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Experimental test on the performance of building and district algorithms to enhance penetration of renewables in residential districts

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Abstract

The objective of this work is to present the configuration of the energy management system acting at building and district level developed in the H2020 project SABINA. The solution is tested experimentally in real time in a semi-virtual environment under similar conditions to what could be found in a real district to validate its capabilities. System consists of two physically distant laboratories, which simulate two buildings of the same district with energy management algorithms acting at building level and an algorithm acting at district level as part of a Demand Aggregator. The SABINA solution consists on a central broker that gathers and stores the information from all the elements involved: the semi-virtual buildings, the market interface, the weather forecast and the setpoints from the building algorithms and the district algorithm. The main novelty is associated to the presence of an experimental platform that allows testing building and district control strategies at the same time in a semi-virtual environment and in real time. The way that buildings algorithms and district algorithm communicate and exchange information is a key aspect to activate the energy flexibility in residential districts.

Introduction

According to the International Energy Agency (IEA, 2019), following the actual energy policies, the electricity consumption of the residential sector will account for the 24% of the worldwide electricity demand by 2030. This huge share of energy consumption puts lights on the critical challenge to decarbonise the residential sector. In recent years, the development of smart meters has enabled a bidirectional connection between grid operators and buildings users that makes possible a smarter management of the buildings' consumption. In particular, Demand Side Management (DSM) has the potential to exploit the residential electrical flexibility using heat pumps (Péan 2018), appliances, lighting, electric vehicles charge and to represent the pulsing heart of the incoming revolution on energy decentralization. Residential DSM mainly lies on two independent concepts. The first one is the energy efficiency improvement by means of an optimized management of the building operation. This is generally performed by a Building Management System (BMS) acting at building level. The other one is Demand Response (DR) (Behrangrad, 2015) that consists of requests made by an upper-level entity concerning energy consumption increase or decrease. However, several barriers related to technology, regulations and to the electricity markets are still present. Technically, prosumers (buildings that are both energy consumers and producers) may contribute in the electricity market. However, for DR services, the impact of a unique residential building is almost negligible due to its low power and energy capacities. For this reason, gathering the available energy capacities of several prosumers seems to be an effective way to overcome this limitation. The actor that manages the energy capacities of many prosumers together is generally called Demand Aggregator (DA). The figure of the DA is emerging as a new type of energy services provider that can modulate the electricity consumption of a group of consumers according to the peak electricity demand or other grid requirements.

The authors did not find any study addressing the complex challenge of creating a centralized DSM system that integrates the optimization at both building and district level and the real-time communication between all the actors involved. In the present research, conducted in the framework of the European H2020 project SABINA (2017), a complete DSM platform has been set up and tested. The solution is applied to a semi-virtual system that involves the real-time connection of virtual components (such as the building models simulated with EnergyPlus) and real equipment (such as weather and photovoltaic stations, a water-to-water heat pump and a community electrical battery). This semi-virtual approach represents the first step of the project with the objective of testing the functionality of the whole SABINA platform and their elements before the implementation in field pilot sites.

In contrast to many other research works where the DA knows all about the buildings' consumption, Lipari et al. (2017) and Olivella-Rosell et al. (2017), inSABINA, the only information that the district algorithm has from the building isthe forecasted upward/downward electrical flexibility respect to a baseline operation, the forecasted rebound effect of the DR and thus the efficiency related to a specific DR activation. Of course, it has other energy, market and emissions related information to run the optimization, but has very few information from buildings. On the other hand, the Building Algorithm (BA) uses an encoder-decoder architecture based on long-short term memory (LSTM) neural networks (Sutskever, 2014) to model the thermal aspects (i.e. building envelope), which are trained using the available detailed EnergyPlus modelsof the case study's buildings.

The present paper focuses on the complex communication chain between all the actors participating in this real DSM case study. It addresses solutions and drawbacks that have come out during the implementation process and it provides useful guidelines for the correct repeatability of the DSM configuration proposed.

Experimental framework

Concept overview

As shown in Figure 1, the complete SABINA solution consists in a central broker that acts as the central communication point of the complete DA platform. It collects the forecast information of weather and electricity market needed by the building and district algorithms to prepare their optimizations and strategies. With these data, the algorithms compute the optimizations and they send the setpoints back to the central broker. This latter finally communicates the algorithms strategies to the buildings involved.

