is subject to monitoring. This allows the validation of the model with a high performance building, making sure this is able to represent advanced dwellings. The availability of metered data provides a baseline for validation which is not available for any hypothetical cases.

In fact the case study consists of a recently built apartment building comprising 15 flats, three of which subjected to a complete monitoring of all energy consumptions and activities.

In particular the dynamic simulations have been carried out for the whole building-plant system of each of this latter three single units, with a small scale design (each room equal to one thermal zone) and a base system scheme A5.

Following the description of the case study and the achieved results.

4.1 Building description

The building studied is an apartment building comprising 15 flats, built in 2012 and situated in Torquay, UK.

The building consists of four floors, the basement for the car park, ground, first and second floors intended for residential purposes and each composed of five apartments along a central hallway (Fig.5).

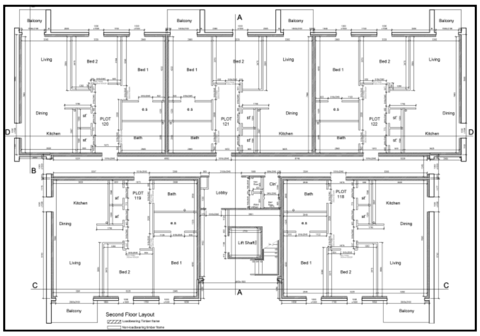

Figure 5 Building second floor plant

The whole building is characterized by a net total floor area of 1921 m^2 and a net total volume of 5255 m^3, while each apartment has 8 heated rooms, a useful floor area of 77 m^2 and a net total volume of 208 m^3.

The building has an innovative steel-wood structure able to reduce thermal bridges and especially construction times. The building layers are also uncommon, designed to have the best thermal, hygrometric and acoustic performances.

In particular, the dispersant surfaces have been designed in order to have high thermal and hygrometric performances.

In fact all the surfaces are composed by several different layers and materials, with a transmittance equal to 0.10 W/m^2K for the external walls, 0.11 W/m^2K for the external ceilings, 0.13 W/m^2K for the external floors, 0.55 W/m^2K for the external doors and 1.2 W/m^2K for the external windows or transparent surfaces.

In addition, the internal partitions have been designed to have the best acoustic performances, based on the so called "Robust details", an online handbook that brings together the best layers in terms of acoustic performances, already tested and recognized by the English building legislation.

The separating walls and floors are composed by multiple layers and they have low transmittance, equal to 0.21W/m^2K and 0.18 W/m^2K respectively. The HVAC plant provided for each apartment is composed by an independent mechanical ventilation system (whose main aim is to ensure proper air change in the winter season and to avoid overheating during the summer) and an independent aluminium radiators heating system, powered by a 28kW combined condensing natural gas boiler, used even for the instantaneous production of the domestic hot water.

A climate control for the supply temperature of the heating plant is provided, together with an internal regulation composed by thermostatic valves able to reduce or increase the flow rate of the heat transfer fluid to the radiators. All the isolated distribution network piping is placed inside the heated environments in order to reduce losses to a minimum value.

As previously specified, three apartments of the building, situated on the second floor, have been subjected to monitoring of energy consumptions and activities.

In particular, in addition to the outside temperature and relative humidity, for each apartment the following data, with a five minutes timestep, have been monitored:

- Occupancy (with Passive InfraRed sensor) of central hallway and living room;
- Window opening in main and second bedroom;
- Balcony door opening in living room;
- Temperature and Relative Humidity in living room and main bedroom;
- Total gas and electricity consumptions;

Even if the apartments have the same dimensions, structural, thermal and HVAC features, and even if the consumptions are very low respect when compared with a standard residential unit, the occupant's influence during the real management of the apartment is very high, as shown by the monitored gas consumptions for the heating system, completely different for the three users (Fig.6).

