A novel model based approach of an integrated ventilation and heating model for monitoring and control

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ABSTRACT

Control of HVAC systems may reduce congestion of the electricity grid on district level by shifting energy demand of buildings and increase the self-consumption of local photovoltaic energy. To achieve an optimal control of ventilation, occupant behaviour should be taken into account. To describe occupant behaviour, usually black box models are used and typically need large amounts of high quality training data. Alternatively, use of physical relations allows for a good predictive power requiring less training data. TNO has developed a novel hybrid modelling approach: SirinE, combining data driven occupancy models with physics models including HVAC component models, a ventilation model and a heat transfer model. The SirinE model is calibrated with standardized monitor data. The SirinE simulation is an integrated modelling environment, enabling calibration of the parameters of both the ventilation and the heat transfer model to a real building. This paper focusses on the AirMaps ventilation model, and the results are compared with monitoring data of a field test of a dwelling.

KEYWORDS

Model predictive control, air handling unit, hybrid building models, energy performance of building, Ventilation

1 INTRODUCTION

A major challenge in the energy transition of the built environment towards energy neutral is how to integrate energy-producing neighbourhoods into an existing energy infrastructure. The exponential increase of the number of heat pumps and electric vehicles on the district level leads to higher peaks in electricity demands. Increasing intermittent availability of different renewable energy sources with associated trade platforms [1] will require energy systems to switch between energy sources seamlessly and at short notice. To ensure stability and security of supply, the energy network will need to incorporate a mix of different commodities (electricity, heat and possibly hydrogen networks) [2] and be capable of smart balancing energy supply and demand on a district level to avoid network congestions. Building level energy management of ventilation, heating and cooling (in houses, offices, hotels, etc.) can play an important role in the reduction of peak demands by distributing energy demand over time and over the different commodities.

The challenge is to develop a building control strategy that reduces the capacity of the required grid connection of a building and increase the local use of local solar energy production. This will also reduce the peak load of exported local renewable energy by consuming it at district level as much as possible.

To be able to balance the energy production within the capacity constraints of the local energy grid a reliable prediction or forecast of both decentralized renewable energy production and energy use of a building is needed, which is able to make short-term (e.g. 1 day ahead) predictions based on different control strategies.

Occupant behaviour shows to be a major factor in the energy demand of a building and therefore it is essential that the consequences of behaviour on the energy use is predicted by the model. As a consequence the prediction model must adapt itself continuously to reflect these changes. This means the occupant models must be trained on data from the buildings.

The current state of the art in research for the control follows two directions. The first one focuses on smart district level control using Artificial Neural Networks and agent based models or Model Predictive Control [3, 4, 5]. Representation of individual building level energy requirements and performance in these models is simplistic and static, using simple fixed demand/supply curves. The second research direction focuses on single building scheduling and control studies using physical models simulated in specific tools, e.g. TRNSYS or Energy-Plus [6, 7] or RC networks [8]. Over the past few years, the academic focus in this research for building control has shifted from black box models to hybrid models because the latter give better predictions and achieve higher robustness of the prediction especially under changing circumstances [2].

Current physical building energy models like TRNFLOW consist of two separate programs for heat transfer and ventilation: TRNSYS and COMIS. If we want a reliable prediction of the energy use of the building these models should be calibrated to adapt to changes in behaviour of the occupants, for example due to events like COVID-19 and to change of tenants. The current state of the art clearly shows the need for uniform scalable and more realistic building models which can tackle multiple functions and model interactions with the grid [9]. The objective of the SirinE model is to develop a building energy models that have:

- Occupant models that are calibrated with building data. Data driven occupant models can be used by both the heat transfer models and the ventilation models.
- A combined integrated software environment to calibrate the parameters of both the ventilation and the heat transfer model.
- Building Information Models serving as a standardized format for input.