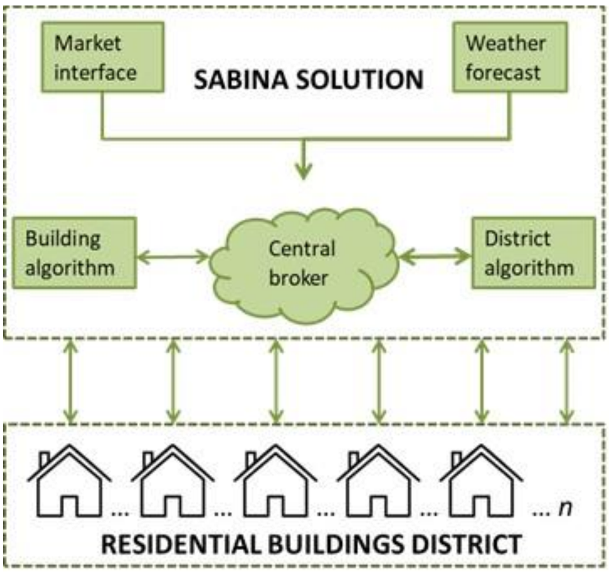

Figure 1: Concept overview

The algorithms are independent from each other, and carry out a multi-level optimization:

- BA consists on the optimization of the energy behaviour of the buildings and acts as BMS. It aims to minimize the energy imported from the grid, thus increasing the use of energy generated on-site (photovoltaic energy production). It uses a model predictive control (MPC) optimization needing to retrieve forecast data from the central broker, Taddeo et al. (2020). The equipment that can be controlled by the BA are listed in Table 1.

System	Controllable setpoint	Range
Heat pump	Supply temperature	40-55 °C
DHW tanks	Bottom temperature	35-50 °C
Battery	Charge/Discharge	±4 kW
Rooms	Temperature	19-25 °C

Table 1: Controllable setpoints and ranges

- MIDA counts on several buildings of the same district and asks them for an energy consumption increase or decrease, Casals (2019). These activation requests are done with the objective to minimize the CO_2 emissions of the electrical grid and they are performed on a daily basis. Forecasted data regarding electricity price and CO_2 emission factors are retrieved from the central broker.

Semi-Virtual laboratories environment

The buildings district is reproduced by the combination of several building simulation models created in EnergyPlus. Two residential buildings of the district are emulated in the IREC laboratories, each of them emulated in one laboratory and interconnected to exchange the weather and photovoltaic production data from SEILAB (located in Tarragona) to SMARTLAB (located in Barcelona). Both emulated buildings have similar features, although there are some important differences.

The SEILAB laboratory includes as real components a water-to-water heat pump, a photovoltaic station and measurements of outdoor meteorological conditions. Data from SEILAB are transferred to the building models accounting for the external conditions, while information on water supply temperature from the real heat pump is provided to one of the building models, which gives back information on the return temperature to the heat pump from the simulated thermal load.

The SMARTLAB laboratory includes a semi-virtual building that uses the same meteorological data as SEILAB. It is equipped with a real ion-lithium battery with a capacity of 10 kWh that provides and receives measurements to and from the building model in EnergyPlus. This modular set up aims focusing on the thermal flexibility provided by the heat pump in SEILAB and, separately, on the electrical flexibility provided by the battery in SMARTLAB.

The simulated buildings are representative of a Spanish multi-story building of the period from 1991 to 2007 and they follow the building code NRE-AT-87, which building typology is described by Tejero et al. (2018). The two buildings have the same geometry and they consist in four identical dwellings with two thermal zones per dwelling, each one with a different occupancy level. To simulate the diversity of the occupants' behaviours in residential buildings, appliances and lighting consumptions follow stochastic profiles for Mediterranean buildings according with Ortiz et al. (2014). Then, each dwelling occupants have different behaviour resulting in different energy demands.

Therefore, the real part of the system includes the equipment installed in the laboratories, SEILAB and SMARTLAB. Péan et al. (2019) perform a detailed description of the laboratories. Figure 2 simplifies the interaction between virtual and real part in the semi-virtual environments. The white-box building models simulate, for both SEILAB and SMARTLAB, the thermal loads, the electrical loads, occupants' behaviour and thermal/electrical equipment performance.

