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Parallel Object-Oriented Algorithms for Building Performance Simulation. Application to an existing dwelling.

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ABSTRACT

In the present work an existing dwelling, situated in the Netherlands, has been modeled by means of a parallel object-oriented simulation tool called NEST-Buildings. The model is based on a pre-defined collection of elements (e.g., walls, rooms, openings, outdoors, occupants, ventilation tubes and boxes, solar radiation distributors, HVAC equipment, etc.) that are connected to each other composing a dynamic thermal system. New configurations can be easily handled by adding or removing elements. Moreover, the building elements can be modeled at distinct levels of accuracy ranging from lumped volumes mixed with one-dimensional to detailed CFD&HT models. This approach makes possible the assessment of general-type buildings (residential, services, old, modern, etc.) using the appropriate modeling level at each component. The work is focused on the global resolution algorithm currently implemented in this computer simulation tool.

1. INTRODUCTION

New policies are progressively converging to nearly zero energy standards. Zero net energy buildings, commonly known as ZEB (Marszal 20011, ACEEE 2015), combine high levels of energy efficiency with renewable energy systems (solar, biomass, windmill, etc.) to offset the energy delivered to the building over the year. The EISA 2007 specifies a zero-energy target for 50% of US commercial buildings by 2040 and for 100% of them by 2050 (US Congress 2007). In Europe, the new regulations seeks nearly ZEB target for all public buildings by 2018 and from 2020 for all new public buildings (EU 2010, 2012). In this regard, architects and engineers should be able to use appropriate tools for assessing the energy consumption in buildings. Experimental methods based on in situ measurements are not only challenging and expensive but they are normally not feasible because of the space usage (residential, hospitals, hazardous environments, etc.). Alternatively, computer simulation software is much more affordable. Buildings performance can be evaluated by means of virtual designs providing a lot more flexibility.

The main challenge in building simulation is the non-linearity of the mathematical model that rules the physical phenomena. Transient heat transfer by conduction, convection and radiation is mixed with moisture and air flows between the outdoor environment and the inside of the building and between the distinct zones, too. All these phenomena are driven by the effect of the weather conditions (sun irradiation, rain, wind, etc.) and the surrounding elements (orientation, other buildings, trees, etc.) on the building through the envelope (walls, panes, roof, soil, etc.), the openings and the infiltrations. In addition, there is the action of the non-natural events such as the HVAC systems or the occupants themselves. Hence, the simulation of buildings at this level requires the use of *i)* highly flexible software tools and *ii)* well though-out system resolution approach in order to succeed within a reasonable time.

The present work has been developed within the "Dwelling Climate Control System (DCCS)" project (DCCS 2013-2016), one of its main objectives is to develop an affordable, easy to use and apply, integral dwelling climate control system in order to reduce the energy use of buildings and improve the air quality by optimizing the parameters of the heating and ventilation systems. For the achievement of such objective, a real dwelling (a semi-detached house in the Netherlands) has been chosen and has been modeled by means of a parallel object-oriented simulation tool called NEST-Buildings. That *virtual building model* has been used as a test bench for the testing of the developed control system. The model is based on a pre-defined collection of elements (e.g., walls, rooms, openings, outdoors, occupants, ventilation tubes and boxes, solar radiation distributors, HVAC equipment, etc.) that are connected to each other composing a dynamic thermal system. New configurations can be easily handled by adding or removing elements. Moreover, the building elements can be modeled at distinct levels of accuracy ranging from lumped volumes mixed with one-dimensional to detailed CFD&HT models. This approach makes possible the assessment of general-type buildings (residential, services, old, modern, etc.) using the appropriate modeling level at each component.

2. NEST-BUILDINGS

2.1 Code description

NEST-Buildings (Damle 2011, López 2016) is a parallel object-oriented code for building performance simulation. The overall model is based on several predefined classes that provide abstraction of the involved physical phenomena, equipment, boundary conditions and events. For illustrating this, the sketch of a house (walls, windows, outdoor, radiation element, rooms, ground, etc.) and its corresponding NEST-Buildings conceptual graph view is shown in Figure 1. A description of each of these concepts is provided in Table 1 as well as the all possible connections among them.

