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***Abstract*—Electricity grids are facing challenges due to peak consumption and renewable electricity generation. In this context, demand response offers a solution to many of the challenges, by enabling the integration of consumer side flexibility in grid management. Commercial buildings are good candidates for providing flexible demand due to their volume and the stability of their loads. However, existing technologies and strategies for demand response in commercial buildings fail to enable services with an assessable impact on load changes and occupant comfort. In this paper we propose the ADRALOC system for Automated Demand Response with an Assessable impact on Loads and Occupant Comfort. This enhances the quality of demand response services from a grid management perspective, as these become predictable and trustworthy. At the same time building managers and owners can participate without worrying about the comfort of occupants. We present results from a case study in a real office building where we illustrate the advantages of the system (i.e., load sheds of 3kW within comfort limits). Presenting a better system for demand response in commercial buildings is a step towards enabling a higher penetration of intelligent smart grid solutions in commercial buildings.**

I. INTRODUCTION

Demand Response (DR) covers technologies and programs that enable and incentivize electricity consumers to change their load profiles. DR has traditionally been applied to address peak loads on the grid, e.g., hot summer load peaks in California, US [1]. However, the potential of DR also covers scenarios for handling emergency situations in the grid, local load peaks and the integration of renewable electricity generation.

Commercial buildings have a major potential to participate in DR programs for several reasons: i) in most countries buildings represent more than half the electricity load and commercial buildings constitute a significant portion of this; ii) commercial buildings have many predictable loads operating on repeating schedules, making them good candidates for DR; iii) many commercial buildings have centralized control, reducing the cost for integrating them in DR programs.

Existing work on integration of commercial buildings in DR programs has considered fast automated demand response based on static preprogrammed building control [1]. Flexible consumption and its impact on comfort have by existing deployments been considered in manual pre- and post-deployment audits [1]. So far occupancy comfort has primarily been considered for energy efficiency and not DR [2]. Work has also proposed standardized protocols for the interaction among system components for DR, e.g., the OpenADR protocol [3]. However, we identified several shortcomings in existing work: a) occupant comfort has only been addressed to a limited extent [4], e.g., ensuring control will satisfy national building and work regulations, b) the impact of predictable occupant behavior has not been included in building control [4] and c) many proposed solutions do not provide the requested load change [1].

In this paper we propose the ADRALOC system for Automated Demand Response with an Assessable impact on Loads and Occupant Comfort. The system can facilitate both direct and indirect control of loads in DR programs. To assess the impact of possible DR events the system integrates prediction of load consumption, occupant behavior and indoor environmental properties. The predictions enable DR events to be scheduled with a knowledge of its impact on the building operations, including load changes and occupant comfort parameters (i.e. room temperature and CO_2 levels). This enables a building operation within the limits of national building and work regulations.

The contributions of the paper are as follows:

- An analysis of the requirements for occupant comfort parameters for DR in commercial buildings with Denmark as a case.
- Propose the ADRALOC system and the combination of models of methods that underpin the functionality of the system.
- A prototype implementation of ADRALOC and experimental results for one case building including the predictability of occupant comfort and load shed (i.e. load sheds of 3kW within comfort limits).

II. BACKGROUND

In Denmark and other European countries, the motivation for considering DR includes integration of renewables in particular wind, maintenance cost (i.e. avoiding upgrades of lines and transformers) and avoiding future peak load problems due to increased electrification for heating (e.g. small and large heat pumps) and transportation. In this work we consider the challenges on the level of a Distribution Service Operator (DSO) in particular. Compared to the US, the peaks in the grid of a Danish DSO occur more scattered throughout the day depending on the mix of commercial, industry or residential buildings.