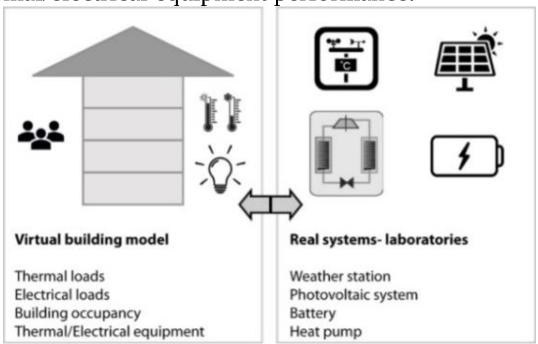

Figure 2: Semi-Virtual configuration

Methods for communication and data exchange

Efficient communication architecture is crucial for a real-time DSM implementation. In the present study, the entire communication platform comprehends several sub-parts and protocols, which are schematically depicted in Figure 3.

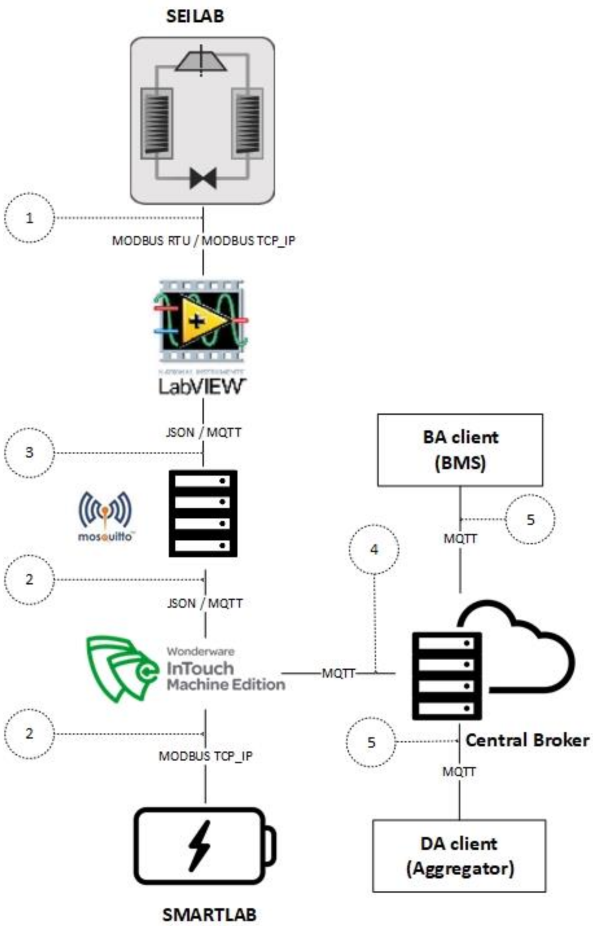

Figure 3: Communication protocols and architecture

1. *Internal communications in SEILAB*: a specific laboratory interface programmed in LabVIEW (2018) allows communication and data retrieving from sensors and actuators. Communication between the SCADA system programmed in LabVIEW and the different sensors, actuators, the heat pump and other devices from the laboratory is implemented with Modbus protocol. The exchange of information between the laboratory and the EnergyPlus model is done via FMI (Functional Mock-up Interface) communication. The basic LabVIEW package does not support the FMUs (Functional Mock-up Units) for co-simulation. Because of that, the use of Python is needed for communicating with the FMU. The use of the Python library *FMPy* allows data exchange between a Python script and a FMU file. Once the data is retrieved from the FMU file, the information is sent to LabVIEW via TCP/IP protocol, creating a server in Python for the exchange of data between the two applications. The data is grouped in an array, separating each variable with a comma. Due to the TCP/IP protocol, the array length has to be constant and it has been set to 64 bits. Once all the variables are grouped in the array, if there is still space left, these empty bits are filled with the character 'Z' as a stop character.

2. *Internal communications in SMARTLAB*: similarly, the central communication node is a SCADA that has been developed using Schneider Electric's Wonderware InTouch Machine Edition program.The SCADA has a driver library (a pack of small programs that enable the functioning of a communication protocol), with a set of communication protocols available. It acts as the central node of the laboratory and uses the SCADA libraries MOTCP (Modbus TCP protocol) to communicate with the local concentrator boards and a MQTT library (MQTT Publisher/Subscriber Protocol for IoT Applications) to communicate with the Mosquitto broker. These local concentrator boards provide a common communication interface to the power emulators, from Modbus TCP to controller area network (CAN) and to the real devices.

