**Project Deliverable Report**

Smart Building – Smart Grid – Smart City

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# Building-side EMS concept and information exchange interfaces definition

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| **Abstract (for dissemination)** | A comprehensive report on 3Smart Building-side Energy Management System (EMS) concept is given. |
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## Revision history

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# Executive summary

The main objective of the project Smart Building – Smart Grid – Smart City (3Smart) funded within the Interreg Danube Transnational Programme is to provide technology and legislative setup for cross-spanning energy management of buildings and utility grids, foremost electricity distribution grids.

One of the main pillars in reaching that objective is to derive a modular energy management tool for buildings which can be easily adapted to different configurations of the building and adds upon the existing building automation system. In this document a concept of such an energy management tool is presented. It is envisioned as a hierarchical structure that consists of three main levels: zone level, central heating/cooling medium preparation level and building microgrid level.

The main underlying technology in the conceptualized energy management tool is model predictive control. It enables to take into account relevant current building conditions and available predictions when deciding how to actuate the building. The hierarchical approach enables vertical two-way synchronization between the different levels based on providing predicted energy consumption towards the higher level and energy prices towards the lower level. Within each level three main types of modules are envisioned: modules/submodules for identification of relevant models and estimation of states and disturbances in these models – for sensing on a particular level; model predictive control modules/submodules – for decision making on a particular level; and interfacing modules/submodules -- for implementing the decisions on the existing building hardware on a particular level.

For each level are posed hardware and functional requirements on adaptation of the typical configurations of building automation systems such that they can be upgraded with the coordination services offered by the building-side energy management tool.

Very important is the concept of building-grid interaction which bundles the grid-side and building-side modules of the envisioned tool for cross-spanning energy management of buildings and grids. The main driving mechanisms for it from the grid side are presented, and also the envisioned interaction between the building- and grid-side.

Finally, input-output functional interfaces are defined for each of the modules and submodules of the building-side tool to kick-off their synchronized developments by different development partners of the 3Smart project.

# 1. Introduction

Buildings are complex nonlinear systems composed of many coupled subsystems such as Heating, Ventilation and Air Conditioning (HVAC) system, building zones, microgrid with energy production units, storages and controllable or passive loads, etc. Typical applications of building Energy Management System (EMS) are oriented only locally – to a specific subsystem, while neglecting interconnections and cooperation among all constituent subsystems. As a result, building as a whole achieves uncoordinated and non-optimal behaviour, see Figure 1.1 for illustration (see also the results of state-of-the-art analysis performed within D3.1.1 document [1]). On the other hand, this also provides an opportunity for additional economic benefits if more subsystems are utilized in a comprehensive and multidisciplinary manner to achieve the mutual goal.

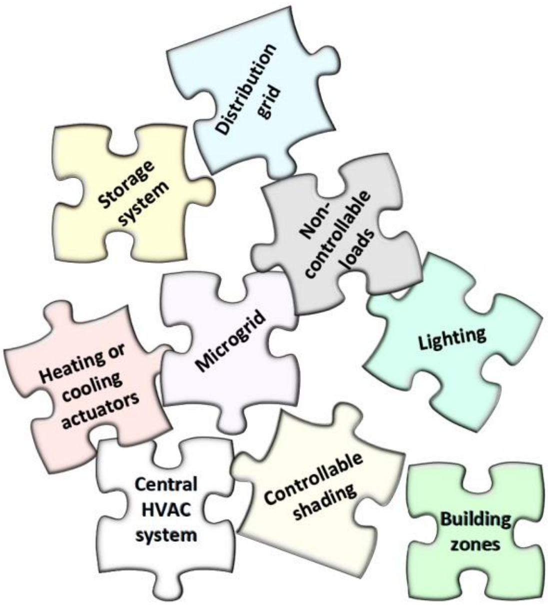


**Figure 1.1:** Standard Building Energy Management concept.

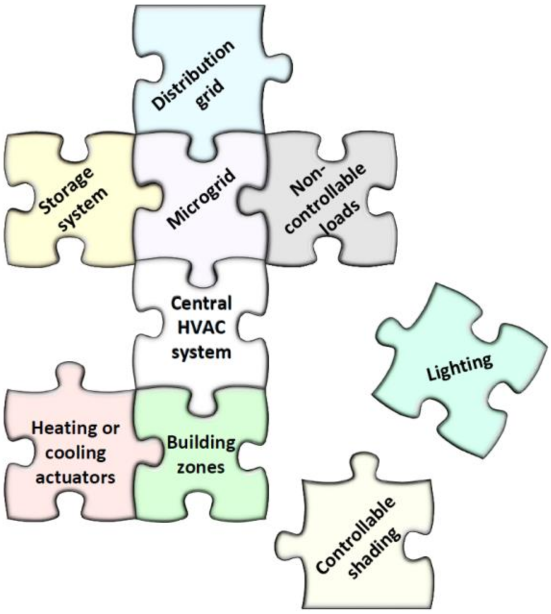


**Figure 1.2:** 3Smart Building Energy Management concept.

The nucleus of 3Smart EMS is a modular Model Predictive Control (MPC) for optimizing comfort and operational energy costs. This puts the 3Smart EMS in a position to provide improved economic and comfort performance compared to standard EMS systems which are not relied on predictions and optimizations. The 3Smart EMS is aimed to be implemented on an open building automation platform added upon the different parts of the existing automation system via small or non hardware interventions in order to impose coordination between those parts, see Figure 1.2. The modular structure of the 3Smart EMS organized in hierarchical levels enables the coordinated operation even if some levels in a concrete implementation instance are missing (perform best with what is available for control). This is enabled via replicated and as much as possible unified interfaces between different levels. Modules of the 3Smart EMS are organized in three levels:

(1) building zones level – encompassing comfort control in all building zones,

(2) central HVAC system level – encompassing the central preparation of media for heating or cooling in the zones, and

(3) building microgrid level – encompassing energy storages and/or loads and/or generation units and/or energy conversion units and/or utility grids junctions, all inter-connected via common electricity and/or heat supply lines within the building.

Such levelization is covering the most general building setup. Although additional options like automated lighting or controllable shading will not be considered in this project, the flexibility of the approach will enable easy integration of them and any other building subsystem into the developed 3Smart EMS.

# 2. 3Smart Building-side Energy Management System

In the majority of buildings in the Danube region, building-side EMS is either non-existing or limited to different building subsystems [1]. Such situation results with economic underperformance of a building. The idea of the overall 3Smart EMS, which spans through both the buildings and the grid, is to enable chained vertical synchronization of all levels and their corresponding modules and submodules: from those in charge of shaping energy consumption in building zones to those on the grid side that balance the energy market inputs, grid technical constraints and aggregated predicted consumption of all prosumers connected to the grid.

3Smart Building-side Energy Management System consists of three levels following the building energy system vertical decomposition in its major parts: (1) building zones level, (2) central HVAC system level, and (3) building microgrid level. Decision-making modules and submodules of the EMS in these levels rely on predictions and mathematical optimizations of comfort and energy costs.

Improvement of energy-efficiency and comfort can be achieved even through the application of only level (1) modules, if they take into account weather forecast, comfort requirements and heat disturbance estimation and decide on the optimal profile of energy consumption for maintaining comfort conditions in each zone. If no other 3Smart EMS level is present, energy prices from the utility grids are directly transferred to level (1) which then induces energy-cost-optimal behaviour for maintaining comfort instead of the energy-optimal behaviour for maintaining comfort.

By including also level (2) next to level (1) in the 3Smart building-side EMS benefits can be multiplied since conventional solutions introduce only energy-connections with the central HVAC system, which consequently cannot take into account the current and near-future energy requirements in the zones, and thus operates with reduced efficiency. Especially important is the ability to intelligently shift the power demand based on the smart grid signals or predicted outdoor temperature that shapes the efficiency of the central HVAC system.

Finally, coming to the level (3), the 3Smart building-side EMS introduces a possibility to manage energy storages, energy conversion systems and controllable loads on the building level. Hence, one can induce minimum energy costs with respect to the planned energy consumption and production profile while making the building an active entity of the smart grid or of the district-level smart energy distribution system. Consequently, level (3) enables further modular build-up of the concept beyond the building area and towards smart districts, grids and cities.

The proposed 3Smart building-side EMS simultaneously adapts the heating/cooling profiles in all zones, central HVAC system operation and energy flows from/to building energy storages and to controllable loads through modular solutions applied on different levels of the building and intra-level coordination mechanism, that rely on mathematical programming and optimal control. The following features of the proposed EMS that do not exist in the current, off-the-shelf, building management products are:

(1) hierarchical predictive control and possibility of operation even if different hierarchy levels of the EMS are missing (perform best with what is available for control, in any combination of existing modules);

(2) openness to integration with versatile building automation networks and heating/cooling elements types in zones, independent of the vendors of low-level controllers, as long as they can be networked and re-configured from local controls to sensors/actuators data coupling to the network, and back;
(3) non-invasive adding upon the existing equipment in zones, in central HVAC, and on the level of building microgrid components, which means none or small hardware interventions;
(4) full anticipation of smart grid conditions and weather forecast in operation with which the building becomes a responsive subject within the smart distribution grid and smart city;
(5) lowering the cost of building operation with respect to current building conditions enabled by smart interconnections between the modules on different levels;
(6) estimation of heat disturbances on the zone level that indicate any additional heat input or sink compared to the current building model used for control (occupants, equipment, window blinds), with possibility to tune models for heat disturbance predictions as well as comfort requirements predictions and exploit them for efficiency gains in predictive zone control.

The key methodology 3Smart EMS relies on is MPC of dynamical systems and the underlying mathematical programming methods. More specifically, the coordination between modules will be attained by communicating the optimized consumption profile to the higher level and energy cost sensitivity to the lower level in the vicinity of the currently declared consumption profile from the lower level (in short, “price-consumption talk” between the levels). This will also enable the possibility of direct communication of each level with the grid side if the corresponding higher levels of the 3Smart EMS are missing on a particular building. That is the essential principle proposed for interconnecting the MPC modules/submodules on the different levels of the EMS.

When it comes to building zones, very few information about the heating/cooling elements in zones will be required for MPC on the zone level. For example, on the building zones level, the information needed for the MPC that decides on the heating/cooling energy to be exerted in each of the zones will be the description which energies are possible to be exerted from the heating/cooling elements for a given temperature in zones and planned medium flow and temperature decided on the HVAC level.

3Smart EMS system is also a demand response solution, which monitors electricity consumption and automatically sheds electricity loads to reduce their usage during peak periods (Critical Peak Pricing). A building equipped with 3Smart EMS will be able to participate in electric load aggregation. This is one of the most effective means of maximizing savings and mitigating risks in today’s emerging power markets.

The predictive control modules on each level have to be connected with proper interfaces of the EMS towards the automation equipment available to enable the accomplishment of the following commands generated by the MPC core of the EMS:

- on the building zone control level: optimal heating/cooling energies for each zone (this can be broadened with mass of air and water for the case when also forced ventilation comes into play in the building configuration for regulation of air

freshness and humidity in zones, but due to the 3Smart pilots structure it is left out of the developments for now)

- on the central HVAC system level: central heating/cooling medium outgoing temperature and/or flow
- on the microgrid level: energy flows in time from/to the energy storages available (e.g. batteries), and/or (more rarely when distributed generation is based on sun or wind, but definitely a choice when it is based on fossil fuels or biomass) energy flow commands for production of the distributed generators, and/or commands for controllable loads.

The basic functional diagram of the entire 3Smart EMS on the building side is shown in Figure2.1.