Therefore, the elements can be linked to each other to form a specific building or room configuration. This makes easy to create new configurations by adding or removing elements to/from the overall model. Each element can be represented in any form as long as it can exchange the necessary boundary information from the rest of the elements in the system. Such an approach gives flexibility of choosing a model for each element and having different levels of modeling (lumped volumes, 1D, CFD&HT...) for different elements in the system without changing the basic program structure. Furthermore, the numerical calculations can be easily done in several parallel processes as the models are uncoupled to each other at code level.

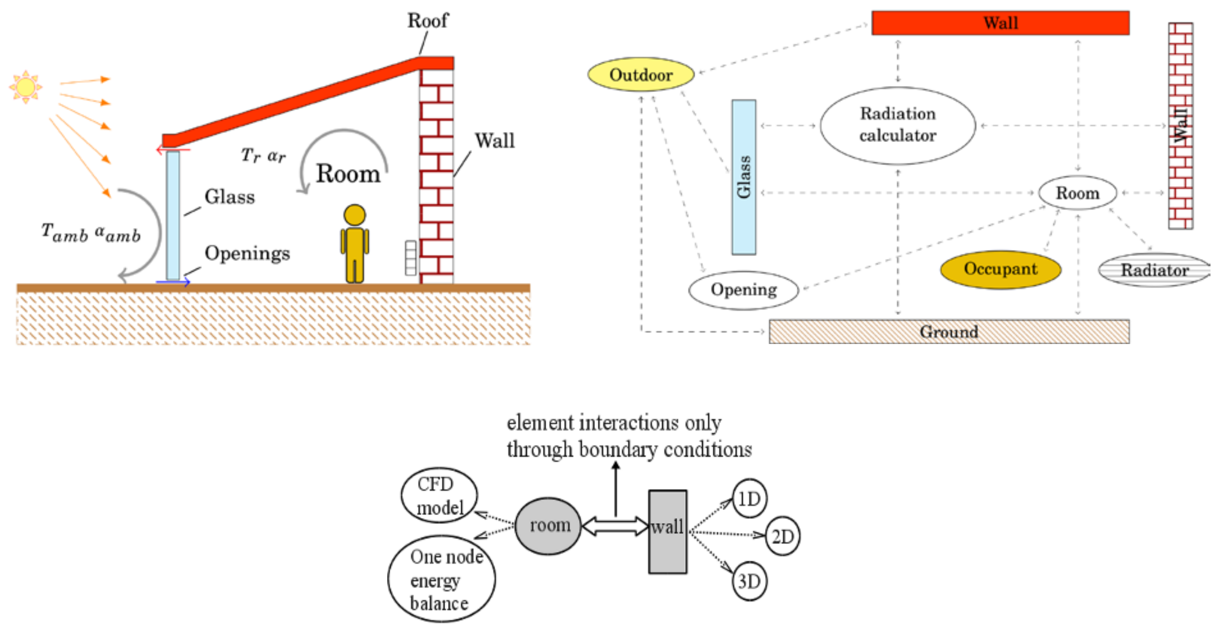

Figure 1. (top-left) Scheme of a room. (top-right) NEST views the system as a vertex-edge graph. (bottom) Flexibility in choosing individual elements models.

Table 1. Summary of the elements (classes) developed for NEST-Buildings.