3. *Intercommunication between SEILAB and SMARTLAB:* it is the link between SEILAB and SMARTLAB used to transfer the status of the laboratories, weather and PV information, as well as operating variables from SEILAB that will be stored in the SMARTLAB database (named Mosquitto broker in this paper).A custom MQTT IREC broker has been implemented to communicate SEILAB and SMARTLAB. This MQTT broker is hosted in a raspberry pi and it is a Mosquitto server. LabVIEW (SEILAB) does not support natively the use of MQTT communication. For that, the use of a MQTT driver is needed. This driver allows subscribing and sending data to a MQTT broker. However, simultaneous connection with two different brokers is not supported. The method adopted is to send data from SEILAB to SMARTLAB, differentiating between the data that remain in SMARTLAB and

the ones that are sent to the central broker. Using two different topics in the MQTT broker in SMARTLAB, the data is sent from SEILAB to SMARTLAB and from SMARTLAB to the central broker including the information from both laboratories.

4. *Communications between laboratories and the central broker*: Communication with the central broker is done through SCADA client. The SCADA acts as a gateway between the Mosquitto broker and the central broker. This is done using an external python script. This latter receives and sets data using an MQTT client connected to the central broker. The collected data are introduced in the SCADA as an external data file during project runtime ("Recipes Tools").
5. *Communication between algorithms and the central broker*: both BA and MIDA have their own client that subscribes and retrieves/stores data in the central broker through MQQT protocols.

Regarding the simulation itself, Figure 4 describes data flow between all the communication points of the experimental test.

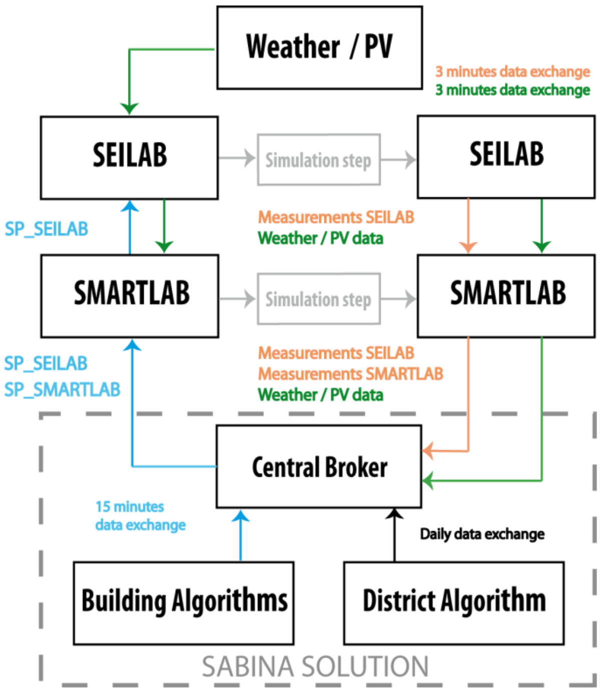

Figure 4: Data flow in the experimental platform

As initialization process, SEILAB collects weather information and it opens the communication with SMARTLAB. These first steps allow initiating the simulations since they provide to the models their initial inputs. Then, the two laboratories perform a simulation step and compute the outputs (*measurements*). Each 3 minutes, SMARTLAB collects the outputs of both systems and publishes them, together with the weather data, to the central broker. This latter stores and provides an on-line real-time graphical representation of the data published. To end the communication chain, SMARTLAB subscribes to all the setpoints (for both SMARTLAB and SEILAB) and sends those corresponding to SEILAB through the Mosquitto broker. In this way, the virtual models have all the inputs needed to perform the further simulation step. Thus, the process is repeated for the entire duration of the test

The BA subscribes and considers the information stored within the Central Broker in order to perform the MPC for both buildings. With both the data received from the central broker and the weather forecast (this latter also published in the central broker), BA computes the optimal setpoints for the controllable elements in the buildings. Then, the optimal setpoints are published back to the central broker with a frequency of 15 minutes.

On the upper level, MIDA establishes a daily data transfer with the central broker in order to retrieve the information published by the forecasts and the BA and to communicate DR activation requests.