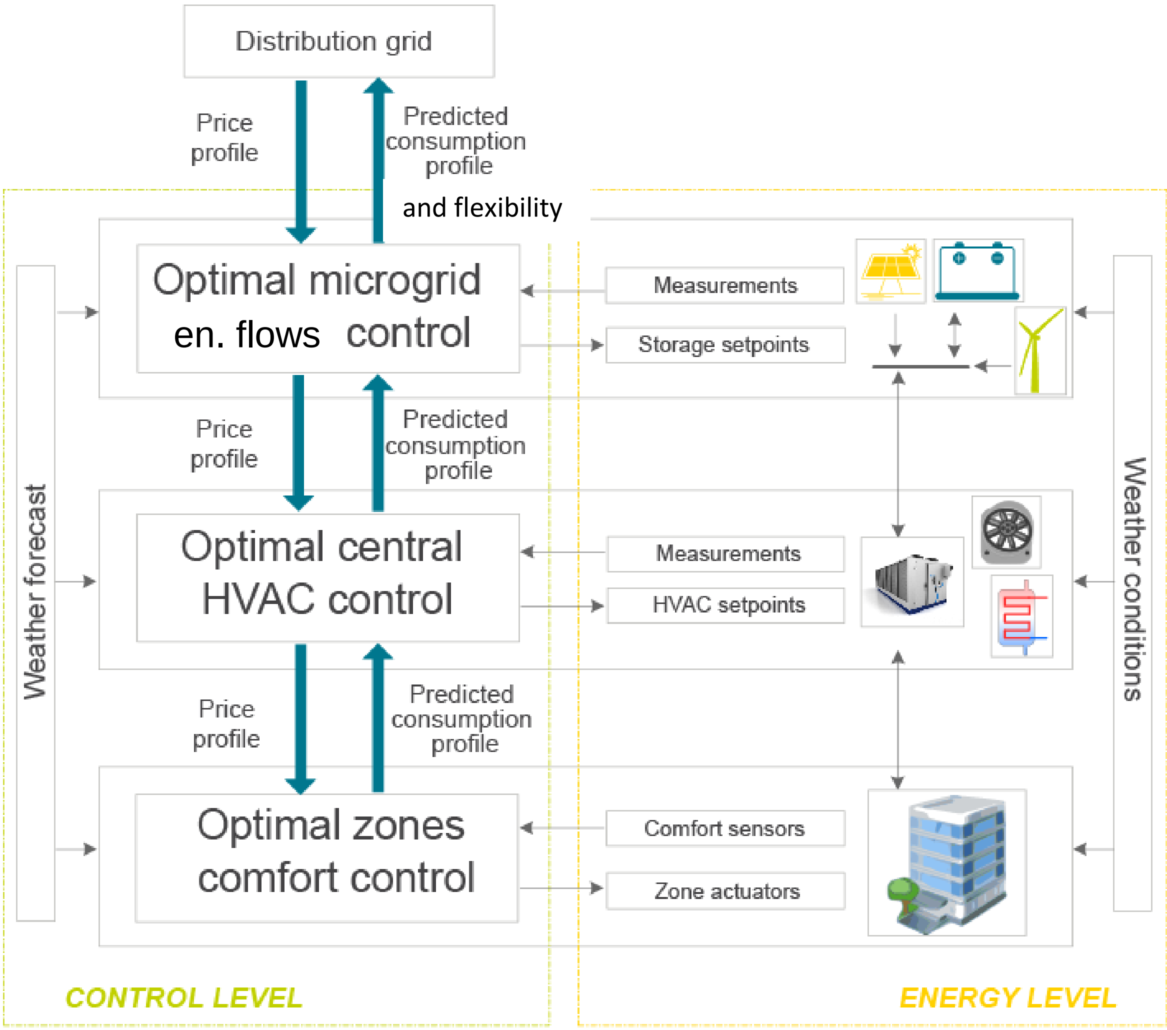


**Figure 2.1:** Functional diagram of the 3Smart EMS hierarchy on the building side.

Prediction possibility exists for weather, grid conditions and grid energy prices (obtained outside the building EMS), and users behaviours (occupancy, shading position, electronic equipment usage, etc.), user comfort setpoints, non-controllable heating and electricity consumption, non-controllable distributed production which are all exploited in the proposed scheme to ultimately achieve the cost optimum of building operation. All levels exploit the weather forecast information in corresponding MPC algorithms, while the highest-level module present also takes over the forecast

of smart grid energy exchange terms and conditions. The interface between control and estimation applications on the one side, and the physical world on the other, is actually a two-way real-time database including relevant building, exterior variables and also internal EMS variables for mutual modules synchronization. On the physical level, the building microgrid consists of generation and storage units, as well as of controllable and non-controllable loads. The storage units are accompanied with a storage management subsystem towards which the commands on energy flows from the microgrid MPC module are directed. It is important for data-based tuning of mathematical models used to enable prediction to acquire measurements of controllable and non-controllable loads, as well as of microgrid generation on the generation units level. Measurements from the HVAC system regarding prepared medium for the zones and returned medium from the zones are also required. Existing controllers within all three levels are required to be networked and configurable.

For implementation of the MPC it is crucial to have a valid mathematical model of the building that describes the relations between zones temperature and thermal power. Hence, system identification techniques need to be employed to obtain the dynamical behaviour of zones and actuators in the zones and in the central HVAC system. The identified zone model can then be used to estimate heat disturbances in zones as well as other potentially unmeasurable model states. On the microgrid level identification of the storage model and estimation of the storage states has to be performed.

The energy consumption models, meaning relations between the commanded variables from the MPC and actual source energy required for these commands to be realized, should be assessed on the zones and central HVAC levels in order to be included in the respective model predictive control problems (on the microgrid level this model is assumed a trivial identity model – i.e. the needed balance energy will be the energy taken from the grid). On the zones level losses in thermal energy between the central HVAC production place and the zones should be taken into account. On central HVAC either input thermal energy from the district heating or input electricity for cooling need to be modelled with respect to the planned profile of commands for medium temperature and flow and the required heating/cooling consumption declared from the zones level.

The overall three-level hierarchical control with depicted inner processes and interconnection to real building systems is presented in Fig. 2.2. Each of the levels consists of prediction and estimation block since predictive optimal controller uses future data profiles for calculation of control commands. In addition, some variables are impossible/hard to measure and mathematical models are used for their estimation. The very centre of each of the levels is the model predictive control algorithm that takes into account different factors for each level (we also name it MPC core of the level). The optimal control commands are first passed to interfaces that, based on them, create actuation signals for existing commercial equipment in the field. The data exchange is performed via information bus or, in other words, real-time database situated either on the central building computer/server or in a cloud computer facility outside the building. From the physical perspective, the optimal control signals are taken from the database and passed to different actuators. Finally, the three levels are interconnected by the so-called price-consumption talk. The most significant part of such a concept is modularity where each of the levels may operate independently, in a standalone way. Previously controllable loads in this case now become passive, non-controllable loads and opportunity for cost savings is therefore not fully exploited, but the remaining modules operate in order to achieve best cost for the building operation in such a

constellation. The non-controllable loads, if they affect the optimization of energy balances in the existing levels, need to be predicted.

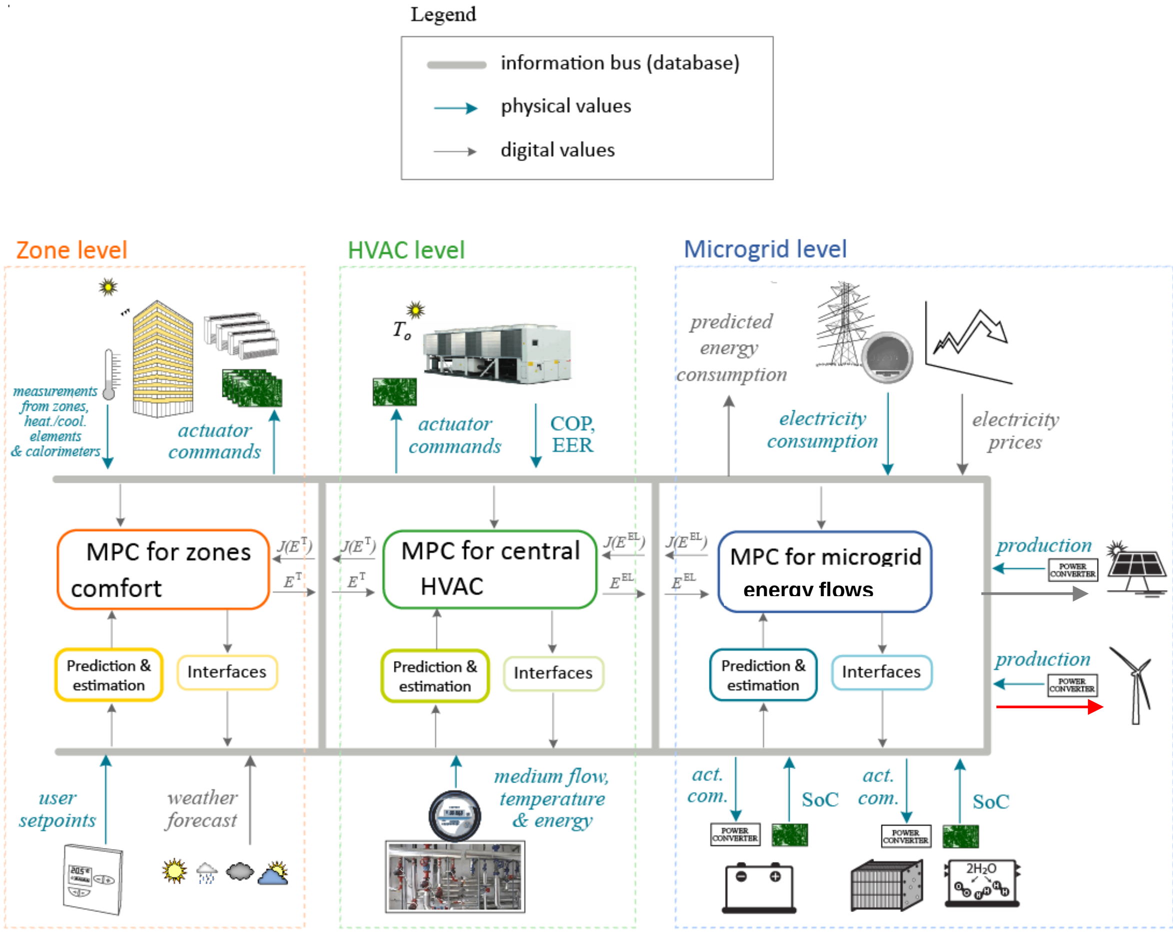


**Figure 2.2:** Three-level hierarchical coordination.

## 2.1. Building zones level

Building zones level represents the lowest level in the proposed hierarchy. This level (shown in Fig. 2.3) takes into account weather forecast, comfort requirements (user set points), energy prices from the higher level, as well as predicted disturbance and comfort set points profiles and decides on the optimal profile of energy consumption for maintaining comfort conditions.

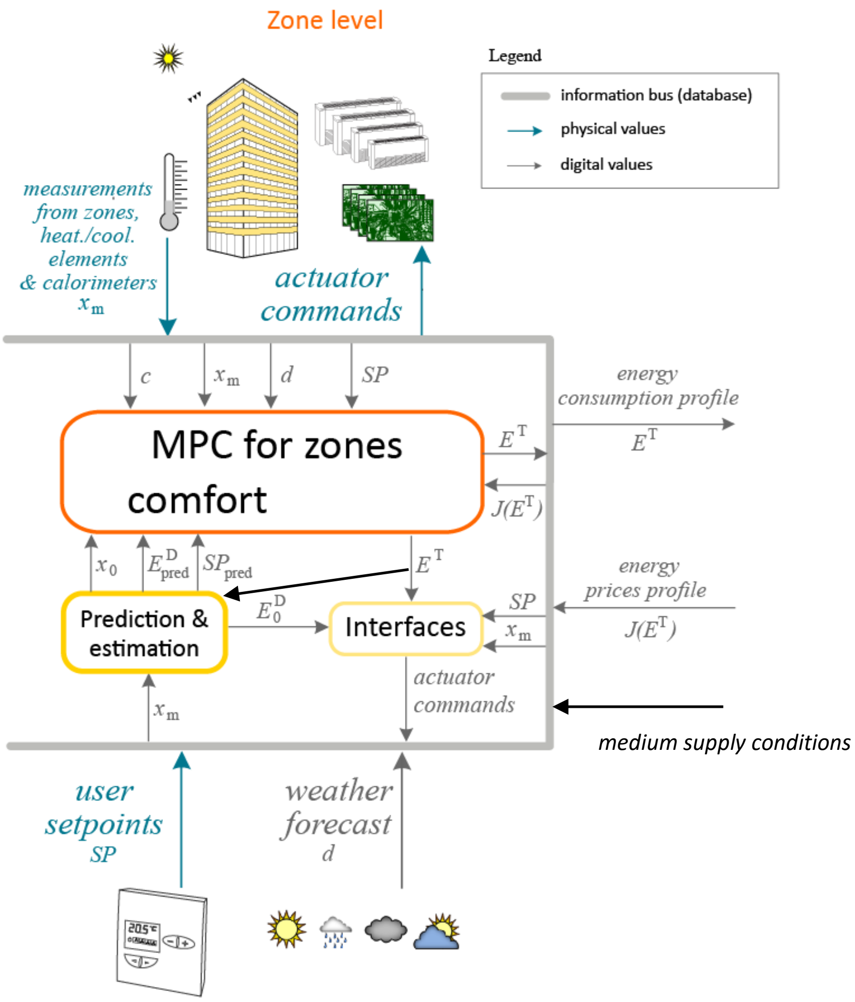


**Figure 2.3:** Building zones level optimal control concept.

The proposed building zones level of the 3Smart EMS is composed of three major parts:

(1.1) Prediction and estimation module that estimates current states ($x_0$) and disturbances ($E^D{}_0$) of the zone thermal model and predicts the future heat disturbance profile ($E^D{}_{pred}$) as well as the temperature setpoints profile ($SP_{pred}$),

(1.2) MPC for zones comfort module employed to calculate optimal thermal energy profiles ($E^T$) per zones by taking into account weather forecast (d), predicted disturbance profiles, current building state, comfort requirements of the end users (the current and the predicted ones), and planned supply medium conditions and energy prices from higher levels ($J(E^T)$, c); supply medium conditions are needed to assess available energies from heting/cooling elements.