For providing DR services on the distribution grid level, the Danish project iPower has defined a number of DR services relevant for Danish settings [5]. We build our work on these services and discuss the following two services in detail: PowerCut planned and PowerCut urgent. The PowerCut service asks a DR provider to cut a load of δP during the time period T. For PowerCut planned the request will be delivered on a regular basis, e.g., daily or weekly, whereas PowerCut urgent is scheduled per event. For both services a contract is made that in detail specifies the technical and economic regulations. In this paper we will focus on these two services, but the concept described can easily be used with other forms of DR, e.g., other types of service or price-based schemes already deployed using the OpenADR protocol [3]. When implementing DR in buildings, different strategies have been used by previous work [1], including global temperature adjustments, duty-cycling of RTUs, increasing of CO_2 setpoints and dimming of light. In this paper we will focus on ventilation systems, as ventilation has a high impact on occupant comfort but our system also applies to other load types.

The comfort of occupants in indoor environments is a priority due to the fact that people spend between 80% and 90% of their days indoors. By definition, thermal comfort is defined by ASHRAE 55 [6] as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". Therefore, it is important that systems for implementing DR in buildings address occupant comfort in relation to national standards and regulations designed to provide good conditions. From a Danish perspective the Danish Working Environment Act [7] recommends that under normal climatic and working conditions, the temperature in the working place should be maintained within 20 °C-22 °C for sedentary work. In addition, the regulations also state that the temperature in the working environment should not be allowed to exceed 25 °C with an air relative humidity between 40% and 60%. In other Danish standards, it is also recommended that the maximum temperature difference within the same working room should not exceed 4 °C, and the temperature in the workplace exhibiting sedentary work should not fall below 18 °C. The maximum allowed CO_2 concentration is 0.1 percent of the total air content in the working place. In terms of the ventilation requirements in the working environment, mechanical ventilation should be capable of providing a minimum of 5 l/s per person in addition to 0.35 l/s per m^2 of floor area. In addition, air supply velocity in the working environment should be maintained below 0.15 m/s accommodating sedentary activity to avoid draughts, where higher velocities are acceptable in the case of temperatures above 24 °C in the summer. The proposed system for scheduling DR events makes it possible to take such thresholds into consideration.

III. SYSTEM CONCEPT

In the following we present the ADRALOC system. The system goal is to enable commercial buildings to provide DR services with an assessable impact on the load change and occupant comfort. The system is designed to run as an instance for each building and use a Building Operating System (BOS) [8] to integrate with the building instrumentations for sensing and actuation of building infrastructures.

Figure 1 gives an overview of the system structure and flow of information in the system. (1) The grid-side represented by a DSO, Balance Responsible Party (BRP) or an aggregator make a DR service request that ADRALOC receives. (2) To process the request, ADRALOC collects relevant sensor data from the building instrumentations via a BOS (e.g. ambient temperature, room temperature, room occupancy, electricity consumption and room-level CO_2) and via external sources (e.g., forecasted solar radiation). (3) The sensor data informs a number of models that predict room occupancy, temperature, CO_2 levels and electricity consumption of individual loads for the time period of the requested DR event. The coverage of the models for the building environment can either be a room or a larger part of the building depending on the level of control. (4) A DR Analyzer looks at the type of DR request and analyzes if the building can respond to the event or not. The analysis is implemented by a multi-objective optimization framework that take into account the various model predictions. The model results enable the framework to evaluate if responding to the request will result in violations of comfort requirements. Additionally, the models for load forecasting enable the framework to consider how well the load can realize the service for a given DR request (5) Given that the analyzer decides to respond to the request, the DR scheduler will schedule the building infrastructures to deliver the requested response. (6) If the building responds to the request, the electricity consumption pattern will change in the requested period following the request.

A. DR Services

For the specification of DR services, ADRALOC, as mentioned, follows the design proposed by the iPower project [5]. In particular, the current iteration of the system focuses on the PowerCut planned and PowerCut urgent services. As an example the DR services could be used to ask a building whether it is able to respond to a PowerCut Urgent from 11:30-12:30 for 3kW. After evaluating the request, the ADRALOC system returns a negative or positive answer to the request. These services can by implementations also be mapped to OpenADR messages [3] such that existing protocol can be used to request services from a range of ADRALOC-enabled buildings.