Data transfer is based on JavaScript Object Notation (JSON) messages. Figure 5 shows, as example, part of a JSON message sent by the BA. The first part of the message represents the zone temperature setpoint communicated to the virtual thermostat of the fourth floor dwelling (DW4). Notice that the timestamp is in Spain local time zone (UTC + 2 hours) and it is included as well as the exact value (22°C) of the temperature setpoint. While the second part refers to the setpoint sent to the real battery. In this case, the message does not refer to a specific dwelling (as the temperature set point was sent to the id DW4) because it is a community battery for the entire building. Notice that the value sent is 1 which means a full discharge of the battery.


```
...
  "id": "DW4",
  "setpoints": [
   {
    "timestamp": "2019-09-18T12:33:03Z",
    "temperature": 22.0
   }
  ]
 }
"setpoints": [
 {
  "timestamp": "2019-09-18T12:33:03Z",
  "batteryPower": 1
 }
...
```


Figure 5: JSON message example

Results

The entire communication architecture has been validated through real-time testing. Results show that, in the case of the BA, dynamic optimized setpoints are effectively published to the central broker and that the semi-virtual models and real devices in the laboratories effectively react to the setpoints changes. On the other hand, the communication that enable DR events is validated through a practical example. Moreover, an insight of the BA performance is provided.

BA real-time operation and performance

Test officially started on September 18that 00:00 but, in order to set up the entire configuration, preparation started the day before. Figure 6 shows the real-time data display of the central broker where the blue line represents the temperature setpoint received (thermostat setpoint temperature) and the black one represents the measured zone temperature (which is the result of the zone air temperature in the building model).

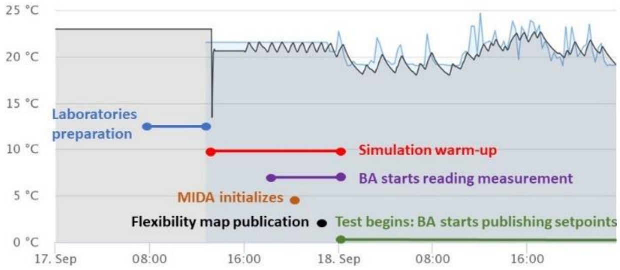

Figure 6: Experiment time-line and BA interaction

The protocol includes a first useful period for laboratories preparation (e.g. battery pre-conditioning, heat pump set up, etc.). When everything is ready, SMARTLAB and SEILAB launch (at the same time, 13:00) their simulation models. A warming up period (red line) is needed since the models should reach a well-stabilized status. During the first hours of the warming up, simulations are not performed in real-time but accelerated in time through Python scripts. In this way, depending on the scripts configurations, it is possible to simulate several days in few hours and to stabilize the models. At 16:00, simulations slow down and they synchronize to real time. From 16:00 to 00:00 test runs in real time and with all the equipment working. However, fixed setpoints (notice that the blue line is constant) are internally sent to the systems by the Mosquitto broker located in SMARTLAB. This period is crucial for the algorithms initialization and performance. Indeed, at 18:00 the BA starts reading the measurements from the central broker in order to create and publish the flexibility map. This latter is an estimation of the upward/downward flexibility capacity of the building compared to the forecasted baseline consumption, Canals et al. (2019). Figure 7 shows the real-time representation displayed in the central broker (published the day before at 11pm with the forecast of the entire day after). In this representation, the black line represents the forecasted building energy consumption while the green line and the blue line represent the forecasted capacities of the building to increase or decrease its consumption for a given hour, respectively.

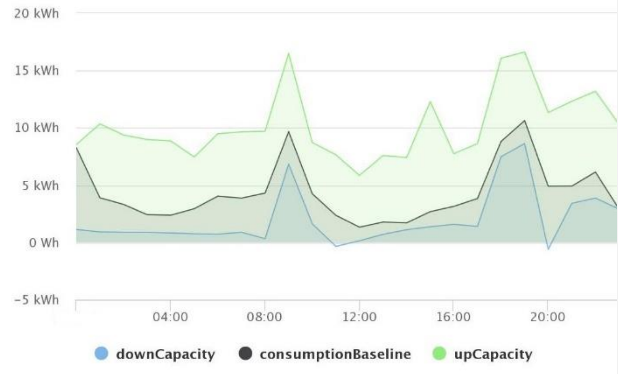

Figure 7: Flexibility map displayed on the central broker

Flexibility map is used by MIDA (that initializes at 8.30pm) in order to compute the DR event for the day after. Finally, BA takes control of the setpoints and the complete DSM configuration is on the move. Notice that, in Figure 6, from 00:00 of September 18thset point (blue line) dynamically changes and that the zone temperature tries to follow it. This image taken from the real-time broker clearly shows that the communication architecture proposed successfully manages to transfer real-time information to the equipment.