(1.3) Interface module which is a link between optimal thermal energies calculated by MPC and real actuator commands required to fulfil the optimal energy commands by heating/cooling elements (fan coils, radiators, floor heating, etc.) and compensate for fast zones disturbances. The interface module can also impose coordination between heating/cooling elements while delivering the required energies to zones such that the heating/electricity power variance is minimized and peak energy demand suppressed.

The MPC and interface blocks will be executed only when the control via the 3Smart EMS is activated, i.e. when at least some zone is required to be controlled through the EMS.

Interface block can be realized in both centralized and decentralized fashion. Centralization is performed by grouping heating/cooling elements based on the major supply duct they are connected to. By doing so and by using a centralized controller for all elements in the group, the operational cost can be additionally reduced by controlling the heating power peak loads and variance on the supply duct. Depending on the complexity of the heating/cooling setup, decentralized implementation can offer significant reduction in computational power required to calculate the actuator commands. The actuator commands depend on the heating/cooling setup. For example for the setup at UNIZGFER, which comprises fan coil units, those commands include fan speeds and optionally valve positions (if they exist) of involved fan coil units. For other setups like e.g. radiators and floor heating those commands will be only the valve positions on the supply duct of the heating element. If the system includes also valves on major supply ducts, these valves can be controlled by the interface directly through a rather simple logic – for a long enough period when no energy is needed by any of the fan coils on a supply duct, these valves will be closed to reduce unnecessary heat losses and possibly a thermal discomfort.

The important feature of the proposed approach for the zones comfort control within the 3Smart EMS zones level presented in Fig. 2.3 and explained above is a direct control of thermal energy inputs per zone rather than generally accepted temperature control. By doing so, a high level of modularity and flexibility for different actuators, configurations and test sites is gained for fast replication of the method. The unmodeled disturbances, such as occupancy, lighting or electronic equipment, are no longer implicitly compensated. In order to ensure offset-free comfort control and to be able to compensate such disturbances, an estimator is introduced in the control loop. The biggest advantages of the direct control of energy inputs on heating/cooling elements are: (i) simple interaction with other levels by ''price-consumption'' talk, (ii) possibility of direct economic cost minimization by using the known price of the energy, (iii) possibility of thermal power variance minimization lowering thus the maintenance cost for central HVAC system and reducing the peak operation costs, (iv) possibility to act in tight comfort requirements where the required reference temperature following is not possible with local hysteresis controllers which are in principle present in current decentralized temperature control solutions for zones.

Guided by the set-up installed on the UNIZGFER building and the considerations above, measurements/data required from the zone to implement 3Smart optimal zones level control in a real building are enlisted in Table 2.1.

**Table 2.1:** List of essential measurements required for implementation of the 3Smart zone level (optimal zone comfort control).

<table>
<tr><th colspan="2">Building elements</th><th>Required measurements/data</th></tr>
<tr><td colspan="2">Building zones</td><td>Zone temperature, zone temperature setpoint</td></tr>
<tr><td rowspan="4">Heating/cooling elements</td><td rowspan="4">Fan coils</td><td>Supply heating/cooling medium temperature (optional)</td></tr>
<tr><td>Return heating/cooling medium temperature</td></tr>
<tr><td>Outgoing air temperature (optional)</td></tr>
<tr><td>Fan speed measurement (usually digital signal indicating discrete</td></tr>
</table>

| | | |
|---|---|---|
| | | speed; usually can be considered equal to the speed command) |
| | Radiators | Supply heating/cooling medium temperature (optional) |
| | | Return heating/cooling medium temperature |
| | | Surface temperature (optional) |
| | Floor heating | Supply heating/cooling medium temperature (discussable) |
| | | Return heating/cooling medium temperature |
| Major supply ducts | | Thermal energy meters (calorimeters) – measurements of the supply medium mass flow, temperature and consumed thermal energy |

## 2.2. Central HVAC system level

The second level in hierarchy is the central HVAC system level. With introduction of this level the benefits of the 3Smart solution from the zone level can be multiplied. Namely, the deficiency of the conventional zone level solutions is that they introduce only energy-connections with the central HVAC system without considering the current and near-future energy requirements in the zones, and thus perform with reduced efficiency, usually by maintaining constant output temperature of the medium (or, simply guided by the outdoor temperature through a pre-defined curve) and constant flow. Especially beneficial is the ability to intelligently shift the cooling demand through interaction with the zones level based on smart grid signals or predicted outdoor temperature that is related to efficiency of the central HVAC system.

The HVAC level optimizes the central heating/cooling medium conditioning process and transportation for building climate system operation (chillers, heat stations, distribution pipes etc.). For the case of non-air-based building climate systems, such as fan coils, radiators etc., heating/cooling medium conditioning and flow is optimized with respect to outside weather conditions and required consumption, which takes into account the efficiency of central chiller or heating station (exemplary map shown in Fig. 2.4). The HVAC level provides, in down hierarchical direction (towards the zone level), optimized prices for the predicted heating/cooling demand from zones, and in the up hierarchical direction provides predicted heating/cooling and electricity load to be supplied from the building microgrid or the distribution grid. On this level, the coordination mechanism adds upon the HVAC unit control by calculating the optimal profile of references for its internal regulation circuits for ensuring proper heating/cooling medium temperature and sometimes also flow towards the building.

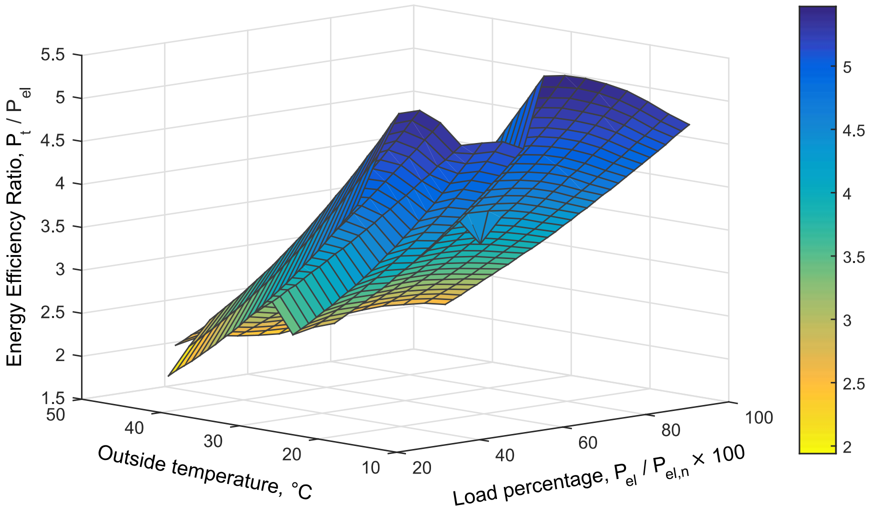


**Figure 2.4:** Example operation efficiency map of the central chiller (type Trane RTAC 200 HE) at University of Zagreb Faculty of Electrical Engineering and Computing for a constant cooling medium temperature and flow.

Figure 2.5 presents the HVAC level optimisation process and connection with the real physical world. Information about building thermal supply requirements $E^T$ is provided from zone level (for different zones and different times on the prediction horizon) together with energy prices from the higher (microgrid) level or directly from the distribution grid. Towards the zone level, HVAC level needs to communicate the predicted profile of supply medium conditions (flow and temperature). Non-controllable heating load (e.g., from digitally non-controllable heating/cooling elements in zones like radiators with thermostat valves) is predicted based on the overall heating load measurement on a calorimeter. Optimisation algorithm takes into account the following information 24 hours ahead: $T_o$ outside temperature forecast, $c$ electricity price profile, corresponding coefficient of performance (COP) for heating or energy efficiency ratio (EER) for cooling, non-controllable loads $E^L$, and temperature profiles from zones T. Outputs are predicted energy consumption $E^C$ and heating/cooling medium temperature and flow commands or some other commands (depending on the test site and flexibility of the central HVAC unit and local controller available). These commands are supplied to an interface of existing commercial controllers in the field and finally passed to central chiller or heating station.

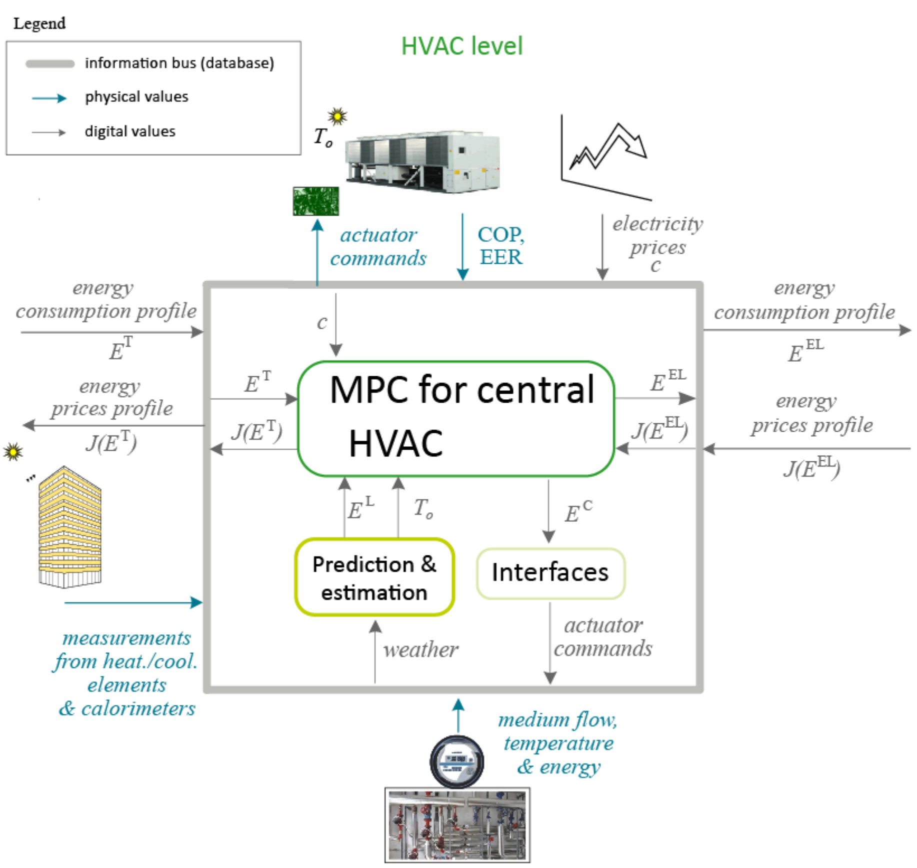


**Figure 2.5:** HVAC level optimal control concept.

Guided by the set-up installed on the UNIZGFER building and the elaboration above, measurements required to implement 3Smart optimal central HVAC control in a real building are enlisted in Table 2.2.

**Table 2.2:** List of essential measurements required for implementation of the 3Smart central HVAC system.

| Building elements | Required measurements |
|---|---|
| Central HVAC system | Thermal energy meter (calorimeter):<br>• measurements of the supply medium mass flow (or, alternatively measured/estimated on a pump, or determined via floor calorimeters measurement),<br>• supply and return medium temperature<br>• overall consumed thermal energy<br>On the zone level it is necessary to measure the outgoing temperature of the heating/cooling element to be able to derive the element model and to create data for prediction of heating/cooling energy requirements per zones. |

## 2.3. Building microgrid level

Finally, the highest level in the building-side EMS hierarchy is the building microgrid level. Microgrid level introduces a possibility to manage energy storages, controllable production and controllable loads on the building level to induce minimum energy costs with respect to the planned

energy consumption and production profile while it makes the building an active entity on the smart grid or on the district-level smart energy distribution system, i.e. enables further modular build-up of the concept beyond the building and towards the smart city.