2 HYBRID BUILDING MODEL SIRINE

SirinE is an energy simulation model of a building which is able to give predictions of energy demand and production of buildings under dynamically changing conditions. It is an environment which consists of a physical building model which solves the ventilation and heat flow balance equations, and a data-driven occupant model which models the interaction of the occupants with building components (e.g. thermostats, windows, electric appliances, etc.) (figure 1). The interaction of the monitored building data and simulation model prediction is used to create a predictive twin. SirinE makes use of standardised data input for both the building and installation information and the monitoring data. Therefore it is easy scalable to different sizes, functions and combinations of building blocks.

The building model of SirinE consists of a heat balance network and a ventilation network that is automatically derived from the Building Information Model (BIM) that describes the geometric configuration and construction properties of the building (consisting of all spaces, walls, windows, doors, roofs, etc.). In SirinE we selected gbXML, , which is an open schema to facilitate the transfer of building data stored in BIM files (gbXML.org). A separate standardized input of SirinE is a description of the building heating, cooling and ventilation equipment and its controllers. We selected IDF, the input file format of the energy simulation software Energy+ as a standard for describing the information of equipment components and configuration. With the automatic generation of the heat network and the ventilation network based on these input files, the simulation model can be easily adapted to different building types, such as apartment buildings, row houses and office buildings. Furthermore the data used to calibrate the model makes use of the standardized ontology of Project Haystack. The simulation model is therefore easily applicable to different building typologies and building functions and calibration time is limited.

A generic occupant class has been created within SirinE to simulate the interaction of the occupants with the building. The occupant class contains distinct subclasses, each associated with a certain occupant behaviour such as the presence of persons in rooms, interaction with windows or interaction with a thermostat setpoint. The implementation is flexible, in the sense that each of the subclasses may incorporate various sets of predictive models, ranging from simplistic approaches (e.g. fixed hourly profiles) to complex data driven models. Receiving the state of the building at each timestep from the building simulator, along with weather information (figure 1), the occupant class instances (agents) predict the behaviour of all occupants in the building for the next time step and transfer the interaction to the heat and ventilation network simulator.

Because the occupant behaviour is itself influenced by the building state, e.g. room temperature, the building heat balance network and ventilation network and occupant agents interact bidirectionally. The occupant models that have been implemented (simple hourly schedules, simple data driven models for thermostat and appliances, Markov chain models for window opening behaviour) highlight the hybrid nature of SirinE.