B. Building Operation Data

To consider the particular conditions in each building require sensor data about the building environment and loads. Recent development in building management systems support this by enabling easier access to building data from various building instrumentations. The ADRALOC depends on the following sensor and building data being available:

- **Room-level sensor data** including room occupancy, temperature and CO_2 level. For instance, for the meeting

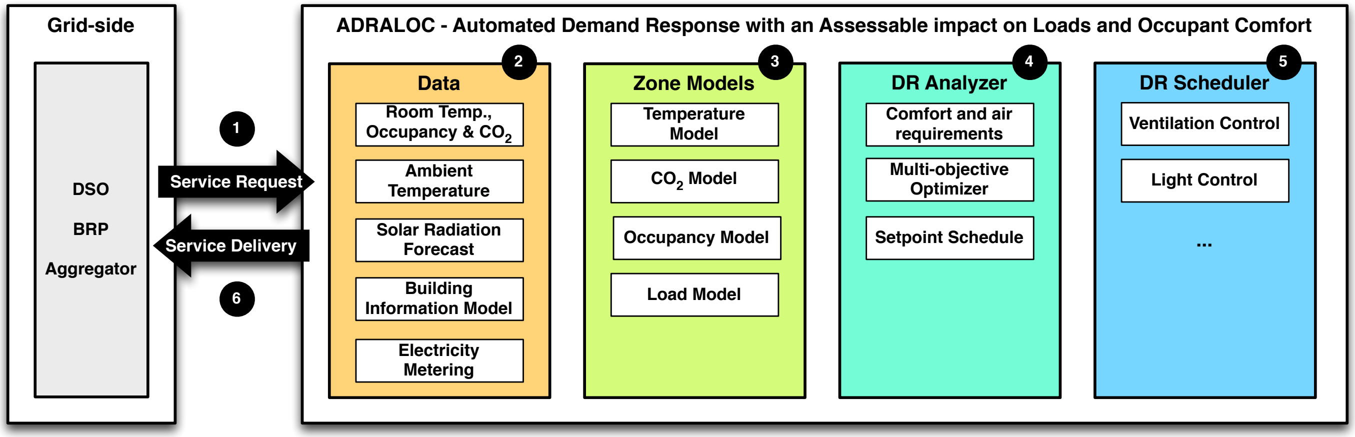

Fig. 1. Overview of the ADRALOC system include the grid-side and the various components of the system.

room “Saturn” at 11:30 that it is occupied, has a temperature of 22.64 °C and a CO_2 level of 689 ppm.

- **Ambient Temperature** from a building-mounted or local weather station. For instance, that the building-mounted weather station reports a temperature of 5.9 °C.
- **Forecast of Solar Radiation** for the specific local area where the building is placed, e.g., from national weather services.
- **Building Information Model (BIM)** with information about building layout, and size and capacity of rooms. For instance, that the ’Saturn’ room is a meeting room for 12 persons with a size of 20.38 m^2.
- **Electricity Consumption** at the level of the infrastructures that will respond to DR requests, e.g., ventilation or lighting. For instance, that the ventilation system at 11.30 used 3.8kW.