The microgrid level optimally balances the electrical energy flows from corresponding production and conversion units (photovoltaic arrays, small wind turbines, CHPs), to controllable or non-controllable loads while economically optimally engaging flows from/to storage units and from/to the utility grid in accordance with technical constraints on the flows that need to be respected (a physical example of the microgrid is shown in Fig. 2.6). Sometimes also production units and non-HVAC consumption units may be controllable directly by the microgrid level which gives additional flexibility (e.g., boilers for domestic hot water may be an example).

Microgrid is the core building supply and distribution centre for electrical energy and possibly other energies (gas, heat). The microgrid level exploits the knowledge of combined model-based and data-based prediction of local electricity generation, non-controllable consumption and weather forecast to provide price-optimal energy flow commands or on-off commands to controllable microgrid elements. Distributed storage characteristics and availability in time (electric vehicles chargers and vehicles themselves) may also be included in consideration. The microgrid level receives predicted consumption from the HVAC level (considered here as the controllable load subject to comfort constraints) and energy prices and service requests from the aggregator (energy exchange terms), and it provides optimal actuation to electricity storages and possibly loads by taking into account the current storages state and the state of loads (e.g., temperature in the domestic hot water boiler). The central HVAC system and the zone electricity loads are indirectly controlled via issued price profiles for electricity consumption. It is important to note that storages enable the shift of consumption which makes the microgrid a transformer of electricity prices from the grid level to the building level. In practically all cases where smart microgrid controls are in action, the microgrid lowers these prices in time for the building. Towards the distribution grid level, planned energy exchange and possibly flexibility in energy exchange with the grid is provided for the issued energy exchange terms by the aggregator.

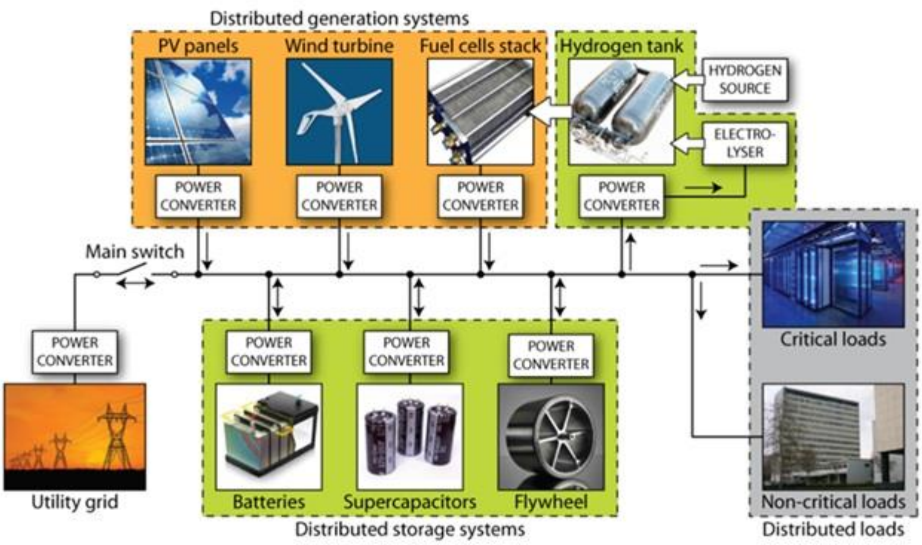


**Figure 2.6:** Exemplary microgrid

Figure 2.7 presents the Microgrid level optimisation process and connection with the real physical equipment. Information about energy requirements are provided from lower levels and electricity exchange terms are received from the aggregator. MPC for microgrid energy flows takes into account the following information: non-controllable consumption profile prediction $E^{L}$, local generation profile prediction from photovoltaics $E^{PV}$ and wind turbine $E^{WT}$, storages state of charge (e.g. for batteries and hydrogen-based storage with fuel cells available, $SoC^{BAT}$ and $SoC^{FC}$), controllable loads state and electricity exchange terms. While taking into account all the physical constraints of the available equipment, optimisation algorithm computes the required charge/discharge energy requirements for electrical storages, i.e. batteries $E^{BAT}$ and fuel cells $E^{FC}$, and the energies for controllable loads, production and conversion units, which are further passed to information database and via available interface submodules finally delivered as reference values for targeted power converters or on-off switch commands for the loads. In standalone operation, microgrid simply uses available storages for buying at low price and selling at high price while satisfying load requirements. In hierarchically interconnected operation, microgrid level transforms electricity prices towards lower hierarchy levels by smart storages, loads and production units actuation.

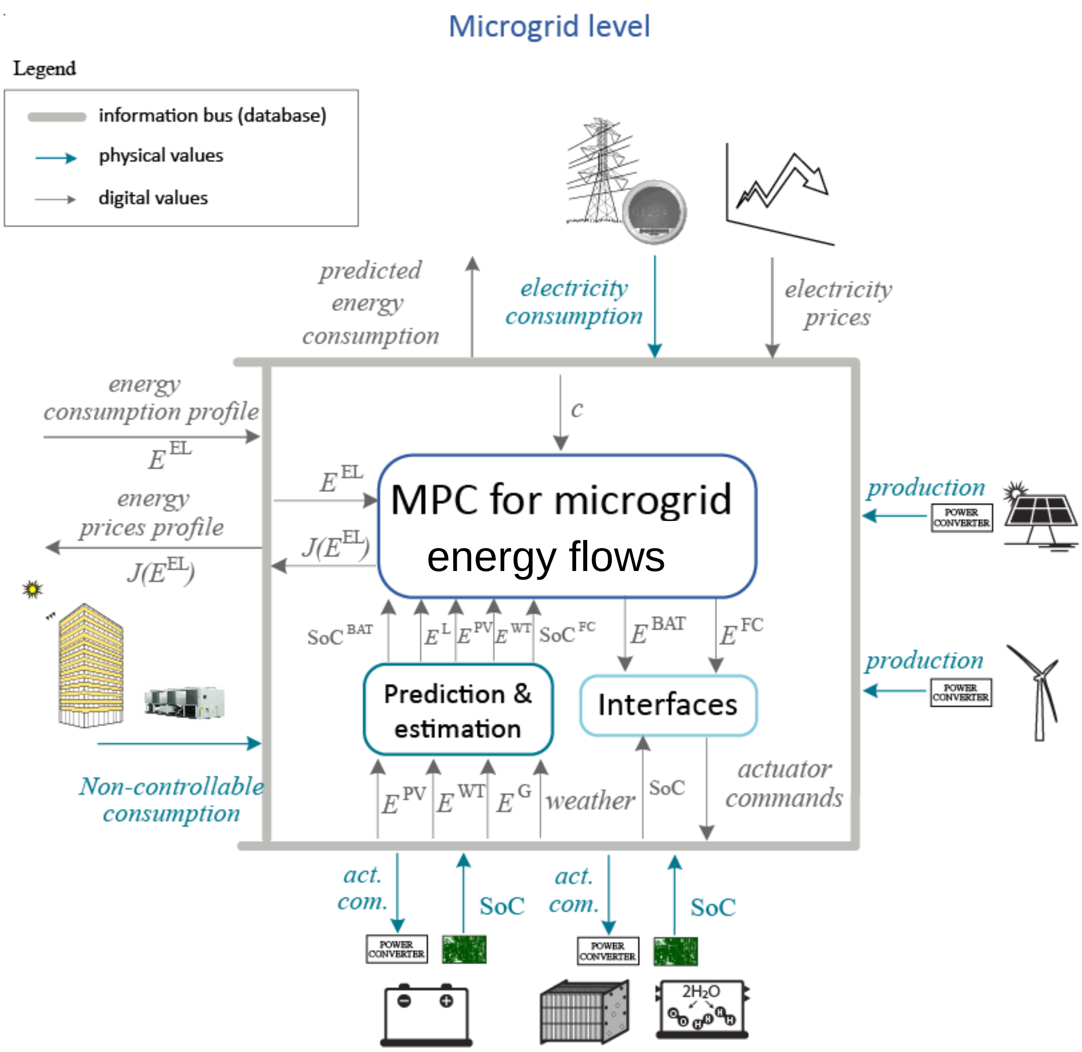


**Figure 2.7:** Microgrid level optimal control concept. In this example only actuation of electrical storages is shown, but also possibilities exist to actuate controllable loads, converting elements such as CHP and production elements.

Table 2.3 lists the requirements of measurements to be performed on different microgrid elements, if they exist.

**Table 2.3:** List of essential measurements required for implementation of the 3Smart building microgrid level. The microgrids and controls can be formed without different elements mentioned, but once they exist in the microgrid, then the mentioned measurements are needed from them.

| Building elements | | Required measurements |
|---|---|---|
| Microgrid | Batteries | State of charge, alternatively voltage and current |
| | Fuel cells | State of charge, alternatively voltage and current |
| | Photovoltaic array | Power production |
| | Wind turbine | Power production |
| | Loads | Non-controllable power consumption |
| | CHP | Power production<br>Heat production<br>Gas consumption |
| | Electric heater for a room | Room temperature setpoint<br>Current temperature in a room |
| | Domestic hot water boiler | Temperature setpoint<br>Current temperature<br>Inlet water temperature |

# 3. Interaction of building-side and grid-side EMS

Electrical energy market and distribution grid are independent systems entities where each of them can provide the building certain market conditions related to exchange of energy between the building and the grid, see Figure 3.1. The hierarchical control system on the building side takes into account the announced market conditions in their entirety and decides how to control the building climate and internal building energy flows through all the levels (zones, central heating/cooling medium preparation, microgrid) in the optimal way such that minimum- or no-discomfort are established at minimum overall price for the building.

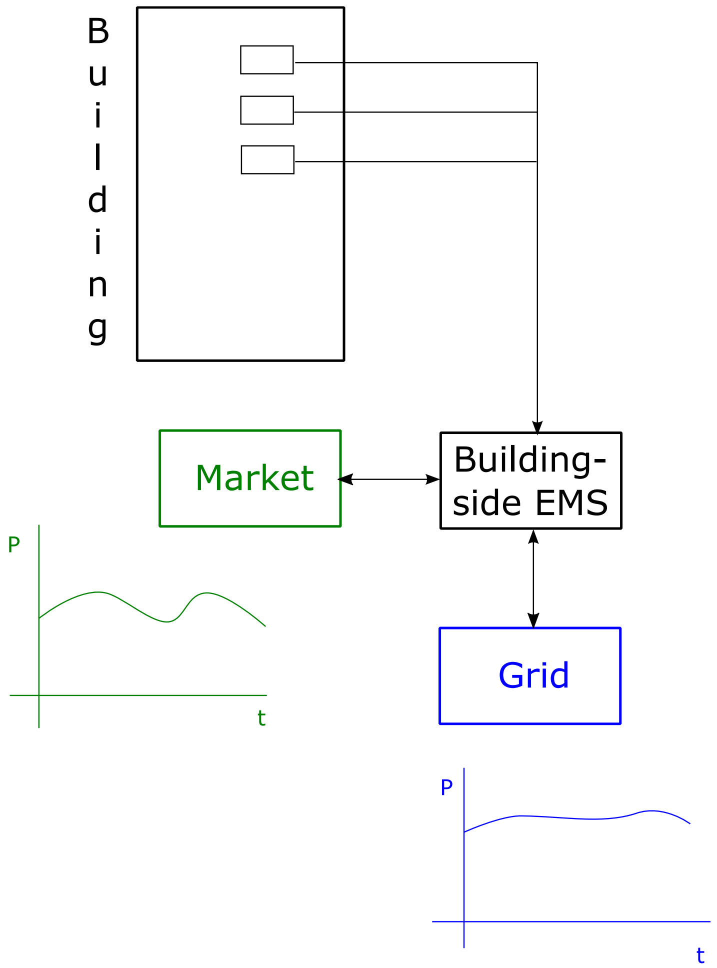


Figure 3.1: Concept of the grid-building interaction

## 3.1 Data for exchange between the grid-side and the building-side EMS

The building-side EMS optimizes the comfort and the overall economic cost of the energy exchange with the utility grids. The comfort deviation is also through a suitable weighing and model-based transformation converted into energy and then finally into cost.
In this section it is assessed what are the different parts of the cost for energy exchange profile between the building and the grid, considering the existence of market and distribution grid entities.