Elements/Classes	**Elements Description**	**Possible Connections**
Outdoor	Weather database manager depending on building location.	Wall, Glass, Opening
Wall	1D Heat conduction and moisture transport is solved. Heat convection, thermal radiation and solar gains can be considered at the boundaries.	Wall, Outdoor, Room, RadBox, SolarDistributor
CompWall	Sub-system composed of multiple Wall layers of different materials.	Wall, Outdoor, Room, RadBox, SolarDistributor
Glass	Wall-like object with optical properties (e.g. solar radiation transparency).	Glass, Outdoor, Room, RadBox, SolarDistributor
MultiGlass	Sub-system composed of N Glass objects and N-1 Rooms (air chambers), e.g. double glazing	Outdoor, Room, RadBox, SolarDistributor
Room	Lumped volume with mass, moisture, energy and CO_2 balance.	Wall, Opening, HVAC, SolarDistributor
RadBox	Solves thermal radiation based on view factors of a given number of walls.	Wall, CompWall ,1)Glass, MultiGlass,
SolarDistributor	Distributes the transmitted solar radiation uniformly to room walls.	Wall, CompWall ,Glass, MultiGlass, Outdoor
HVAC (radiator, TRV, mechanical ventilation)	Controls the heating and ventilation of rooms.	Room
Opening	Air movement between rooms and outdoor due to density differences. Infiltrations are also managed ~~here~~ small Openings.	Room, Outdoor
Occupant	This includes people behavior (heat, moisture and CO_2 generation) into the simulation. People events are managed by means of Schedule objects.	Room
Schedule	Manages events that produce the Occupants or the controller devices.	Not a system element

2.2 Algorithm for solving the overall model

The resolution scheme of the overall model is based on a block-Jacobi like method. During this procedure, every element of the system is visited to call the resolution routines of their particular sub-models. After this, each element changes its state (e.g. room temperature, CO_2 concentration, doors and windows mass flows, radiators heat output, etc.). Once all the elements have been iterated, the program synchronizes their input/output data in order to maintain them up to date with the state of their neighboring elements (i.e. new mass flows, room temperatures, ambient temperatures, solar irradiation, etc.). This is repeated several times until the elements are well coupled so that they do not change their state. At this point, the whole set of elements is converged to an instantaneous building state. Then, the program checks for changes in the schedules of the openings and the occupants. Finally, the simulation ends or it continues towards the next time step.

This scheme is summarized in Figure 2. It is important to highlight that the distinct elements composing the system are computed in several parallel processes (i.e. the different branches in the scheme). This is an important property of the block-Jacobi like approach. The fixed-point iterations approach requires that the system components can be resolved apart from any other, which in turn enables parallelization. In particular, the code is programmed for running in distributed memory systems. This means that the elements that belong to different processes cannot directly share their data. For managing this problem, during the synchronization operation the processes communicate the appropriate data with each other using the Message Passing Interface standard (MPI).