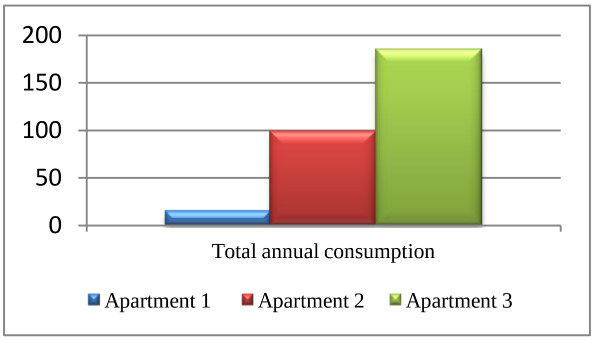

Figure 6 Total monitored gas consumptions (m^3)

4.2 Simulations

In order to apply the integrated and dynamic building – plant system model to the three apartments with monitored data, the three-dimensional modeling of the entire building has been created, as shown in the following Fig.7. In particular every room has been modeled for the three apartments while only one thermal zone has been created for the other apartments and boundary zones.

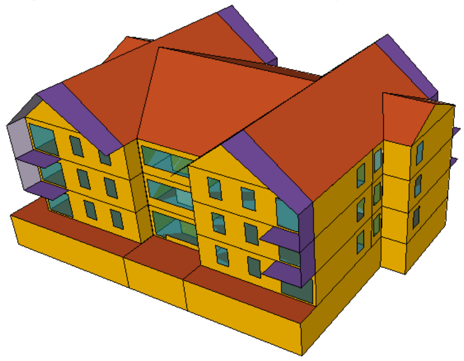

Figure 7 Complete model for building envelope (Trnsys3D)

After, the characterization of the entire building envelope in Trnbuild tool has been performed and finally three different dynamic simulations have been carried out, each one applying the integrated model only for one apartment, simulating the others boundary thermal zones only with an "ideal load" approach (i.e. no HVAC systems really simulated).

In particular the main assumptions done in the whole process has been the following:

- Plymouth 2002 weather file has been used (the closest available weather file), correcting it with the real temperature and relative humidity coming from the monitored data.
- Set point temperature for the heating system of each apartment equal to the average internal temperature monitored in the same unit (for the three apartments) or equal to the global average internal temperature monitored (for the other apartments);
- Solar factor or g-value of all the transparent surfaces equal to 0.265 and internal shading devices able to considerably reduce the external solar radiation fraction directly transmitted to the internal environment;
- Continuous air change due to infiltrations equal to 0.06/h and increase of the latter to 0.15/h when the inside temperature is higher and the outside temperature is lower than

the one monitored, in order to reflect the real opening and closing of the external doors and windows.

- Continuous air change volume due to the mechanical ventilation, for all the apartments except the apartment 3, equal to 85.1 kg/h, and increase of the latter to 170.2 kg/h in the summer. For these apartments the temperature of the incoming air in the winter season is equal to the one coming from an heat recovery with an efficiency of 87%, while in the summer season is equal to the one coming either from the heat recovery or directly from the outside, when the conditions for the activation of the heat recovery bypass are satisfied (note that air change volume, heat recovery efficiency and bypass logic have been derived from the constructor details);
- Continuous air change volume due to the mechanical ventilation, for only the apartment 3, equal to 170.2 kg/h, both in the winter and in the summer season. For this apartment the temperature of the incoming air is always equal to the one coming either from the heat recovery or directly from the outside, the latter when the conditions for the activation of the heat recovery bypass are satisfied (in this case the temperature set point for the activation of the bypass is supposed lower than the same for the others apartments in order to permit the bypass to be activated even in the winter season);
- Internal electric gains of each apartment equal, for the three apartments, to the total electric consumptions monitored in the same unit, minus the energy related to the electric showers, whose activation is supposed for the monitoring timesteps with higher consumptions. For the other apartments the internal electric gains are supposed equal to the average of the three above.
- Internal occupancy provided, for each apartment, only for the two thermal zones with PIR sensor, the central hallway and the living room. When the PIR sensor has registered a positive occupation of the area during the monitoring timestep, it has been supposed to have one person in the hallway and two people in the living room.