But firstly a common time base of operation needs to be assessed in the sense of time intervals within which the cost does not change. We refer to it as **the polling interval and its duration is named the common sampling time**. In different implementations of the 3Smart integrated building-grid EMS the common sampling time can take on different values. Its usual values are expected to lie between 5 minutes and several hours. The common sampling time will dictate the maximum sampling time used for the top-level building-side optimization. Implementation at large might engage significant computing resources for optimization if too low common sampling time is chosen and its value must be carefully selected. The common sampling time should be also used when calculating the average power from the energy consumption. It will have consequences on time resolutions required for operations on the smart meter (storage size, processing power, etc.) and on the intensity of data exchange between the building and the energy system actors (communication cost, energy for communication).
Instantaneous response to the grid requesting for a change in building power consumption at any moment is left out of scope. The slowest possible reaction time to the emergency event for the configuration considered here amounts one common sampling time.

The following economic parameters defining the cost for energy exchange with the grid are to be taken into account in the building-side EMS:

G1. **Cost of maximum power.** This is usually calculated on a monthly basis. Two options are proposed: i) in certain day of the month only the increase of the maximum power compared to maximum registered power from the previous days in the month is penalized, at the beginning of the month the initial maximum power is set to zero; ii) alternatively, simpler option with fixed daily cost – maximum daily power value is charged with a fixed, regulated, cost. E.g., in Croatia, this is 4 €/kW + VAT per month, or in our case 0,13 €/kW + VAT of maximum power value per day. This cost is only charged for power taken from the distribution network, not for power sold.

G2. **Cost of energy, day-ahead.** The aggregator is a market entity and it participates in the market by bidding demand profile (e.g., 24-hour kWh/h blocks) for a certain day-ahead (DA) price (here we assume all bids are successful). DA prices are a result of market clearing process, however in the project they will be considered as known values based on historical data (HUPEX, SIPEX, EEX). They will be used by building-side EMS as known values for the optimization process, i.e. for cost minimization which results in optimal demand profiles for given prices. The values for day-ahead prices and the resulting demand profile need to be known 12 hours prior to start of the observed day, meaning 12 to 36 hours before the dispatch between the two midnights. It should be mentioned that the building-side EMS receives day-ahead energy prices (24 prices, for each hour). The building will (e.g. at 9:00 each day) send to the aggregator the energy consumption profile it would apply between the following two midnights in case of a fixed price determined as the average price for the previous day, such that the aggregator can better bid on the market and finally send prices to the building/buildings.

The building-side EMS needs to obey the DA profile it declared. In case it is not able to due to some unforeseen events later in the day, it needs to participate in the intra-day market to compensate for the incorrect DA forecast.

G3. **Intra-day pricing for maintaining the declared day-ahead profile.** At the intra-day market, the building-side EMS needs to pay for energy which is missing/surplus from the profile announced day-ahead. There are two options for valorising the intra-day prices related to this in the project: i) simpler one: values will be taken as day-ahead energy prices multiplied by a factor of 1,2 (20% higher) and thus the cost for the hour when the deviation occurs will be expressed as: (energy in the hour * DA hour price)+(absolute value of energy deviation from DA * 1.2 DA hour price); ii) instead of DA*1,2 existing intra-day prices are used (we will actually consider them as forecasts and use historic values from markets with available intra-day historical price data).

G4. **Intra-day pricing to incentivize deviation from the declared day-ahead profile.** The building-side EMS can announce available set of energy exchange values for potential provision of services to the grid – in simplistic cases the polytope containing energy exchange profiles where costs G1-G4 evaluated together plus internal building costs are economically even better for the building than the costs G1-G3 plus internal costs. In principle, availability should be assessed in interaction of the building and the aggregator which announces the price willing to pay per kWh of reserve energy within a certain time interval of the common sampling time, and the building decides on the amount of reserve energy (reserve power) it can offer under these price conditions for flexibility. In case the aggregator needs the flexibility service it will send the required profile for the remainder of the day that is confined in the polytope to the building-side EMS and it will then follow it. In reality, the DSO does not always have continuous SCADA monitoring of the MV or LV network. This means it will probably request the altered profile soon after receiving the planned day-ahead profile from the aggregator and thus the entire desired pilot site energy exchange with the distribution grid might be known before the start of the day of delivery.

It should be mentioned that cost scenarios G1-G4 are modular, like the entire 3Smart EMS. This means that, for example, the building can only optimize its own operation using known/forecasted DA prices, not providing additional flexibility to the aggregator (only DA energy, penalizing deviations and maximum daily power: G1-G3). On top of this, the building can be active on the intra-day market by providing the polytope of its economically favourable consumption profiles attained based on the aggregator offer for the intra-day service. In that case, the building uses all the prices G1-G4.

## 3.2 Data exchange procedure between the grid and the building

In principle, the following data exchange will occur periodically at the beginning of each polling interval:

A) The building optimizes its energy consumption profile on the highest used module within the building-side EMS by optimizing the cost on the time horizon of known market conditions which consists of maximum power cost (G1), cost for energy based on day-ahead prices (G2) and cost of deviation from the day-ahead declared profile (G3). Each time instant of the common sampling time it returns to the grid-side EMS (its aggregator part) the predicted energy consumption profile. The polytope of feasible energy consumption profiles will be

provided also once intra-day prices for incentivization of deviation from the day-ahead profile are issued by the grid-side EMS. Day-ahead prices are once per day received from the aggregator and also the intra-day prices for penalization of deviation from the declared day-ahead consumption profile. Intra-day prices for incentivization of deviation from the day-ahead profile can be issued every sampling instant when the service is not called, and from that sampling instant onwards the building responds with the new flexibility polytope corresponding to these prices. For emergency situations, it may happen that the grid announces both the changed price sequence for intra-day incentivization of deviation and the sequence of required energy exchanges starting from that moment. In such a situation, the building will respond immediately but it cannot be obliged to obey the required energy exchange sequence unless it is confined in the previously declared polytopes and all G4 prices are higher compared to the previous prices for which the polytope was created.

B) Once per day, usually in the morning at about 09:00, the building optimizes its energy consumption profile for the period between the following two midnights for the case of a flat price in that interval, where the flat price will correspond to the mean value of the day-ahead energy prices for the current day. In this optimization, costs (G1-G4) will be used for the part of the prediction horizon belonging to the current day, while only cost G1 and fixed cost G2 will be used for the part of the prediction horizon belonging to the following day under the assumed fixed price scenario. In such a way optimized consumption profile will be sent to the aggregator to help in its bidding process on the market.

C) Once per day before noon and after receiving day-ahead prices from the aggregator, the building announces its day ahead energy consumption profile to the market. The building-side EMS computes it by applying the same optimization as under A for the period up to the second following midnight whereas in the part of the prediction horizon for the next day only costs G1 and newly acquired G2 are applied.

D) The aggregator can announce the profile for the requested flexibility service that is confined in the flexibility polytope previously declared by the building and the building provides it. Before the requested profile ends, no new intra-day prices for deviation from the declared day-ahead profile can be declared by the grid.

# 4. Basic principles of the building-side EMS IT architecture

In order to make the 3Smart building-side EMS functional, minimum intrusive on the existing system and comfortable for operation, several basic requirements on the overall IT architecture need to be followed.

These requirements are:

(i) **Software switch.** As the EMS in principle builds upon some pre-existing automation functions in the building, there should be installed a possibility for an easy roll-back towards the pre-existing automation system configuration. We will refer to this feature as the software switch. The software switch should be available to building operators via the pre-existing or newly built SCADA system. It should be modularly deployed, such that EMS features can be turned on or off level by level. Even within levels the modularity should be enforced, and this especially is required for the zones level where modularity would enable smooth introduction of the EMS, zone by zone. Any detected EMS failure, e.g. EMS server error, should result in automatic software switch activation. In that case all the pre-existing elements of the automation system are automatically reconfigured to operate in the way they operated prior to the EMS installation. Reconfiguration of the automation equipment needed for the EMS to start operation is also automatic.

(ii) **Easy build-upon the existing SCADA.** If the SCADA system already exists in the building, the EMS should use its already existing database to make the interventions of EMS installation cheapest and as less invasive as possible. The newly acquired signals in the system (e.g. calorimeters or sensors on heating/cooling elements in zones, batteries state of charge, etc.) should also be integrated in SCADA if financially acceptable such that the building operators continue to have a complete information about the system and that they are able to monitor it. The EMS modules' data fetching and data writing procedure will have to be adaptable to different structures of the pre-existing data bases in SCADA systems. **When no SCADA exists as a part of the pre-existing building automation system**, then it is necessary to construct the database of the building sensors and actuators from scratch such that data are easily accessible by the different EMS modules. In such a case it is desirable to introduce a primitive SCADA for building operators to easily use the software switch functionality described under (i).

(iii) **Bidirectional data flow between the building and the EMS.** Data in the building should be sampled with time resolution of 1 minute or less. Change on value method of data acquisition is also acceptable. Those variables that are used by the EMS to send commands to the automation system should be written by the EMS in the database and from that point their propagation further towards the automation system should be made possible.

The principal outlook of the IT part of the automation system with included EMS is given in Figure 4.1.

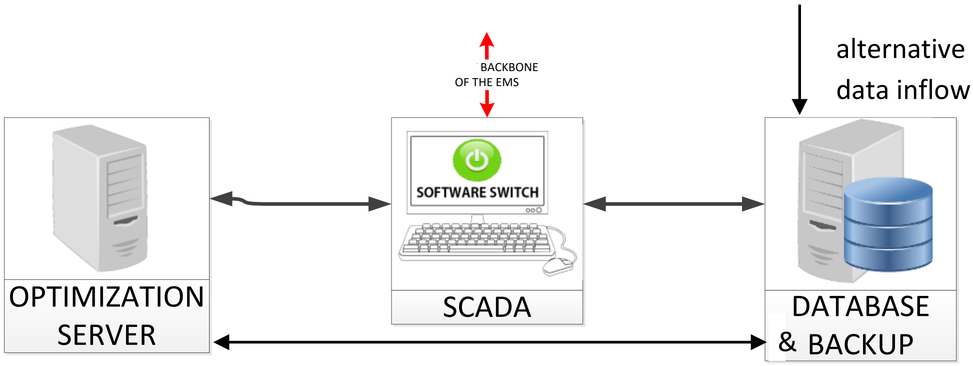


Figure 4.1. The principal outlook of the IT part of the building automation system with included EMS

Besides the SCADA computer with the implemented database of relevant building variables, there is an optimization server that runs EMS modules and a database backup for periodical storing of data from SCADA in a large and permanent data volume, usually also in the cloud. Note that such a constellation enables the designed EMS to function as a service which can be selectively and modularly switched on or off. If it is financially prohibitive to include all the needed data in the database of the SCADA system, additional data bases can be introduced, as necessary.

The optimization server should be a reliable computer with installed programmes needed to execute the EMS modules. Currently two major programmes are required to be run: 1) the application for execution of modules – here Python is preferred due to its easy high-level programming, large number of libraries and compatibility with various optimization tools, and 2) the optimization software – inevitably the modules will include different mathematical optimization programs.

## 4.1 The EMS database organization

MySQL database is preferred to be used within the EMS database.

MySQL offers a free database manager, but that database manager will probably never be used because the data from the database will be managed from the same software which will implement the modules (e.g., Python).

The data in a database is accessed via database queries. Middleware services like Windows Communication Foundation (WCF) can also be used to improve security when reading and writing data. What is important is the datatype of each different data that will be stored in the database. A list of required prescribed units for different types of variables and minimum required precision to cover all possible uses of that variable within the EMS is given in Table 4.1. For other occuring units the minimum precision is not prescribed.

| Variable | Unit | Minimum precision |
|---|---|---|
| **Temperature** | °C | At least one decimal place |
| **Heating/cooling energy** | kWh | At least three decimal places |
| **Heating/cooling medium mass flow** | $m^3$/h | At least three decimal places |
| **Heating/cooling power** | kW | At least three decimal places |
| **Batteries state of charge** | % | At least two decimal places |

| | | |
|---|---|---|
| **Electric power** | kW | At least three decimal places |
| **Electrical energy** | kWh | At least three decimal places |
| **Voltage** | V | At least three decimal places |
| **Current** | A | At least three decimal places |
| **Solar irradiation** | $Wh/m^2$ | At least two decimal places |

Table 4.1. List of building-side EMS variables, the prescribed unit and minimum required level of precision for inclusion in the EMS database

As far as organization of data within the database is concerned, contractors that perform the building upgrade including the database creation or existing SCADA database extension need to supply the datapoint list for the data base. The expected data in the database and type of access (reading or reading/writing) must be defined in the conceptual project for the building. All variables that will represent commands for the building automation system will be of type read/write and the building upgrade must enable the way for these commands to take effect from the database to the physical elements.