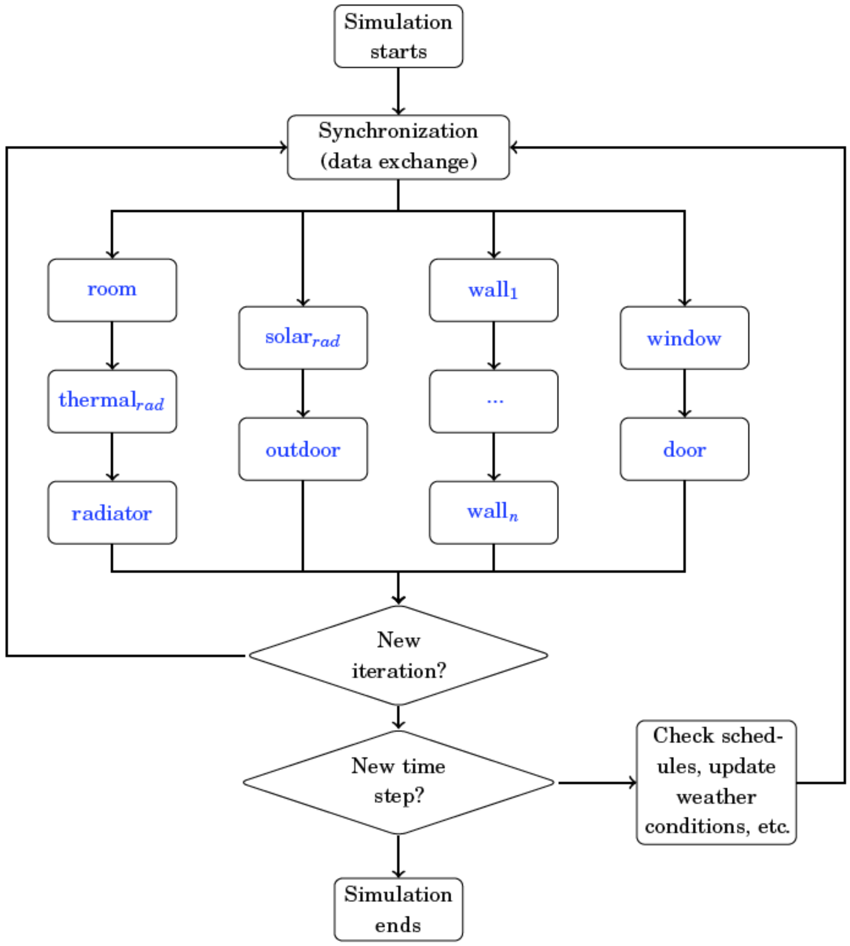

Figure 2. Block-Jacobi like algorithm implemented in NEST-Buildings.

2. CASE STUDIES

A real semi-detached house located in Lemmer (Netherlands), with two floors and 12 rooms (see planes of the house in Figure 3), has been virtually modeled by linking elements like walls, composite walls, glass walls, rooms, radiation calculators, outdoors, openings, ventilation tubes, radiators, boiler, ventilation box, etc. and simulated in a transient mode. The front of the house is oriented 20º azimuth. The walls are assumed to be made of common bricks and the floors of concrete. The mechanical ventilation extracts air from the livingroom-kitchen (room3), the toilet located in the ground floor (room 5) and the bathroom (room 10). There are radiators in all rooms except the garage (room 1), the hallway with stairs (rooms 4 and 11), the toilet (room 5) and the attic (room 12).

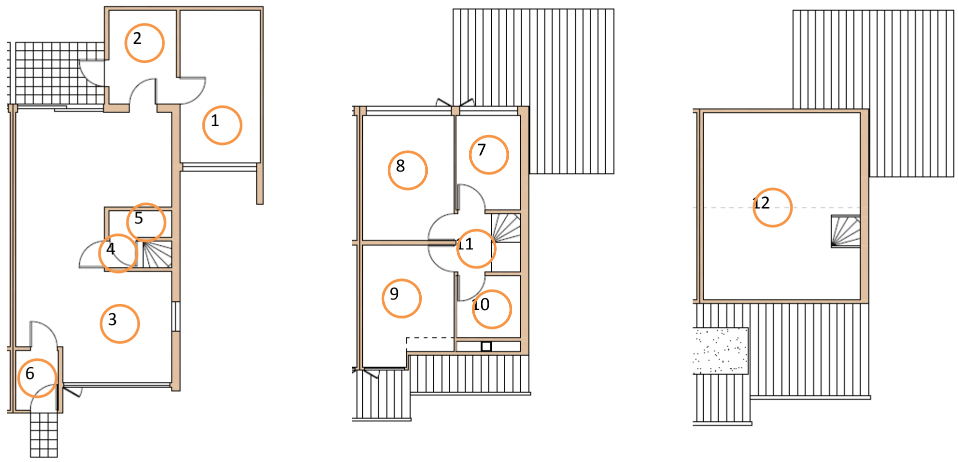

Figure 3. Planes of the simulated semi-detached house. From left to right: ground, first and attic floors.

That *virtual building model* has been used as a test bench for the testing of the developed control system. The developed control system controls two systems in the building: the boiler, through the water *setpoint* temperature (which also acts as the on/off mechanism), and the ventilation system, through the whole-house extract fan speed.

In present work three simple control strategies have been studied (see Table 2). In all them the control of the boiler is the same: Boiler turns on when temperature of the room where thermostat is located, i.e. the living room (room 3) drops below *Tsetpoint-threshold*, but does not turn off until the temperature rises above *Tsetpoint+threshold*. The boiler control is a simple timer with room *setpoint* temperature settings according to the occupancy schedule.