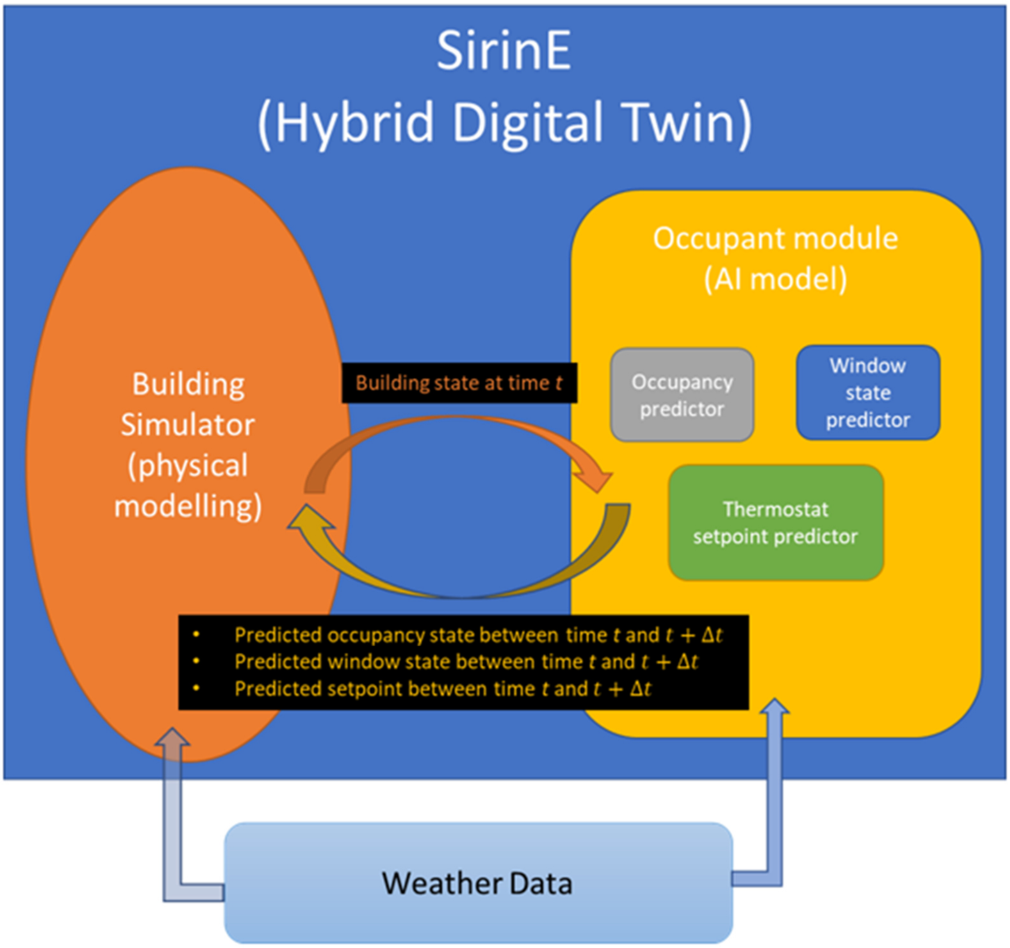


Figure 1: Figure caption

3 VENTILATION MODEL OF SIRINE: AIRMAPS

To calculate the losses due to ventilation and infiltration TNO has developed a multizone airflow model, AirMAPs [10]. Similar to COMIS [11] it is based on a network model. Each zone in the building is considered homogeneous for temperature and is represented by a node. The nodes are connected in a network to model the airflows. The connections between the different zones and between the zones with outside can simply be openings, grilles, windows or cracks or ventilation components such as fans, ducts and the like (see figure 2).

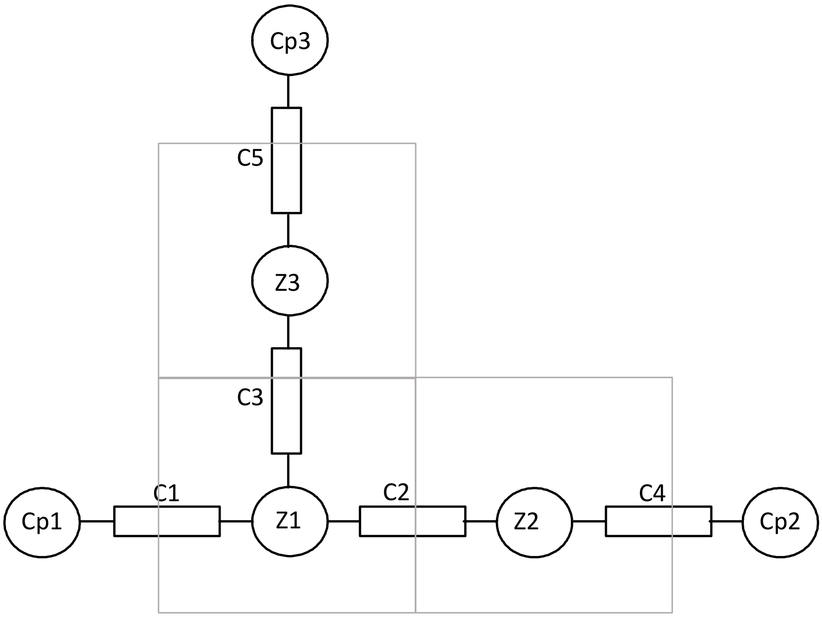


Figure 2: Example of an AirMAPs ventilation network, Z are the zones, C are the connections and Cp are the outside nodes represented by a pressure due to wind.