C. Modeling Building Conditions

Scheduling DR events with an assessable impact on occupant comfort and load shed requires knowledge of the conditions during an eventual event. Therefore, we use the building data to run several prediction models with the purpose of predicting, at a room-level, occupancy and resulting temperatures and CO_2 levels. At a building infrastructure level, the models predict the possible load change resulting from scheduling changes to the operation of the building infrastructures. To make it easy to deploy ADRALOC for new buildings, the models have been designed to require as little historic data for training and as few building specific parameters as possible. As the focus of the paper is the overall system design, we omit details about the individual models and instead refer to papers describing the details of our models. All models output a time-series of prediction values for a given prediction horizon, e.g., 3 hours. ADRALOC incorporates the following prediction models:

- For predicting occupancy presence we apply a multi-label classification model at the room level. The model learns patterns of occupancy from down to a few weeks of historical data and combines these with contextual data. The contextual data includes the type of room, season and day type (i.e. weekday, weekend or holiday). The model is based on a support vector machine classifier as described in more detail in Sangogboye et al. [9].
- For predicting temperatures and CO_2-levels, we use a generic zone model. The model is based on greybox modeling where we use the same base model and parameterize it for each zone (i.e. a room). The goal is for the generic model to be simple enough to automatically get most parameters from the BIM data and use automatic parameter estimation on historical measurements to learn any missing parameters. The base model consists of a thermal RC network submodel and a transient CO_2 balance submodel. When predicting, the model is given input parameters for predicted occupancy, assumed system control strategy (heating and ventilation), forecasted ambient temperature and forecasted solar radiation. Further details regarding the model is given in Arendt et al. [10].
- For load prediction we apply a neural network model. The model is trained with historic electricity consumption and other parameters that can have an impact on the consumption. Such parameters include occupancy-levels, ambient temperatures and solar radiation levels. When predicting loads similar data is provided to the model based on available forecasts and predictions. The neural network model consists of 36 separate networks and feature selection is applied to prioritize good features. See Wollsen et al. [11] for more detail about the neural network model.

D. DR Analyzer

The goal of the DR analyzer is to decide based on the predicted values which responses the building can provide. The analyzer is implemented using the Controleum framework, a multiple-objective optimization framework that utilizes genetic algorithms to create solutions for non-linear multi-objective multi-issue problems [12]. The Controleum framework consists of a core optimizer and a series of additional modules for the domain in question. The core optimizer works by creating a population of schedules with setpoints for a predetermined period of time. These are then evaluated by concerns, essentially atomic agents, and the result is graded. The grades are then used to mutate and evolve the populations and the process is repeated for a series of generations in order to determine if there is a solution and if so, find the best one. This way, it is able to evaluate legal requirements, comfort concerns and constraints set by DR signals independently.

For building responses involving ventilation, the concerns compare the predicted temperature and CO_2 levels to comfort thresholds for both parameters. For temperature the thresholds are defined as a comfort band of +/- δt around T_c, a specified comfort temperature and for CO_2 the threshold is an upper limit L_{CO_2}. Each concern will then look at the information relevant to them and utilize it to create a fitness-result, such as a CO_2 concern returning a better value for lower concentrations and an unfit value for concentrations beyond the L_{CO_2} threshold. Likewise, concerns for temperature comfort, temperature variations, lighting levels, etc. take into account the values provided by the models.

We will explain the concrete steps using an example. The example covers a building with a number of rooms. Table I lists all values used in the example. The goal of the analyzer is a schedule represented as a matrix of setpoints for the respective actuation points at different times a day. In the example, the building has an actuation point for the overall ventilation system and a particular meeting room has a schedule determining actuation of light. The ventilation system can be turned on (1) or be completely turned off (0). The lights are dimmable from 0 (off) to 100 (fully on). For the building and meeting room we have a number of sensor values including occupancy, temperature (T), CO_2 level and ventilation system consumption.

To illustrate the computational process lets assume that we receive a request to deliver a PowerCut urgent of 3kW with 10% error margin from 1:00 to 2:00. To decide if we can respond to the request we run the various models to predict the room and building conditions for the next two hours (values in italic). Given these values Controleum will try to find a schedule that optimize the fitness-results given the various concerns for CO_2, temperature, light-levels and load shed. In the example Controleum find such a solution that include turning off the ventilation system during the hour and because occupancy is predicted in the meeting room for some of the hour dim the light for one quarter of an hour. Our load forecasting models for ventilation and light predicts that this schedule will provide a load shed between 2900 and 3200 W which is within the 10% error margin.