As for the other variables the occupancy on-off value for the three main apartments derives directly from the monitored data, while for the other apartments an average value of the latter is provided.

- The monthly gas consumption of the three main apartments, used to compare real and simulations results, is directly derived from the monitored data, removing from the global monthly consumption the one related to the domestic hot water, this equal to the average gas consumption of the summer months (from May to September);
- Applying of the integrated and dynamic building – plant system model to the three apartments with monitored data with the adoption of the heating plant simplifications S2.1 and S2.2 and recovery of all the losses and internal energy changes related to the distribution subsystem because the isolated distribution network piping is placed inside the heated environments.

4.3 Results

Due to the high number of available outputs, the comparison between the simulation results and the monitored data has been restricted to the output parameters able to describe the main thermal behavior of the building. So, the comparison has been proceeded, for each of the three apartments, for:

- Trend of the average internal temperature during the winter season (controlled temperature) and during the summer season (temperature controlled only through the mechanical ventilation);
- Monthly gas consumption for heating;

The results are the following:

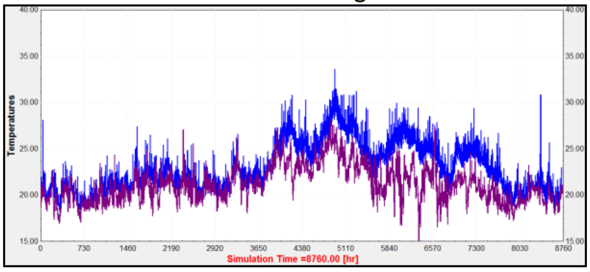

Figure 8 Apartment 1 internal monitored (violet line) and simulated (blue line) average temperature (°C).

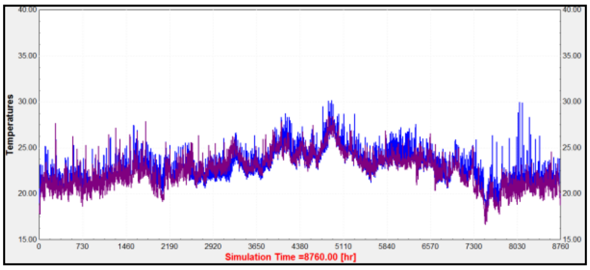

Figure 9 Apartment 2 internal monitored (violet line) and simulated (blue line) average temperature (°C).

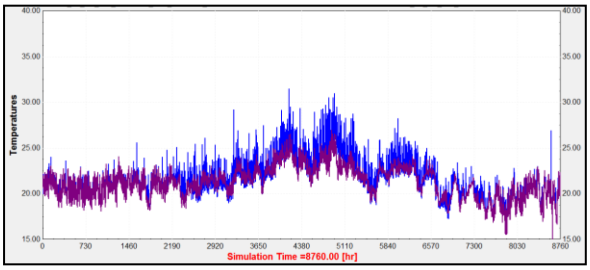

Figure 10 Apartment 3 internal monitored (violet line) and simulated (blue line) average temperature (°C).

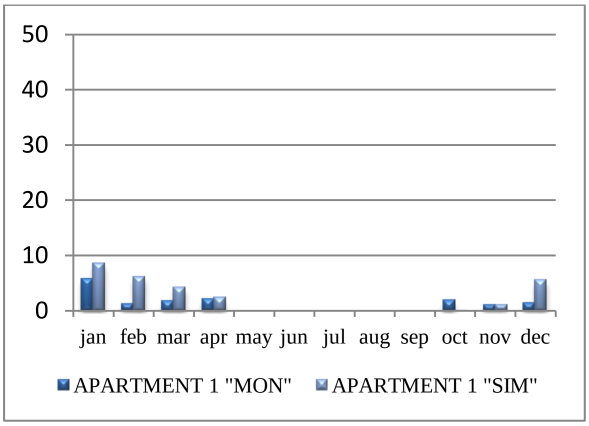

Figure 11 Apartment 1 monitored (“MON”) and simulated (“SIM”) monthly gas consumptions (m^3).