In the first case the ventilation fan does not work, rooms are closed (just infiltrations are considered). In the second case, the control of the ventilation system is assumed to run at the lowest fixed speed setting, which is the default manual setting for most households. In the third case the controller controls the fan speed according to the occupancy schedule: the fan speed is the minimum (1) when the house is not occupied and to a higher speed (2) when it is occupied.

In the three situations the rooms are kept closed and just infiltrations through the doors are considered. Infiltration is set to assure minimum required ventilation rates in mechanical ventilated houses at minimum fan speed.

Table 2. Studied ventilation strategies.

case	Ventilation control
1	No – fan does not function
2	No – ventilation speed is constant
3	Yes – fixed schedule

An occupancy schedule which is the same during weekdays and different for the weekend has been used and shown in Figure 4. There is an adult couple living in the house. On Saturday two guests visit the house in the evening. Mainly the living room, bedroom and sporadically the bathroom are used. All doors are closed, however infiltrations through doors and windows are considered. Three days have been simulated: from Friday to Sunday. Nevertheless, simulations start 24h hours before in order to have a more reliable initial map of temperatures, velocities and pressures at the beginning of the two or week analysed days. So, the total simulated time is 96h for these 72h tests.

Simulations were performed in February, using the weather for a typical year in Eelde, Netherlands (closest meteorological station to Lemmer, where the real test bench is located (METEO 1999)). A typical winter week has been chosen: temperatures around 0ºC, 2 sunny days and 2 cloudy days, and not windy.

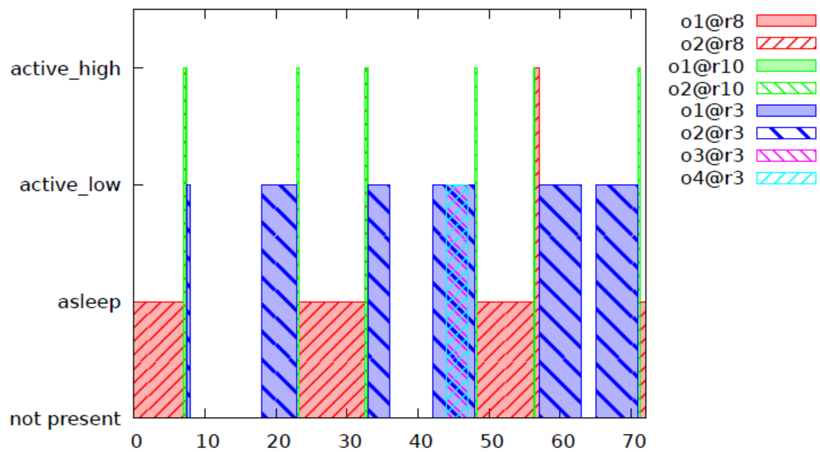

Figure 4. Occupancy patterns and activity levels for 2 occupants, o1 and o2, plus two guests, o3 and o4, over the 72hr Friday - Sunday period.

The thermal performance of the house without air flow model was previously analysed in detail in [4].

3. RESULTS

The left side of Figure 5 shows the thermal characteristics for the three studied cases. It includes the room setpoint temperature from the controller and the resulting temperatures in the various rooms. The room 3 is the living room and kitchen, 5 is the downstairs toilet, 10 is the bathroom and 8 the master bedroom. Solar irradiation on two external vertical façades is also shown, along with the external air temperature. Thermal behaviour of the whole house in the three situations is very similar, especially in heated rooms. However, it can be observed that in case 1 at the beginning of the first day, Friday, the house is at higher temperature than in the other two cases. This is due to the fact that in this case there is not ventilation, so the house does not cool down by the infiltrated fresh air.

The ventilation characteristics are depicted in the right side of Figure 5 and show the resulting CO_2 levels in the rooms, along with the exhaust duct and ventilation set point. The CO_2 levels are a function of occupancy and changes in ventilation rates are due to temperature and pressure driven ventilation effects.