When solving this network of connections, the pressures in the zones are determined at which the incoming and outgoing mass flows per zone are in balance. This fixes the air volume flows through the connections. In combination with the air temperatures in the zones and outside, the energy loss through ventilation can then be calculated. In combination with a pollution source, both the concentration per zone and the spread of pollution between zones can be calculated.

SirinE simulates the occupant behavior, equipment controllers, equipment dynamics and the effect on the combined heat network and the AirMAPs ventilation network in a combined simulation environment. After the start of a timestep the heat network calculates the energy loses making use of the ventilation flow calculated by AirMAPs and the zone temperatures. Based on this calculation of the heat network, the new zone temperatures are calculated, which are again used inAirMAPs during the following timestep. A typical timestep is in between 5 and 15 minutes.

The ventilation model AirMAPs calculates the air mass flow over a connection (and converts this to an air volume flow) based on the pressure difference across the connection. Factors to be considered include, the flow exponent and the net opening of the connection and the specific gravity of the air.

In the ventilation model AirMAPs the following driving forces are consider:

- wind attack
- thermal stack
- fans

The wind pressure distribution over a building envelope is simulated using wind pressure coefficients (Cp values). The wind pressure coefficient multiplied by the dynamic pressure of the wind speed gives the local under or overpressure as a result of wind attack. The thermal stack concern the driving forces due to temperature differences and differences in height of openings between inside and outside or between zones. These pressure differences arise as a result of differences in the density of air. The fan is described by a so-called test data component

(TD), for this purpose for different pressures across the component the air volume flow which is maintained by the component is specified. The air volume flow is interpolated linearly between the specified pressure differences. So it is actually a component where the user can specify what the component air volume flow will deliver depending on the pressure difference across the component. This method can also be used for self-adjusting grills.

In the ventilation model AirMAPs, 3 types of connections can be modelled:
- an opening (marked CR)
- a test data component (denoted by TD)
- an open window or door (marked OW)

An opening CR can be used for a non-self-regulating grille, a gap or air leak, a window or a duct. Parameters of importance are the net area of the opening, which takes into account the flow resistance or constriction and the flow exponent. A test data component (TD) is described above for the fan and can be used also for self-regulated grills. For an open window or open door, a distinction is made between:
- an airflow in one direction (rectified airflow)
- an air flow in both directions (the so-called turbulent exchange).

The pressure difference that occurs across an open window (OW) due to the differences in the air pressures to the left and right of the opening (rectified pressure difference in one direction) is used to determine the airflow in one direction (rectified airflow). At this point, an open window (OW) works exactly the same as an opening (CR), as indicated above. In addition, with an open window, an air flow in one and the other direction can also occur simultaneously due to temperature differences between inside and outside, which lead to pressure differences over the height of the window, and turbulence in the wind attack. In the case of an open window, the following must also be specified for this:
- the height of the open window (m).
- the number of sides of the open window where constriction of the air can take place.

If a window is located in the middle of a facade, constriction can take place all around and the number of sides is 4. A door, on the other hand, is adjacent to the floor on 1 side, where no constriction occurs. The number of sides is then 3. If the door further adjoins an inner wall on 1 side (before and after the door), then the number of sides is 2. The calculation of the airflow in 2 directions, the so-called turbulent exchange, is taken from the Visual Basic program LargeOpeningNL. This program is based on empirical formulas derived from measurements performed in the TNO laboratory in the 1980s for openings with external and internal gaps between spaces [12][13]. A fluctuating pressure difference across the open window is calculated based on the wind attack, the turbulence in the wind attack and the temperature difference between one side of the open window and the other. Then the maximum pressure difference is calculated due to thermals and wind attack including gusts. If the rectified pressure difference is zero, the turbulent exchange is maximum. If the rectified pressure difference is greater than or equal to the aforementioned maximum calculated pressure difference, the turbulent exchange becomes zero. Between them, the turbulent exchange decreases linearly. In this way a good description of the air exchange over large openings is possible, taking into account that the rectified pressure difference will counteract the turbulent exchange.