E. DR Scheduler

The DR scheduler has the job to schedule the plan for the various building infrastructures that should take part in the DR event. It interfaces with the BOS to issue the changes in setpoints at the right moment in time.

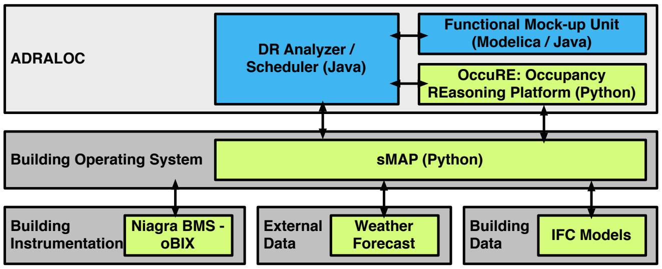

Fig. 2. System Setting for the ADRALOC system including system components and data sources

IV. EVALUATION

In this section we present evaluation results for the ADRALOC system. The evaluation focuses on a case building which is the GreenTech House (GTH) in Vejle, Denmark. The GTH building is a working environment that houses a range of organizations and companies with different business purposes within and across different office spaces in the building. It is a three-story building with 50 rooms that comprises mostly of office spaces, a cafeteria, meeting rooms and bathrooms. We evaluate the models prediction capabilities and the achieved load shed and resulting occupant comfort during DR events.

A. Implementation

For the evaluation we made a prototype implementation of ADRALOC in a combination of Java, Python and Modelica code. Figure 2 gives an overview of the system setup. We host the system on a cloud setup of virtual machines so the system in the future can be scaled in respect to the number of controlled buildings. We utilize the open-source sMAP [8] platform as BOS to integrate with the various building instrumentations. In the particular case building the data is exposed by a Niagram BMS via the oBIX interface. The generic zone and forecasting models are integrated into the DR Analyzer using the Functional Mock-up interface and the occupancy prediction is provided by the OccuRE platform that implements the used prediction algorithms [13].

B. Results

To evaluate ADRALOC we have conducted two demand response events in the case building. Both events triggered the ventilation system on and off. One event was scheduled on a weekday at 9.45 in February 2016 and the second at week day at 11.30 in November 2015. Both events lasted for one hour. We did not use ADRALOC to schedule these two events but in this paper we consider in hindsight what our models would have suggested in these two cases. In our ongoing work we are deploying ADRALOC for longer term direct building operation. Figure 3 and 4 shows the power consumption of the ventilation system during each of the events. The power curves reveal that we in both cases achieved a load shed of around 3.5 kWh. After the events the load increases to bring back the building within setpoint limits. On data from both events we ran the models of the ADRALOC system to evaluate the system on real data.

TABLE I
EXAMPLE OF A DR ANALYZER SCHEDULE INCLUDING SENSOR INPUTS AND MODEL PREDICTED VALUES.

	Now	0:15	0:30	0:45	1:00	1:15	1:30	1:45
Inputs								
$Occupancy$	1	*1*	*1*	*1*	*1*	*0*	*0*	*0*
T [W]	22	*22.1*	*22.3*	*22.2*	*22.4*	*22.5*	*22.7*	*22.5*
Schedule								
$Light$	100	100	100	100	50	0	0	0
Forecast								
$Shed_{v_{building}}$ [W]	0	0	0	0	2800	3000	3100	3200
$Shed_{light}$ [W]	0	0	0	0	100	0	0	0

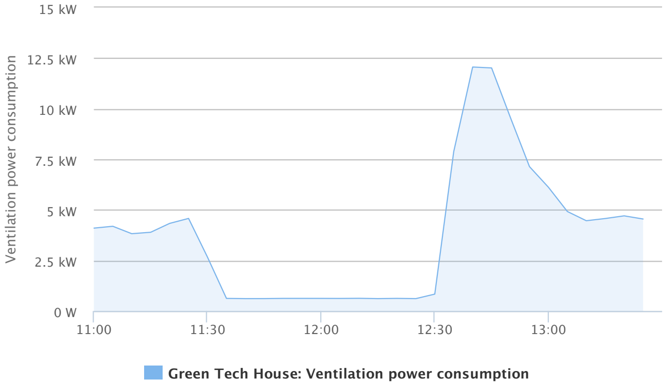

Fig. 3. Ventilation power consumption during November DR event.