EMS modules will be adapted for each particular site by the pilot hosts and pilot technical leaders in terms of correct communication of modules with the database. Pilot hosts and pilot leaders will be trained on the training events related to WP4 how to do that. The database needs to be documented by the contractor such that it is easy to broaden it further with different variables/data that will be used for inter-communication and synchronization between the different EMS modules. This broadening of the database will have to be done also by pilot hosts and pilot leaders.

If there is an existing SCADA in place on the building, with a corresponding database, the intention is to make use of it maximally, if possible, such that its existing database is exploited and extended to represent the database for the EMS. This will facilitate integration of all new signals added during the building upgrade in SCADA, and will not present a challenge to building operators with respect how to operate the building through the SCADA.

If it is economically justified, additional data bases may be introduced.

It is up to the individual pilot site how the newly acquisitioned data in the database will be presented on the existing SCADA or newly built SCADA, but definitely a key for long-term comfort operation is to extend the SCADA screens with key newly acquired signals to perform monitoring of the whole system operation in a comfortable way by the building operators.

# 5. Definition of information interfaces of the building-side EMS modules

In this chapter definition of interfaces of different EMS modules is given to facilitate their development and their interconnection when they are being developed by different partners. For each planned module described are its inputs and outputs. All module inputs are fetched from the EMS database, all module outputs are written back into the database. Thus, the database is the point of synchronization of different modules as well as the interface of the EMS towards the remaining physical and IT infrastructure. This principle should be practiced for all EMS modules. Exceptions should be rare, stressed and well justified.

## 5.1 Zone-level modules

The 3Smart EMS on the zone level consists of the following modules and submodules:

- Model predictive control module for zones comfort control

- Prediction and estimation module on the zone level, consisting of the following submodules:
  - Submodules for identification of a simple model of zone heating and cooling elements:
    - Fan coils identification module
    - Radiators identification module
    - Floor heating/cooling units identification module
  - Submodule for identification of the simplified building thermal dynamics model
  - Submodule for estimation of the states of the simplified building thermal dynamics model including also the estimation of heat disturbance in zone
  - Submodule for prediction of the heat disturbance evolution per zone
  - Submodule for prediction of the comfort setpoint in the zone

- Interface module on the zone level:
  - Fan coils energy input control submodule
  - Radiators energy input control submodule
  - Floor heating/cooling units energy input control submodule

Now goes input and output definition of the individual modules and submodules, in line with Figure 2.3. If the module/submodule has some internal states that need to be memorized between the two consecutive module calls, these states will be also mentioned. It is suggested that these states are stored in the internal memory of the module or the particular module instance and not in the database, in order to simplify the database structure and reduce the amount of data that needs to be communicated between the database and the modules.

| **Model predictive control module for zones comfort control**[1] | | |
|---|---|---|
| **Frequency of module calls: hourly (possibly iteratively to achieve vertical synchronization with HVAC and microgrid level) or some other frequency, to be determined with the common sampling time for grid-building interaction (Section 3)** | | |
| **Variable name** | **Notation** | **Description** |
| **Module inputs** | | |
| Estimates of the current states of the simplified building thermal dynamics model | $x_0$ | Non-measured states of the simplified model are estimated here. |
| Predicted profile of comfort setpoints | SP | Temperature and other comfort setpoints that are predicted based on models tuned on historical data |
| Predicted profile of actuation in rooms/zones that are outside the EMS control | manual actuation commands for the room heating/cooling elements | Users may be in control to set a manual command for the room heating/cooling elements or some rooms/zones may be permanently outside the EMS control, and the EMS should be able to respect it; currently just extrapolation of the current manual selection will be used for predictions |
| Predicted profile of cumulated heating/cooling disturbances in zones | $E^{D}_{pred}$ | Disturbances predicted based on models tuned on hstorical data |
| Predicted profile of outdoor temperature | $T_o$ | Predicted profile of outdoor temperatutre received from the weather forecast service |
| Predicted profile of solar radiation on building envelope sides | $I_{solar}$ | Predicted profiles of solar radiation received from the weather forecast service |
| Identified parameters of the simplified building thermal dynamics model | $A_{room}$,$B_{room}$,$C_{room}$,$D_{room}$ | Parameters identified through a procedure listed below |
| Predicted profile of temperature of the heating/cooling medium | $T_{supply\_med}$ | Values computed through an optimization on the central HVAC level |
| Predicted profile of flow of the heating/cooling medium | $q_{supply\_med}$ | Values computed through an optimization on the central HVAC level |
| Profile of the energy price for the heating/cooling energy | $J^*(E^T)$ | Profile of prices for the heating/cooling demand that is generated by the first higher module |
| Identified parameters of a model that relates attainable | $A_{HE}$,$B_{HE}$,$C_{HE}$,$D_{HE}$ (common annotation for either | Parameters identified through one of the procedures given |

[1] If this module is the highest MPC module present in the EMS instance, then this module will also take over the communication with the grid. In that case it will be extended with the respective abilities and data interfaces which are in this document given to the microgrid-level MPC module.

| | | |
|---|---|---|
| heating/cooling energy on a zone element with respect to the predicted medium profile and flow, as well as to the room temperature | $A_{fc}, B_{fc}, C_{fc}, D_{fc}$ or $A_{rad}, B_{rad}, C_{rad}, D_{rad}$ or $A_{fh}, B_{fh}, C_{fh}, D_{fh}$) | below |
| Identified parameters of the heat loss model | $C_{loss}, D_{loss}$ | Parameters of the model that relates the supply medium flow and temperature with the medium temperature at the inlet of the heating/cooling elements |
| Adjustable parameter of the optimization problem for price-comfort weighing | $\delta$ | Parameter for the comfort part of the criterion function in predictive control |
| Adjustable parameter of the optimization problem for allowed comfort setpoint violation | $\sigma$ | Parameter for the comfort part of the criterion function in predictive control |
| **Module outputs** | | |
| Optimal profile of heating/cooling energy from actuators in zones | $E^T$ | Heating/cooling consumption profile calculated for each room controlled through the EMS, that is transferred to the interface submodule of the zone level, and also to the HVAC level MPC module |
| Optimized profile of temperatures in zones | $T$ | Predicted temperature profiles for zones that will be needed on the central HVAC level |

Table 5.1.1 Input-output variables definition of the model predictive control module for zones comfort control

| | | |
|---|---|---|
| **Fan coils identification submodule** | | |
| **Frequency of submodule calls: monthly or even seasonally** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Historical temperature profile from zone (minute-scale of the sampling time) | $T$ | Data taken from the database |
| Historical profile of fan actuation in the zone (minute-scale of the sampling time) | FS | Data taken from the database |
| Historical temperature profile of the supply medium from a calorimeter (minute-scale of the sampling time) | $T_{supply\_cal}$ | Data taken from the database |
| Historical temperature profile of the return medium from a calorimeter (minute-scale of | $T_{return\_cal}$ | Data taken from the database (might not be needed, but will be available) |

| | | |
|---|---|---|
| the sampling time) | | |
| Historical profile of the flow from a calorimeter (minute-scale of the sampling time) | $q_{cal}$ | Data taken from the database |
| Historical profile of energy recorded on the calorimeter (minute-scale of the sampling time) | $E_{cal}$ | Data taken from the database |
| Historical temperature profile from the return medium temperature sensor on a fan coil (minute-scale of the sampling time) | $T_{return\_fc}$ | Data taken from the database |
| Historical temperature profile from the supply medium temperature sensor on a fan coil (minute-scale of the sampling time) | $T_{supply\_fc}$ | (optional) If not existing, measurement of the temperature on the calorimeter should be used, and additionally a characteristics of the temperature drop along the pipeline from the heat loss model should be used |
| **Submodule outputs** | | |
| Parameters of the fan coil model that relates fan coil actuation, room temperature and medium conditions registered on a calorimeter to fan coil energy transmitted to room air in a defined time period; also parameters of a simple relation between heating energy and electrical energy for fans for different supply medium flows and temperatures | $A_{fc}$,$B_{fc}$,$C_{fc}$,$D_{fc}$ | Parameters needed for calculation of maximum energy for the MPC module, for the interface submodule functioning, and for calculation of energy inputs for identification of a simplified building dynamic model and for on-line estimation of its states and disturbances; electricity consumption model needed on the first higher level MPC modules |

Table 5.1.2 Input-output variables definition of the fan coils identification submodule

| | | |
|---|---|---|
| **Radiators identification submodule** | | |
| **Frequency of submodule calls: monthly or even seasonally** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Historical temperature profile from zone (minute-scale of the sampling time) | T | Data taken from the database |
| Historical profile of valve actuation in the zone (minute-scale of the sampling time) | $V_x$ | Data taken from the database |
| Historical temperature profile of the supply medium from a | $T_{supply\_cal}$ | Data taken from the database |

| | | |
|---|---|---|
| calorimeter (minute-scale of the sampling time) | | |
| Historical temperature profile of the return medium from a calorimeter (minute-scale of the sampling time) | $T_{return\_cal}$ | Data taken from the database (might not be needed, but will be available) |
| Historical profile of the flow from a calorimeter (minute-scale of the sampling time) | $q_{cal}$ | Data taken from the database |
| Historical profile of energy recorded on the calorimeter (minute-scale of the sampling time) | $E_{cal}$ | Data taken from the database |
| Historical temperature profile from the return medium temperature sensor on a radiator (minute-scale of the sampling time) | $T_{return\_rad}$ | Data taken from the database |
| Historical temperature profile from the supply medium temperature sensor on a radiator (minute-scale of the sampling time) | $T_{supply\_rad}$ | (optional) If not existing, measurement of the temperature on the calorimeter should be used, and additionally heat loss model for the piping should be used |
| **Submodule outputs** | | |
| Parameters of the radiator model | $A_{rad}$,$B_{rad}$,$C_{rad}$,$D_{rad}$ | Parameters needed for calculation of maximum energy for the MPC module, for the interface submodule functioning, and for calculation of energy inputs for identification of a simplified building dynamic model and for on-line estimation of its states and disturbances |

Table 5.1.3 Input-output variables definition of the radiators identification submodule

| | | |
|---|---|---|
| **Floor heating/cooling units identification submodule** | | |
| **Frequency of submodule calls: monthly or even seasonally** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Historical temperature profile from zone (minute-scale of the sampling time) | T | Data taken from the database |
| Historical profile of valve actuation in the zone (minute-scale of the sampling time) | $V_x$ | Data taken from the database |
| Historical temperature profile of the supply medium from a | $T_{supply\_cal}$ | Data taken from the database |

| | | |
|---|---|---|
| calorimeter (minute-scale of the sampling time) | | |
| Historical temperature profile of the return medium from a calorimeter (minute-scale of the sampling time) | $T_{return\_cal}$ | Data taken from the database |
| Historical profile of the flow from a calorimeter (minute-scale of the sampling time) | $q_{cal}$ | Data taken from the database |
| Historical profile of energy recorded on the calorimeter (minute-scale of the sampling time) | $E_{cal}$ | Data taken from the database |
| Historical temperature profile from the return medium temperature sensor on a floor heating/cooling element (minute-scale of the sampling time) | $T_{return\_fh}$ | Data taken from the database |
| Historical temperature profile from the supply medium temperature sensor on a floor heating/cooling element (minute-scale of the sampling time) | $T_{supply\_fh}$ | (optional) If not existing, measurement of the temperature on the calorimeter should be used, and combined with the heat loss model for the pipeline |
| **Submodule outputs** | | |
| Parameters of the floor heating/cooling element model | $A_{fh}$,$B_{fh}$,$C_{fh}$,$D_{fh}$ | Parameters needed for calculation of maximum energy for the MPC module, for the interface submodule functioning, and for calculation of energy inputs for identification of a simplified building dynamic model |

Table 5.1.4 Input-output variables definition of the floor heating/cooling units identification submodule

| **Submodule for identification of the simplified building thermal dynamics model** | | |
|---|---|---|
| **Frequency of submodule calls: monthly or even seasonally** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Historical temperature profile measurement in rooms/zones of the building (minute-scale of the sampling time) | $T$ | Data from the database |
| Outdoor temperature profile measurement (minute-scale of the sampling time) | $T_o$ | Data from the database |
| Solar irradiance estimation on | $I_{solar}$ | Data from the data base |

| | | |
|---|---|---|
| all relevant building surfaces (minute-scale of the sampling time) | | |
| Historical profile of energy inputs from heating/cooling elements in zones (minute-scale of the sampling time) | $E^T$ | Stored in the database or calculated based on the heating/cooling element model |
| **Submodule outputs** | | |
| Parameters of the simplified building thermal dynamics model | $A_{room}$,$B_{room}$,$C_{room}$,$D_{room}$ | Model to be used for zone-level MPC, states estimation of the simplified model, as well as the estimation of heating/cooling disturbances |