CO_2 profiles follow the occupancy schedule: at night the CO_2 concentration increases in the bedroom. The air quality in this room would be regarded as poor. On Saturday, when there are two guests in the living room, CO_2 concentration in that room increases noticeably. On Sunday, the occupants spend almost all day in the house, except for a couple of hours at lunchtime, CO_2 profile shows two peaks according to these occupancy periods. When occupants leave a room, an exponential decay of CO_2 is observed. The higher is the fan speed, the greater is the decay.

Case 2 shows higher CO_2 levels than case 3, mainly in those periods where in case 3 fan speed is set to 2. CO_2 concentrations in bedroom are similar in these two cases since in case 3 for night period (for noise reasons) fan speed has been set to the minimum speed, which is the same as in case 2. Anyhow it can be clearly seen the beneficial effect of having mechanical ventilation since the CO_2 concentration is much higher in case 1.

For comparison purposes a set of performance indicators have been defined. They measure the differences of the different cases in terms of energy consumption and air quality and are defined as follows:

Energy consumption performance indicator ($ECPI_{room\_number}$): Sum of the heat output from all the radiators of room during a simulation period. ECPI is in kW·h.

Air quality performance indicator ($AQPI_{room\_number}$): The duration that a room when occupied (one or more people present) has a CO_2 level above the threshold of 1200ppm (which is given as air quality limit in Dutch regulations). AQPI is in ppm·min, thus gives an indication of the duration and magnitude that the threshold CO_2 level has been exceeded.