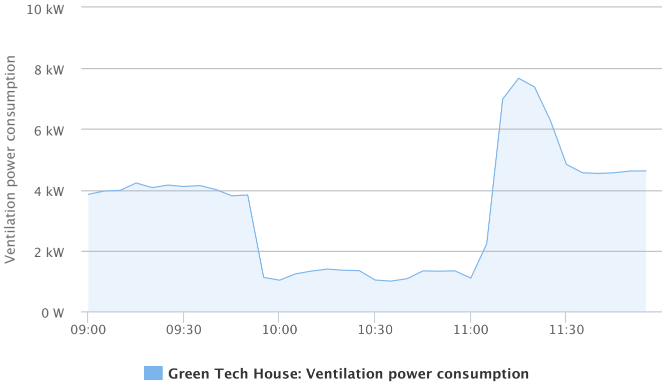

Fig. 4. Ventilation power consumption during February DR event.

Of particular importance in regards to occupant comfort is the impact on CO_2 levels. Therefore, we analyze in detail the outputs of our generic zone models for CO_2. This model takes as input our predictions of occupancy and also outputs temperature predictions but due to space limitations we do not cover these predictions in detail. In the case building the ventilation system has a CO_2 threshold of 700 ppm which is below the 1000 ppm DK work regulation requirement. Out of the fifty rooms in the case building we focus on two rooms in particular. One of them is a meeting room which might trigger CO_2 violations if many people attend a meeting during a DR event and an open space office which is a common case in many buildings. Figure 5 and 6 shows the simulated and measured CO_2 levels in the meeting room (a) and the open space office room (b) for the November and February events, respectively. The simulation results are given assuming both that the ventilation system is on ($CO2_{sim,on}$) and off ($CO2_{sim,off}$) which was the situation during the DR events. In all cases we can see that the simulations predict that if we turn off the ventilation system we will not violate the DK limit of 1000 ppm in either the meeting room and the open office. Therefore, ADRALOC would in both situations also had scheduled DR events if only taking into consideration CO_2. As expected the measured CO_2 values in all four cases increase during the DR events due to lack of mechanical ventilation. Comparing to measured CO_2 to $CO2_{sim,off}$ reveal that the simulations are able to identify the right trends. In some of the cases the measured CO_2 rose a bit higher than our predictions most clearly in the meeting room for the February event. The reason is that more people attended a meeting than our models predicted. The overall mean absolute percentage error for $CO2_{sim,off}$ compared to the measured values is 6.87%.

To evaluate the possible load shed the ADRALOC system also performs forecasting of the ventilation loads. In Figure 7 we include an example for the February test where we estimate at 8.00 the load for the next three hours. As long as the ventilation system runs in normal mode the forecasting is quite accurate. At 9.45 we turn off the ventilation system for the DR event and from this point onwards the forecasting enable us to predict the load shed. The load shed can be predicted as we know that if we toggle off the ventilation it will go to a load-power mode of around 1 kW.