Table 5.1.5 Input-output variables definition of the submodule for identification of the simplified building thermal dynamics model

| **Submodule for estimation of the states of the simplified building thermal dynamics model including also the estimation of heat disturbance in zone** | | |
|---|---|---|
| **Frequency of submodule calls: every minute** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Parameters of the simplified building thermal dynamics model | $A_{room}$,$B_{room}$,$C_{room}$,$D_{room}$ | Model identified with the procedure from above |
| Temperature measurement in rooms/zones of the building (minute-scale of the sampling time) | T | Current temperature measurement in room/zone |
| Outdoor temperature(minute-scale of the sampling time) | $T_o$ | Current outdoor temperature measurement |
| Solar irradiance estimation on all relevant building surfaces (minute-scale of the sampling time) | $I_{solar}$ | Current amount of the solar radiation on different surfaces of the building (estimated from local measurements) |
| Applied energy input from heating/cooling elements in zones (minute-scale of the sampling time) | $E^T_0$ | Energy input that is to be realized on heating/cooling elements in the room/zone between the current sample and the next minute |
| **Submodule outputs** | | |
| Estimated states of the simplified building thermal dynamics model | $x_0$ | States needed for the MPC module on the zone level |
| Estimated heat disturbance in zone | $E_0^D$ | Current disturbances needed for the MPC module, for the interface submodule, and also for disturbance prediction |

Table 5.1.6 Input-output variables definition of the submodule for estimation of the states of the simplified building thermal dynamics model including also the estimation of heat disturbance in zone

| Submodule for prediction of the heat disturbance evolution per zone – tuning and on-line operation | | |
|---|---|---|
| **Frequency of submodule calls: every minute or at the frequency determined by the common sampling time, needs to be assessed for on-line operation; monthly or seasonally for tuning of the prediction model** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Historical profile of the estimated heat disturbance in zone (hourly level aggregates) | $E^D$ | Profile of the estimated heat disturbance in the past needed for off-line model tuning |
| <other relevant historical profiles that will be tested for correlation> | | For prediction most probable candidates in regression vectors, besides previous $E^D$ samples themselves are time and weather variables (solar irradiance, temperature, pressure, wind speed and direction, humidity,etc.) |
| Samples of variables required for on-line prediction performance | | Those variables that will be selected for use in prediction will be fetched from the database on-line to calculate prediction of heat disturbances |
| **Submodule outputs** | | |
| Prediction model parameters (for off-line operation of the submodule) | $\theta_{ED}$ | Needed for on-line operation of the module |
| Predicted heat disturbance evolution per zone (for on-line operation of the submodule) | $E^D$ | Needed for the MPC module on the zones level |

Table 5.1.7 Input-output variables definition of the submodule for prediction of the heat disturbance evolution per zone

| Submodule for prediction of the comfort setpoint in the zone – tuning and on-line operation | | |
|---|---|---|
| **Frequency of submodule calls: every minute or at the frequency determined by the common sampling time, needs to be assessed for on-line operation; monthly or seasonally for tuning of the prediction model** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Historical profile of the setpoint in zone | SP | Profile of the comfort setpoints selected in the past needed for off-line model tuning |
| <other relevant historical profiles>... | | For prediction most probable candidates in regression vectors, besides previous SP samples themselves are time and weather variables (solar |

| | | |
|---|---|---|
| | | irradiance, temperature, pressure, wind speed and direction, humidity,etc.) |
| <long-term extension: connection with the company business-information systems to enhance prediction and on-line setpoints change> | | Very important connection point between the EMS and the business information system of a company (travel orders, vacations, sick leaves, different known occupancy schedules for meetings/lectures...) |
| **Submodule outputs** | | |
| Prediction model parameters (for off-line operation of the submodule) | $\theta_{SP}$ | Needed for on-line operation of the submodule |
| Predicted setpoint evolution in the zone | SP | Needed for the MPC module on the zones level |

Table 5.1.8 Input-output variables definition of the submodule for prediction of the comfort setpoint in the zone

| **Fan coils energy input control submodule** | | |
|---|---|---|
| **Frequency of submodule calls: every minute** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Energy input references for fan coils (one or several, depending whether more rooms are handled at once for coordination reasons) | $E^T$ | Energy input command for fan coils that needs to be followed, computed by MPC module on the zone level |
| Parameters of the simplified building thermal dynamics model (one or several, depending whether more rooms are handled at once for coordination reasons) | $A_{room}$,$B_{room}$,$C_{room}$,$D_{room}$ | Model obtained through the identification procedure above |
| Parameters of the fan coil model that relates fan coil actuation, room temperature and medium conditions registered on a calorimeter to fan coil energy transmitted to room air in a defined time period (one or several, depending whether more rooms are handled at once for coordination reasons) | $A_{fc}$,$B_{fc}$,$C_{fc}$,$D_{fc}$ | Model obtained through the identification procedure above |
| Current setpoint temperature / comfort setpoint (one or several, depending whether more rooms are handled at | $SP_0$ | Needed to check whether the user has changed a setpoint in order to quickly adapt to the new setpoint (on a sampling |

| | | |
|---|---|---|
| once for coordination reasons) | | time lower than the sampling time of MPC) |
| Setpoint used for the particular time and zone/zones in last MPC computation of the required thermal input from heating/cooling elements | $SP_{MPC}$ | Needed to check whether the user has changed a setpoint in order to quickly adapt to the new setpoint (on a sampling time lower than the sampling time of MPC) |
| Currently estimated heat disturbance for the zone (one or several, depending whether more rooms are handled at once for coordination reasons) | $E_0^D$ | Needed to correct the required thermal heat input from actuators if the estimated disturbance has changed from the time of MPC computation |
| **Submodule outputs** | | |
| Computed current commands to fan coils actuators | $FS_0$ (can be also fan coil valve command if both can be actuated) | To be applied to the fan coil / fan coils |
| Computed future planned actuations of the fan coils actuators | FS | Possibly needed to better estimate electricity load and heating/cooling profile in the building in near future |

Table 5.1.9 Input-output variables definition of the submodule for fan coils energy input control

| **Radiators energy input control submodule** | | |
|---|---|---|
| **Frequency of submodule calls: every minute** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Energy input references for radiators (one or several, depending whether more rooms are handled at once for coordination reasons) | $E_0^T$ | Energy input command for radiators that needs to be followed, computed by MPC module on the zone level |
| Parameters of the simplified building thermal dynamics model (one or several, depending whether more rooms are handled at once for coordination reasons) | $A_{room}, B_{room}, C_{room}, D_{room}$ | Model obtained through the identification procedure above |
| Parameters of the radiators model that relates radiators actuation, room temperature and medium conditions registered on a calorimeter to radiators energy transmitted to room air in a defined time period (one or several, depending whether more rooms are handled at once for coordination reasons) | $A_{rad}, B_{rad}, C_{rad}, D_{rad}$ | Model obtained through the identification procedure above |

| | | |
|---|---|---|
| Current setpoint temperature / comfort setpoint (one or several, depending whether more rooms are handled at once for coordination reasons) | $SP_0$ | Needed to check whether the user has changed a setpoint in order to quickly adapt to the new setpoint (on a sampling time lower than the sampling time of MPC) |
| Setpoint used for the particular time and zone/zones in last MPC computation of the required thermal input from heating/cooling elements | $SP_{MPC}$ | Needed to check whether the user has changed a setpoint in order to quickly adapt to the new setpoint (on a sampling time lower than the sampling time of MPC) |
| Currently estimated heat disturbance for the zone (one or several, depending whether more rooms are handled at once for coordination reasons) | $E_0^D$ | Needed to correct the required thermal heat input from actuators if the estimated disturbance has changed from the time of MPC computation |
| **Submodule outputs** | | |
| Computed current commands to radiators actuators | $V_{x0}$ | Command to be applied to the valve/valves of radiators (one or several, depending whether more rooms are handled at once for coordination reasons) |
| Computed future planned actuations of the radiators actuators | $V_x$ | Possibly needed to better estimate electricity load and heating/cooling load profile in the building in near future |

Table 5.1.10 Input-output variables definition of the radiators energy input control submodule

| **Floor heating/cooling units energy input control submodule** | | |
|---|---|---|
| **Frequency of submodule calls: every minute** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Energy input references for floor heating/cooling elements (one or several, depending whether more rooms are handled at once for coordination reasons) | $E_0^T$ | Energy input command for floor heating/cooling elements that needs to be followed, computed by MPC module on the zone level |
| Parameters of the simplified building thermal dynamics model (one or several, depending whether more rooms are handled at once for coordination reasons) | $A_{room}, B_{room}, C_{room}, D_{room}$ | Model obtained through the identification procedure above |
| Parameters of the floor heating/cooling elements model that relates their actuation, room temperature | $A_{fh}, B_{fh}, C_{fh}, D_{fh}$ | Model obtained through the identification procedure above |

| | | |
|---|---|---|
| and medium conditions registered on a calorimeter to radiators energy transmitted to room air in a defined time period (one or several, depending whether more rooms are handled at once for coordination reasons) | | |
| Current setpoint temperature / comfort setpoint (one or several, depending whether more rooms are handled at once for coordination reasons) | $SP_0$ | Needed to check whether the user has changed a setpoint in order to quickly adapt to the new setpoint (on a sampling time lower than the sampling time of MPC) |
| Setpoint used for the particular time and zone/zones in last MPC computation of the required thermal input from heating/cooling elements | $SP_{MPC}$ | Needed to check whether the user has changed a setpoint in order to quickly adapt to the new setpoint (on a sampling time lower than the sampling time of MPC) |
| Currently estimated heat disturbance for the zone (one or several, depending whether more rooms are handled at once for coordination reasons) | $E_0^D$ | Needed to correct the required thermal heat input from actuators if the estimated disturbance has changed from the time of MPC computation |
| Heat disturbance used for the particular time and zone/zones in last MPC computation of the required thermal input from heating/cooling elements | $E_{MPC}^D$ | Needed to correct the required thermal heat input from actuators if the estimated disturbance has changed from the time of MPC computation |
| **Submodule outputs** | | |
| Computed current commands to floor heating/cooling units actuators (valves) | $V_{x0}$ | Command to be applied to the valve/valves of floor heating/cooling elements (one or several, depending whether more rooms are handled at once for coordination reasons) |
| Computed future planned actuations of the floor heating/cooling units actuators | $V_x$ | Possibly needed to better estimate electricity load and heating/cooling load profile in the building in near future |

Table 5.1.11 Input-output variables definition of the floor heating/cooling elements energy input control submodule

## 5.2 Central HVAC system level modules

The 3Smart EMS on the central HVAC system level consists of the following modules and submodules:

- Model predictive control modules for central HVAC control, with the following submodules
  - Heating substation model predictive control submodule
  - Heat pump model predictive control submodule

- Prediction and estimation module on the central HVAC system level, consisting of the following submodules:
  - Submodule for identification of a heat pump efficiency map
  - Submodule for estimation of the parameters of the thermal losses model in piping
  - Submodule for prediction of the total non-controllable energy consumption on the central HVAC unit

- Interface module on the central HVAC system level

Module for interfacing the computed commands towards the existing regulation systems in central HVAC units

Now goes input and output definition of the individual modules and submodules according to Figure 2.5.

| **Heating substation model predictive control submodule**[2] | | |
|---|---|---|
| **Frequency of submodule calls: hourly (possibly iteratively to achieve vertical synchronization with zone and microgrid level) or some other frequency, to be determined with the common sampling time for grid-building interaction (Section 3)** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Energy inputs planned from individual heating elements in zones | $E^T$ | Energy inputs optimized within the zone level MPC |
| Predicted profile of temperature evolutions in zones | T | Received from the zones level MPC, needed to assess the attainable energy in the zones and to assess the required electrical energy in case of fan coils, for their operation in delivering certain energy amount $E^T$ |
| Price profiles for electricity and heat; for electricity local characterization of the value function of the optimization around the planned profile $E^{EL}$ | $J^*(E^{EL})$, $c_h$ | Prices obtained from the microgrid level or from the distribution grid |
| Parameters of the heating element model that relates its actuation, room temperature and medium conditions | $A_{HE}, B_{HE}, C_{HE}, D_{HE}$ ($A_{fc}, B_{fc}, C_{fc}, D_{fc}$/ $A_{rad}, B_{rad}, C_{rad}, D_{rad}$/ $A_{fh}, B_{fh}, C_{fh}, D_{fh}$) | Model obtained through the identification procedure in the zone level, used to determine maximum possible energy |