To solve the AirMAPs ventilation network, the zone pressures must be calculated in such a way that the incoming and outgoing mass flows in each zone are in balance. To make this possible, a system of linearized equations is set up in the solve routine that describes the current balance for each zone. Solving this system of equations then gives the pressures in the zones. This process has to be repeated a number of times (iteratively) because the ventilation flows do not change linearly with the pressures. The process continues until the current error (mass balance error) per zone is less than the specified permissible deviation.

The AirMAPs ventilation model is used in the SirinE simulation environment but is also combined with a RC heatnetwork in the ungoing HORIZON2020 Sphere project to calculate and commission the performance of NZEB dwelling.

4 COMPARISON OF THE RESULTS OFAIRMAPS G WITH FIELD DATA.

In a single-family home in Delft (Netherlands), CO2 and temperature measurements were carried out in the living room, the three bedrooms and the attic in the period from 19 August to 27 September 2020. A floor plan of the house is shown in figure 3. The house is a terraced house, with the landing in open (stairs) connection with the attic. The attic is one room. The house is equipped with a balanced ventilation system. The environment consists of houses/residential buildings with varying heights up to a maximum of 4 floors.

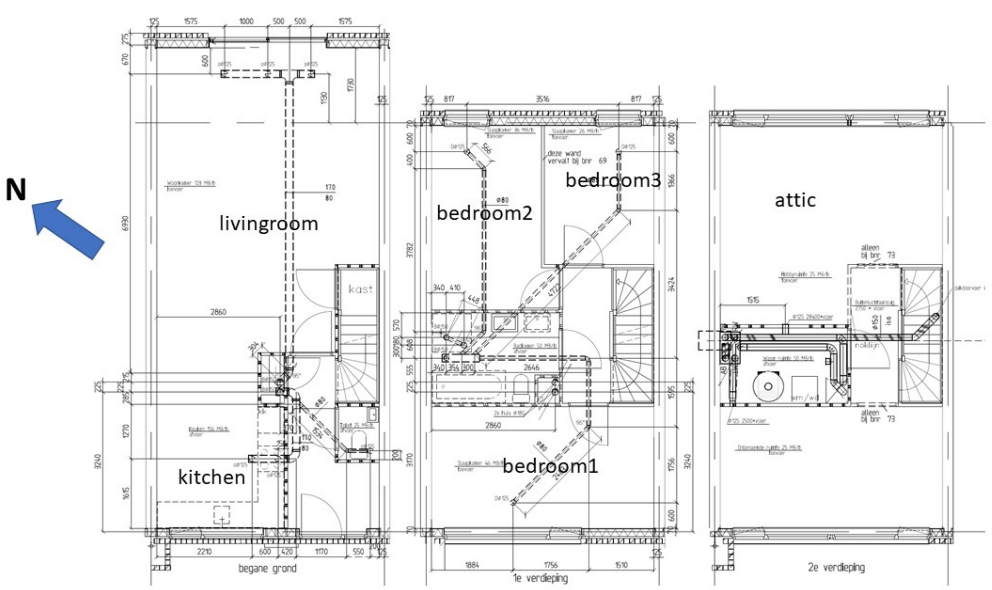


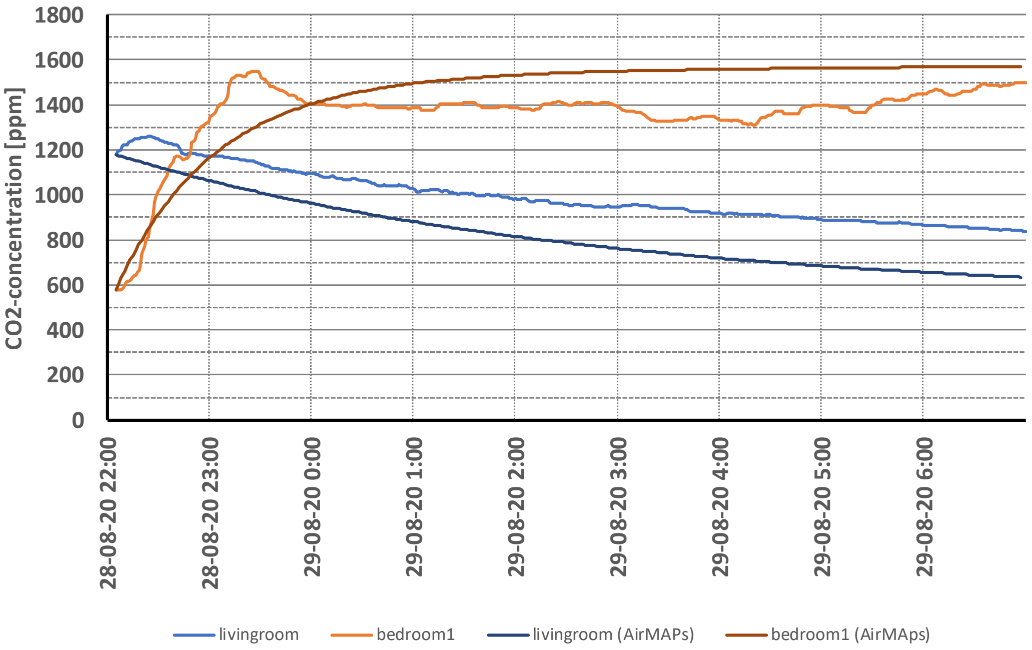
Figure 3: Floor plan of the terraced house of the field test

Various scenarios have been considered in the home with regard to the presence of people (i.e. CO2 production), window positions, positions of interior doors and position of the ventilation system. Subsequently, these scenarios were simulated with AirMAPs and compared with the measurements.