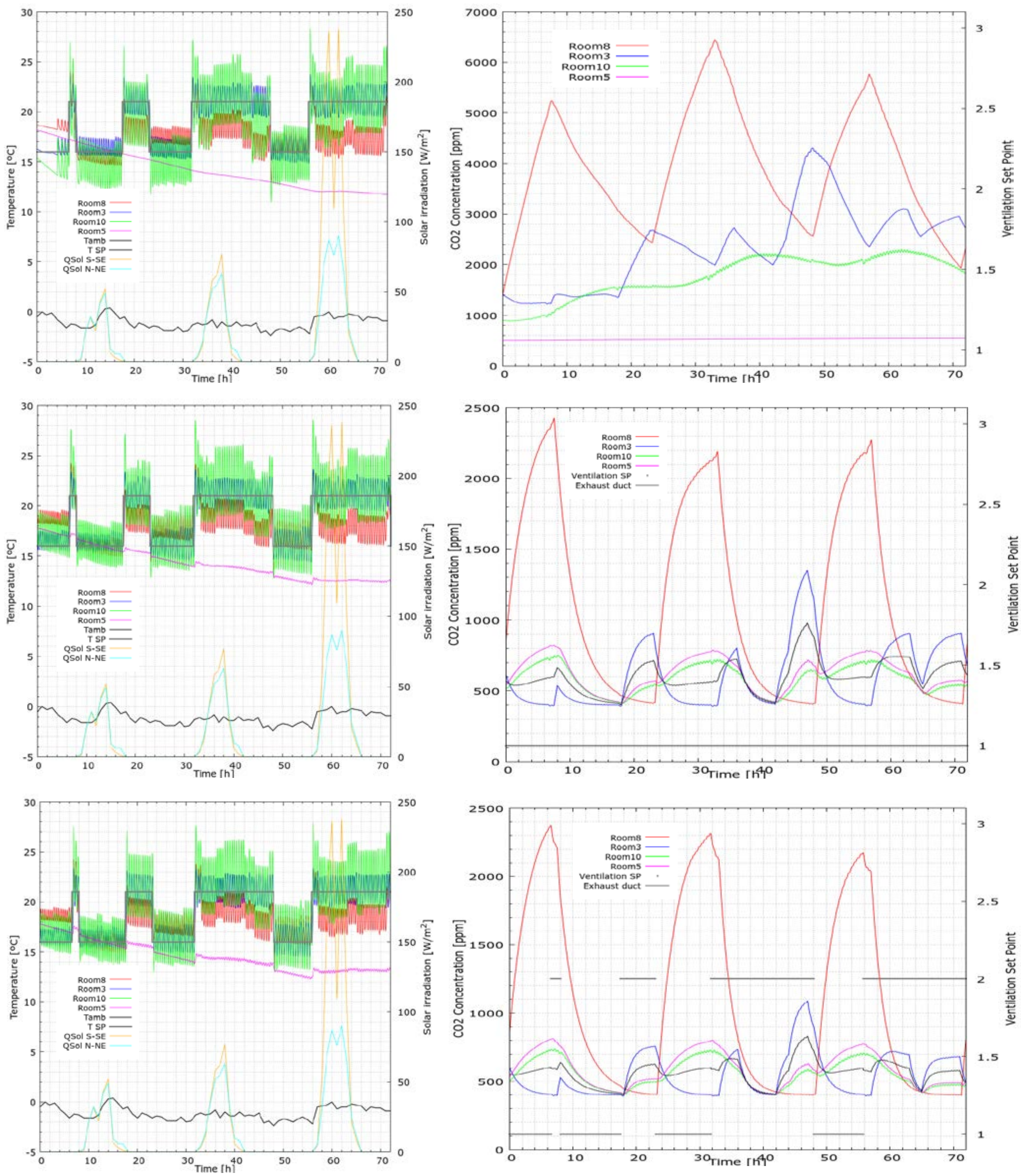

Figure 5. (From top to bottom) Case 1, case 2 and case 3. (Left) Temperature evolution of different rooms, setpoint and ambient and solar irradiation on south and north façades. (Right) CO_2 concentration evolution of different rooms and at exhaust duct, and ventilation setpoint.

Table 3 shows performance indicators at the three studied cases. In general it can be observed that on one hand the ECPI indicator is higher for those cases where ventilation is working, and on the other hand AQPI values are smaller. From a thermal and fluid-dynamic point of view it responds to a logical behaviour: when ventilation is working means that the air sucked by the ventilation system is replaced by air coming from the outside, that it is much colder that the inner (heated) air. For that reason the heating demand is greater, which is translated directly to a higher ECPI. This is why in case 3, where higher ventilation fan speed is used, the amount of cold air that enters the house is higher, thus, the heating demand is greater. However, since the house is more ventilated, the CO_2 concentration is lower, meaning that the quality of the air is better, so the AQPI is lower.

Table 3. Performance indicator of the three studied cases

	Case 1	**Case 2**	**Case 3**
ECPI3	62.7	86.1	93.3
ECPI2	19.3	25.2	27.0
ECPI7	16.7	22.0	23.7
ECPI8	17.5	23.0	24.9
ECPI9	21.9	28.5	30.6
ECPI10	19.7	26.0	28.2
TOTAL	157.9	210.9	227.7

AQPI3	$2.33 \cdot 10^6$	$1.02 \cdot 10^4$	$0.00 \cdot 10^0$
AQPI8	$4.77 \cdot 10^6$	$9.71 \cdot 10^5$	$1.03 \cdot 10^6$
TOTAL	$7.09 \cdot 10^6$	$9.82 \cdot 10^5$	$1.03 \cdot 10^6$

6. CONCLUSIONS

A virtual building model of a real dwelling located in the Netherlands has been built-up and tested at three different control situations. The effect of the ventilation control on the air quality and the energy performance of the house has been analysed. It has been observed that the higher ventilation fan speed is used, higher is the amount of cold air that enters the house, thus, the heating demand is higher. However, the quality of the air, measured as CO_2 concentration in the occupied rooms, is better.

So far, the full simulation of the overall building model is based on block-Jacobi and/or Gauss-Seidel algorithms. With the current implementation, the computational time for performing practical simulations may become an important impediment as the size of the building and events probability increases (e.g. block of flats simulation, a hospital, a mall center, etc.). Further research is necessary for attaining fast simulations. Better overall algorithms, the use of optimum time stepping, proper mesh sizes, convergence criteria, loop control strategies and the use of other non-linear solvers (i.e. Newton like methods), will be assessed in future works. The advances in this direction will help first to better understand the behavior of the already available algorithms and later to speed up the simulations. The second is important in the attainment of optimal designs of dwellings and buildings in general.

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