V. CONCLUSIONS

In this paper we proposed the ADRALOC system for Automated Demand Response with an Assessable impact on Loads and Occupant Comfort. We presented results from a case study in a real office building where we illustrate the advantages of the system (i.e., load sheds of 3kW within comfort limits). In our future work we are further improving the intelligence of the system in regards to handle more load types and the capabilities of the prediction models. We are also in the process of deploying the system for long term tests

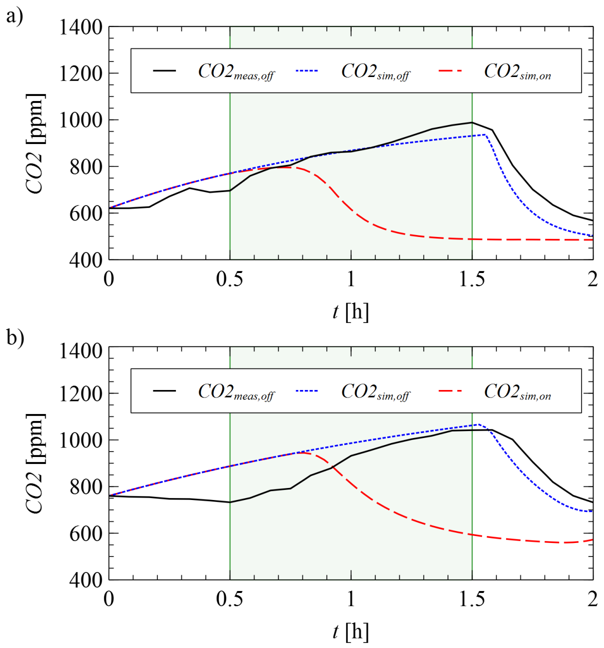

Fig. 5. CO_2 results for November event for a meeting room (a) and an open space office room (b).

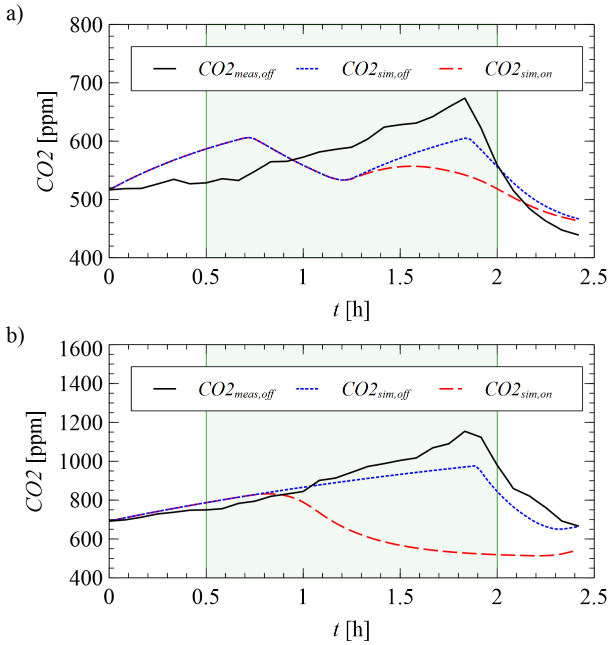

Fig. 6. CO_2 results for Februar event for a meeting room (a) and an open space office room (b).

in two case buildings. We will then evaluate on the various models and how they handle various types of sensors and the information detail required as well as required model accuracy. Finally, we will cover handling missing information, such as sensors or actuators becoming unavailable and general fault-detection.

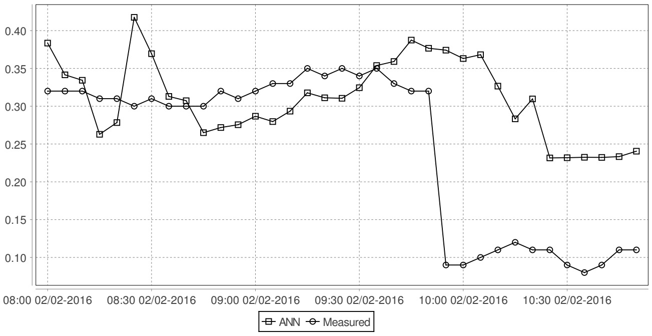

Fig. 7. Load forecasting results for the ventilation system.

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