A ventilation model of the house has been made for this purpose in AirMAPs. The air permeability of the house is estimated to be 40 dm3/s at 10 Pa. This is a fair value for this house given the year of construction. Furthermore, the supply and extract air volume flows of the balanced ventilation system were measured in the home and modeled in AirMAPs. The overflow gap under the inner doors has been measured and measures 1.5cm by 90cm and is modeled in AirMAPs. The weather data, such as wind speed, wind direction and outside temperature, were used from the nearby Voorschoten weather station. The wind pressure coefficients were determined with the Cp generator of TNO, whereby obstruction/shelter by the immediately adjacent houses was considered. The wind pressure coefficient multiplied by the dynamic pressure of the meteorological wind speed gives the under- or overpressure on the facade or roof of the building.

In figure 4 the measured and simulated CO2-concentrations in the livingroom, bedroom1, bedroom2 and the attic are given for a specific scenario. In this scenario the revolving window in bedroom1 is opened (2 cm open, Anetto=175 cm2, height 130 cm) and the door of bedroom1 is opened (4 cm open, Anetto=650 cm2, height 200 cm)). Two persons are present in bedroom1. The balanced ventilation system is switched to the low position. The windspeed is 3 m/s and roughly perpendicular to the front facade (facade at which bedroom1 is located). The outside temperature is 14˚C,while the temperature in the dwelling is roughly 21 to 22˚C

Figure 4 shows that the CO2-concentrations calculated with AirMAPs resemble quite well with the measured concentrations. The CO2-concentration in bedroom1 is, as might be expected, a first order response on the CO2-production in this bedroom, while the attic clearly shows a second order response. In the attic the measured CO2-concentration as well as the calculated concentration with AirMAPs in the beginning increases and at the end decreases (showing to some extend an S-curve).