In order to evaluate algorithm performance against its optimization objective, the same platform has been tested with both optimized setpoints (computed by the algorithms) and with standard setpoints (scheduled ones). The first solution is called *SABINA Scenario* while the second one is called *Reference Scenario*. Scenarios have identical boundary conditions such as weather data, people occupancy, appliances profiles for the same buildings. Actually, the only difference lies in the system setpoints. The key performance indicator used to evaluate the benefits achieved by the BA is the Energy Shift Flexibility Factor (FFs), Le Dréau et al. (2016). In SABINA framework, the building level optimization aims to shift the energy consumption toward sunlight hours in order to maximize the use of on-site renewable energy (photovoltaic). For this reason, Equation 1 represents the formulation of the Energy Shift Flexibility Factor for this case:

$$FF_S = \frac{\int_{DT} l(t)\,dt - \int_{NT} l(t)\,dt}{\int_{DT} l(t)\,dt + \int_{NT} l(t)\,dt} \qquad \text{Eq.1}$$

Where the power consumed *l(t)* during daytime (DT, representing the sunlight hours) is integrated in time, as well as the power consumed during nighttime (NT). Consider that the term *l(t)* represents the building electrical consumption and do not account for grid interaction. FFS = 1 means that all the energy consumption has been realized during daytime hours; meanwhile, FFS = -1 represents the opposite, that all consumption has been done during NT. FFS = 0 means that the total amount of energy consumed during day and night is the same. Figure 8 shows the results for the two scenarios tested, SABINA and Reference. Green bars represent the building energy consumption during daytime meanwhile red bars represents the consumption during nighttime. Notice that, in SABINA solution, the BA achieves to both reduce the total consumption and to shift part of it towards daytime.

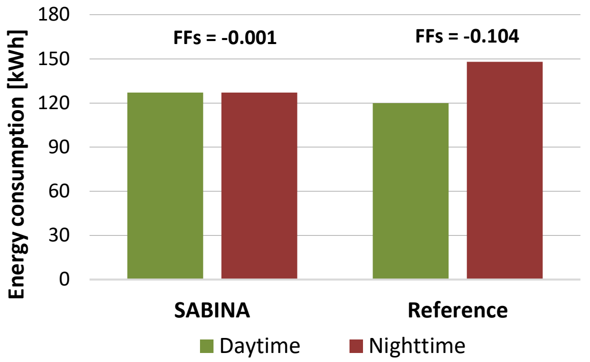

Figure 8: Energy flexibility factor

MIDA real-time operation

DR request consequence could be analysed comparing the BA consumption forecast (computed and published one hour before the DR event) and the actual building consumption during the activation hour. Figure 9 shows the difference between real building consumption (green bars) and the building consumption forecasted by the BA (red bars). The hour before MIDA demand response activation, real consumption and forecasted consumption have a 7% difference between them.On the other hand, during the activation hour, real consumption and forecasted one are completely different. Indeed,Figure 9shows how MIDA's request affects system behaviour. During the DR event, MIDA asked for a downward activation. This means that MIDA asked the BA to modify the setpoints to be sent to the building in order to decrease consumption.Actually, this is what the BA did. Notice that the forecasted consumption of the activation hour (red bar on the right side of Figure 9) is much higher than what the building really consumes (green bar on the right side).

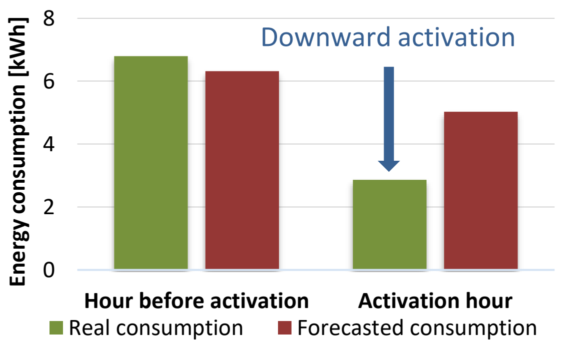

Figure 9: MIDA real-time DR activation

Lessons learnt

The implementation of the entire SABINA platform has been a joint effort between many players that set up the central broker, implemented the BA, the MIDA and tested the entire system in laboratories. However, during tests preparation and operation many obstacles have been tackled. For instance:

- **Real-time flexibility potential evaluation:** in the flexibility activation process, the initial idea was that MIDA would ask for an amount of energy. Then, the BA would respond what could be possible to do and then MIDA would redistribute the flexibility in its portfolio of buildings indicating the final activation value to the BA. However, due to a computation time limitation in the MPC of the BA, it was impossible to do all this in 15 minutes as expected. **Actions taken:** to solve this issue, the process was changed so the MIDA asks for an amount of energy, the BA responds what it can do and then MIDA asks to activate this amount of energy or none. Additionally, the duration of this process was enlarged to 30 minutes.

- **Communication issues between laboratories:** During the first tests, it was observed that communications between laboratories dropped. It concerned to the location of the MQTT drivers, installed in the SCADA that manage laboratory equipment. **Actions taken**: External MQTT drivers (Python libraries) were used together with the drivers implemented in SCADA. Moreover, all the control and monitoring systems in the laboratories were connected to an Uninterrupted Power Supply (UPS) to ensure that they never lose power.

- **MIDA was constantly rejected from the central broker:** MIDA suffered of constant rejections from the central broker. It was finally discovered that there was a problem caused by the MQTT library used for Python and a flag related to the message retention. **Actions taken:** Change the library and the classification of the flag. Once done the problem never occurred again.

- **Messages delays/advances:** Several delays or advances are appreciable in the values stored in the central broker. This is caused by the scheduled message publication in the broker. Setpoints are published every 15 minutes while *measurements* do it every 3 minutes. This does not mean that all messages are sent every 15 minutes, it means that the broker should have all the messages before this 15 minutes pass to publish them all at the same time. However, when a system is subscribed to a topic through MQTT, it is able to read the message at the moment that the broker receives it, even though it is not published. Therefore, when this occurs, the system takes this information before it is published, advancing for some minutes the response of the system and presenting these displacements in the broker. **Actions taken:** No actions taken.

- **No response from the buildings:** it may happen that a building could not provide a positive/negative answer on time to the DA. The solution is done in a way that, when this occurs, MIDA will not take into account the specific building and will perform the optimization without it. Similarly, real buildings could be unable to provide an answer to a flexibility request. Then, the response is considered null and the building is discarded.

Conclusion

This paper has shown the implementation of a DSM platform and its real-time testing in a semi-virtual environment. As first step of a broader application, the communication between laboratories, central broker and algorithms has been implemented and validated. BA successfully publishes real-time optimized setpoints that are then correctly transferred to the laboratories equipment. Moreover, it performs the building consumption shifting expected. On the other hand, MIDA successfully manages to establish a connection with the electricity market, with the forecast services and to request DR event to the BA. The real-time performance is validated thanks to the central broker display that allows the visualization of the results in real-time.

The complete DSM platform implemented gives insight of the practical issues that came out when connecting different actors in a real time system.

Optimizations computational efforts seem to be the main disadvantage. The use of complex optimization strategies such as the MPC slows down the response of the system making unfeasible a fast communication between the building and the district algorithm. Indeed, the optimization of the encoder-decoder models took around 4.5 minutes per control step on a computing workstation with a GPU Nvidia RTX 2080 Ti. Regarding MIDA computational time, it strongly depends upon the number of buildings considered. In the case where the districts includes five hundreds buildings, the computations lasts for less than ten seconds.

Moreover, the articulated communication network implemented comprehends too much communication points (clients, brokers) that make the system very susceptible to internet network problems. Many data back-up strategies have been used in order to make the system able to dynamically react to unexpected operations. However, for real buildings applications, there will not be a communication line between buildings (such as the present between laboratories). Individual servers could be embedded in the local BMS and act as gateway between the building and the central broker transferring the entire set of information.

A remark should be done regarding the real-time simulation architecture. Communicating EnergyPlus with FMI has proven not be the most indicated approach to set up a semi-virtual environment. The communication established by FMI is effective in exchanging weather and control inputs to the systems but is not able to provide the needed communication flexibility with the simulation models. Software communication flexibility (intended as the possibility to access in any time to input/output of the simulation) has to be carefully chosen for a correct implementation of a real-time application.

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