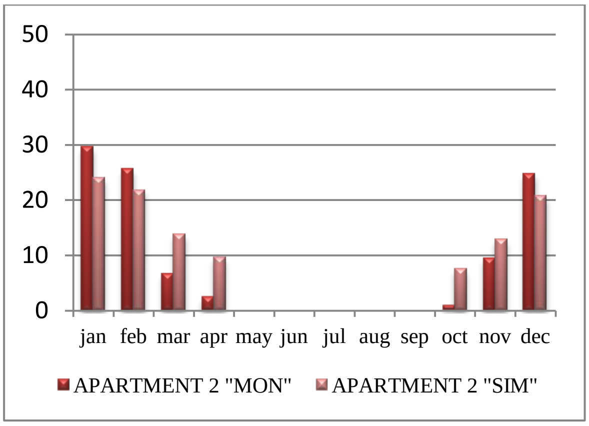

Figure 12 Apartment 2 monitored (“MON”) and simulated (“SIM”) monthly gas consumptions (m^3).

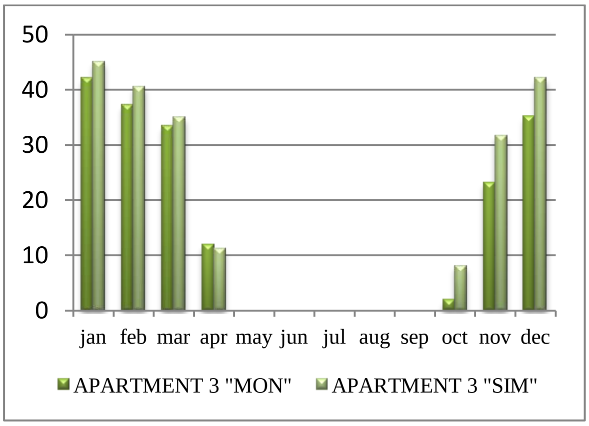

Figure 13 Apartment 3 monitored (“MON”) and simulated (“SIM”) monthly gas consumptions (m^3).

It can be stated that:

- The simulation trend of the average internal temperature during both the winter and the summer season reflect in a very reliable way the same as in the monitored data, especially for apartments 2 and 3.

Only for the first apartment the simulation sometimes overestimates the internal temperature.

- Even the trend of the monthly gas consumption between the simulated and monitored data is similar for all of the apartments. In particular the average annual consumption coming from the simulation is 11% overestimated compared to the real one for the apartment 2, while 16% overestimated for the apartment 3. The percentage overestimation of the gas consumption for the apartment 1 is higher but it doesn’t matter because the consumption of that unit is practically zero both in the monitoring an in the simulations.

Then taking into account that:

- The simulated building is characterized by very high thermal performances and low energy consumptions (the gas consumption for heating of the apartment 3 is approximately equal to one-tenth of that for a common residential unit);
- The heat balance that describes each unit is very sensitive even to small variations of each component, from the different solar gains due to different exposures to the presence or absence of people, the management of the electrical equipment and to the different possible adjustments of all HVAC components;
- The apartments are indeed characterized by very different consumption from each other, showing how the occupant's influence during the real management of the apartment is very high;
- Nonetheless the assumptions made for the applying of the dynamic simulations have been extended without distinctions to all apartments;

the results obtained through the application of the dynamic and integrated model can be considered excellent as the latter is able to predict the behavior of the whole building-plant system for extreme cases such as the one presented above.

5 Conclusions

This paper presents a detailed simulation model of actual dwellings in the UK, which can easily be configurated to study a range of design alternatives (both in terms of systems and system attributes) throughout the design process of building plants for similar buildings.

In particular the “adaptable and dimensionless” integrated model described in the paper is able to provide a complete energy simulation with a very high accuracy and a workload equal or even less that the time necessary to perform a complete stationary simulation for an high number of different building-plant systems in different design scales and conditions.

In fact the model has been developed to help architects and designers to adress time/accuracy issues , both in terms of quality and low engineering costs.

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