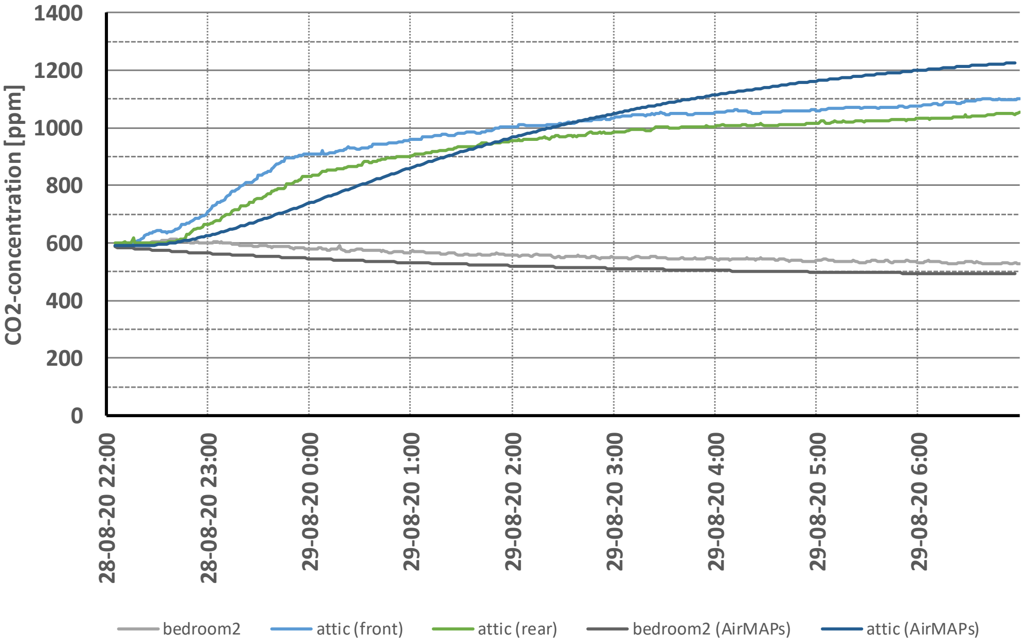


Figure 4: Comparing simulation results AirMAPs with measurements

5 HEATNETWORK SIRINE

To calculate the heat losses a heat network is constructed, where each room is considered a thermal zone. Each zone z_i is represented by a temperature node T_{zi} in the heat network. Each physical layer of boundary surfaces (i.e. walls, floor, ceiling and roofs) constitutes a temperature node in the heat network. For kth layer of the jth boundary surface $S_{j,k}$ ($k = 1$

corresponds to the innermost layer, $k = n$ to the outermost one), a temperature node $T_{Sj,k}$ is added to the heat network. In addition all boundaries (outdoor environment, ground etc.) are represented by a single external temperature node [14].

6 IMPLEMENTATION OF SIRINE FOR A MODEL PREDICTIVE CONTROLLER IN AN ENERGY POSITIVE DISTRICT

In the Horizon 2020 project Syn.ikia, we are deploying the predictive twin SirinE in a model predictive controller (MPC) to use a temporary excess capacity of on-site solar energy as efficiently as possible. This MPC is applied in a demo Sustainable Positive Energy Neighbourhood (SPEN) in Uden. This neighbourhood consists of an apartment building with 39 apartments, each having its own PV panels and ground source heat pump for domestic hot water and space heating, and common neighbourhood PV and Electrical Vehicle charging stations.

To shift the energy load of the apartments to better utilize the energy generated by the photovoltaic panels, we calculate the optimal time to start heating the buffer vessel for domestic hot water and the time to start the space heating. We can shift the start time of space heating quite easily because the dwelling is both well insulated and has a large building mass in the floors and walls. Therefore the building will react quite slow to cooling down and heating up the rooms. The implementation of the model predictive controller is foreseen in the last quarter of 2022.

7 CONCLUSIONS

The paper provides an overview of a novel hybrid modelling approach for buildings. The comparison of the field measurements and the AirMAPs ventilation model looks quite promising. A unique quality is that the building model uses a standardized data format for both the BIM (gbXML), the equipment configuration (IDF) and the building data (Haystack), Therefore the model is scalable, automatically generates a network and uses matrix solvers to efficiently simulate the network. Next step is to implement and test the model predictive controller in the Sustainable Positive Energy Neighbourhood (SPEN) in Uden.

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