[2] If this module is the highest MPC module present in the EMS instance, then this module will also take over the communication with the grid. In that case it will be extended with the respective abilities and data interfaces which are in this document given to the microgrid-level MPC module.

| | | |
|---|---|---|
| registered on a calorimeter to energy transmitted to room air in a defined time period; for the case of fan coild contains also the simplified electricity consumption model | | attainable in the zone with a certain temperature and flow of the prepared medium; in case of fan coils used also to assess the required electrical energy for fan coil operation |
| Parameters of the thermal losses model in piping and hydraulics model between the heating substation output and the floor calorimeters | $\theta_{piping}$ | Thermal losses in piping are needed to be evaluated in the cost function of the HVAC level MPC, and to determine the maximum available energy for individual heating/cooling elements in zones, and also to determine the electricity consumption for fan coils; hydraulics model is needed for flow calculation on the floor calorimeters |
| Prediction of the non-controllable heating load | $E_{h\_non\_controllable}$ | Needs to be included in the cost function (it might not be necessarily needed for the case of the heating substation) |
| **Submodule outputs** | | |
| Profile of the outgoing medium flow from the heating substation towards the building | $q_{sup}$ | The value valid for the first sampling period is to be transmitted to the interface module |
| Profile of the outgoing medium temperature from the heating substation towards the building | $T_{sup}$ | The value valid for the first sampling period is to be transmitted to the interface module |
| Local characterization of the value function of the optimization around the planned profile $E^T$ | $J^*(E^T)$ | This local characterization is transmitted back to the zone level |
| Predicted profile of heating energy consumption from the external source (e.g. district heating grid) | $E_{HVAC\_h\_overall}$ | This profile can be declared to the district heating operator |
| Predicted profile of electricity consumption | $E_{HVAC\_e\_overall}$ | This profile is declared to the microgrid level |

Table 5.2.1 Table of input-output variables for the heating substation model predictive control submodule

| |
|---|
| **Heat pump model predictive control submodule[3]** |
| **Frequency of submodule calls: hourly (possibly iteratively to achieve vertical synchronization with zone and microgrid level) or some other frequency, to be determined with the common sampling** |

[3] If this module is the highest MPC module present in the EMS instance, then this module will also take over the communication with the grid. In that case it will be extended with the respective abilities and data interfaces which are in this document given to the microgrid-level MPC module.

| time for grid-building interaction (Section 3) | | |
|---|---|---|
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Energy inputs planned from individual heating/cooling elements in zones | $E^T$ | Energy inputs optimized within the zone level MPC |
| Predicted profile of temperature evolutions in zones | T | Received from the zones level MPC, needed to assess the attainable energy in the zones and to assess the required electrical energy in case of fan coils, for their operation in delivering certain energy amount $E^T$ |
| Price profiles for electricity with local characterization of the value function of the optimization around the planned profile $E^{EL}$ on the microgrid level | $J^*(E^{EL})$ | Prices obtained from the microgrid level or from the distribution grid |
| Forecasted profile of the outdoor temperature | $T_o$ | Outdoor temperature is an important variable for the heat pump thermal efficiency model |
| Parameters of the thermal efficiency model of the heat pump (dependence on outdoor temperature, starting medium temperature towards the building and thermal load) | $\theta_{hp\_effiicency}$ | Required to determine the electrical energy load for the required heating load, outdoor temperature and different starting medium temperatures |
| Parameters of the heating/cooling element model that relates its actuation, room temperature and medium conditions registered on a calorimeter to energy transmitted to room air in a defined time period | $A_{HE},B_{HE},C_{HE},D_{HE}$ $(A_{fc},B_{fc},C_{fc},D_{fc}/ A_{rad},B_{rad},C_{rad},D_{rad}/ A_{fh},B_{fh},C_{fh},D_{fh})$ | Model obtained through the identification procedure in the zone level; for the case of fan coils contains also the electricity consumption model |
| Parameters of the thermal losses model in piping and hydraulics model between the heating substation output and the floor calorimeters | $\theta_{piping}$ | Thermal losses in piping are needed to be evaluated in the cost function of the HVAC level MPC, and to determine the maximum available energy for individual heating/cooling elements in zones; hydraulics model is needed for flow calculation on the floor calorimeters |
| Prediction of the non-controllable heating/cooling load | $E_{h\_non\_controllable}$ | Needs to be included in the cost function |
| **Submodule outputs** | | |

| | | |
|---|---|---|
| Profile of the outgoing medium flow from the heat pump towards the building | $q_{sup}$ | The value valid for the first sampling period is to be transmitted to the interface module |
| Profile of the outgoing medium temperature from the heat pump towards the building | $T_{sup}$ | The value valid for the first sampling period is to be transmitted to the interface module |
| Local characterization of the value function of the optimization around the planned profile $E^T$ | $J^*(E^T)$ | This local characterization is transmitted back to the zone level |
| Predicted profile of electricity consumption | $E_{HVAC\_e\_overall}$ | This profile is declared to the microgrid level |

Table 5.2.2 Table of input-output variables for the heat pump model predictive control submodule

| **Submodule for the identification of a heat pump efficiency map** | | |
|---|---|---|
| **Frequency of submodule calls: monthly or even seasonally** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Historic profile of energy measured on the output of the heat pump via a calorimeter; or a combination of direct measurements of outgoing and return temperature on the source and indirect flow measurement through a cumulation of floor calorimeters flow measurements (minute samples; if there is a storage device near the heat pump and measuement is performed after the storage, then perhaps this period may be prolonged to obtain more representative values) | $E_{heat\_hp}$; or a combination of temperature and flow measurements | Heating/cooling energy output from the heat pump |
| Historic profile of electricity consumption measurements on the heat pump | $E_{hp}^{EL}$ | |
| **Submodule outputs** | | |
| Parameters of the thermal efficiency model of the heat pump (dependence on outdoor temperature, starting medium temperature towards the | $\theta_{hp\_effiicency}$ | Required to determine the electrical energy load for the required heating load, outdoor temperature and different starting medium temperatures |

| | | |
|---|---|---|
| building and thermal load) | | |

Table 5.2.3 Table of input-output variables for the submodule for identification of a heat pump efficiency map

| **Submodule for estimation of the parameters of the thermal losses model in piping** | | |
|---|---|---|
| **Frequency of submodule calls: monthly or even seasonally** | | |
| **Variable name** | **Notation** | **Description** |
| **Submodule inputs** | | |
| Historic profile of energy measured on the output of the heat pump via a calorimeter; or a combination of direct measurements of outgoing and return temperature on the source and indirect flow measurement through a cumulation of floor calorimeters flow measurements (minute samples; if there is a storage device near the heat pump and measuement is performed after the storage, then perhaps this period may be prolonged to obtain more representative values) | $E_{heat\_hp}$; or a combination of temperature and flow measurements | Heating/cooling energy output from the heat pump |
| Historic profile of energies measured on calorimeters on different building supply parts | $E_{hp}^{cal}$ | |
| **Submodule outputs** | | |
| Parameters of the thermal losses model in piping and hydraulics model between the heating substation output and the floor calorimeters | $\theta_{piping}$ | Thermal losses in piping are needed to be evaluated in the cost function of the HVAC level MPC, and to determine the maximum available energy for individual heating/cooling elements in zones; hydraulics model is needed for flow calculation on the floor calorimeters |
| Parameters of the thermal efficiency model of the heat pump (dependence on outdoor temperature, starting medium temperature towards the building and thermal load) | $\theta_{hp\_effiicency}$ | Required to determine the electrical energy load for the required heating load, outdoor temperature and different starting medium temperatures |

Table 5.2.4 Table of input-output variables for the submodule for estimation of the parameters of the heat pump efficiency model

| **Submodule for prediction of the total non-controllable consumption on the central HVAC unit – tuning and on-line operation** | | |
|---|---|---|
| **Frequency of submodule calls: every minute or at the frequency determined by the common sampling time, needs to be assessed for on-line operation; monthly or seasonally for tuning of the prediction model** | | |
| **Variable name** | **Notation** | **Decsription** |
| **Submodule inputs** | | |
| Historical profile of the non-controllable consumption as a difference between the energy on the central HVAC unit output (possibly measured indirectly) and the measurements on floor calorimeters | $E_{non\text{-}controllable\_HVAC}$ | |
| <other relevant historical profiles>... | | For prediction most probable candidates in regression vectors, besides previous non-controllable energy samples themselves are time and weather variables (solar irradiance, temperature, pressure, wind speed and direction, humidity,etc.) |
| | | |
| ... | | |
| **Submodule outputs** | | |
| Prediction model parameters (for off-line operation of the submodule) | $\theta_{non\text{-}controllable\_HVAC}$ | Needed for on-line operation of the module |
| Predicted non-controllable heating/cooling energy evolution (for on-line operation of the submodule) | $E_{non\text{-}controllable\_HVAC}$ | Needed for the MPC submodules on the central HVAC level |
| | | |
| ... | | |

Table 5.2.5 Input-output variables definition of the submodule for prediction of the non-controllable consumption in the central HVAC system

| **Module for interfacing the computed commands towards the existing regulation systems in central HVAC units** | | |
|---|---|---|
| **Frequency of module calls: every minute or at the frequency determined by the common sampling time, needs to be assessed for on-line operation; monthly or seasonally for tuning of the prediction model** | | |
| **Variable name** | **Notation** | **Description** |
| **Module inputs** | | |
| Outgoing medium supply temperature for the building | $T_{sup}$ | |

| | | |
|---|---|---|
| Outgoing medium floor or temperature in the building | $q_{sup}$ | |
| **Module outputs** | | |
| Temperature reference for the outgoing medium | $T_{sup,0}$, pump reference | Received from te MPC submodule |
| Temperature reference for the flow or an equivalent variable, e.g. temperature | $q_{sup,0}$ reference (or pressure difference) | Needed for the MPC submodule on the central HVAC level |

Table 5.2.6. Input-output variables for module for interfacing the computed commands towards the existing regulation systems in central HVAC units

## 5.3 Microgrid level modules

The 3Smart EMS on the microgrid level consists of the following modules and submodules:

- Model predictive control module for microgrid energy flows control
- Prediction and estimation module on the microgrid level, consisting of the following submodules:
    - Submodule for identification of battery parameters
    - Submodule for estimation of battery state of charge
    - Submodule for prediction of the total non-controllable energy consumption on the microgrid level
    - Submodule for prediction of the photovoltaic array production
- Interface module on the microgrid level for battery charging/discharging in accordance with the issued energy exchange command
    - Module for issuing commands towards the storage power converter based on the commanded energy exchange signals

| **Model predictive control module for microgrid energy flows control** | | |
|---|---|---|
| **Frequency of module calls: hourly (possibly iteratively to achieve vertical synchronization with zone and central HVAC level) or some other frequency, to be determined with the common sampling time for grid-building interaction (Section 3)** | | |
| **Variable name** | **Variable annotation** | **Variable description** |
| **Module inputs** | | |
| Cumulative predicted controllable energy consumption that needs to be served by the microgrid, electricity and | $E^{EL}$, $E^{H}$ | Energy inputs optimized within the HVAC level MPC |

| | | |
|---|---|---|
| heat | | |
| Grid price conditions | $p_{grid}$ | Prices and conditions obtained from the distribution grid/grids (Section 3) |
| Prediction of the overall non-controllable electricity/heat/gas consumption profile | $E^{EL}_{non-controllable\_load}$ $E^{H}_{non-controllable\_load}$ $E^{gas}_{non-controllable\_load}$ | |
| Prediction of the overall non-controllable generation profile of electricity/heat/gas | $E^{EL}_{non-controllable\_gen}$ $E^{H}_{non-controllable\_gen}$ | |
| Parameters of the battery/batteries model, if exist | $\theta_{batt}$ | |
| Battery/batteries state of charge, if exists | SOC | |
| Internal states of controllable loads, if exist (e.g., representative temperature in the domestic hot water boiler or refrigerator) | $x_{cont}$ | |
| Controllable loads state limits, if exist (e.g., upper and lower limit of the domestic hot water boiler or refrigerator) | $x_{cont\_lim}$ | |
| Controllable loads energy conversion model, if exist (e.g. power to heat model in the domestic hot water boiler or refrigerator) | $\theta_{cont}$ | |
| State of the heat storage, if exists (e.g., representative temperature of the heat tank) | $T_{hs}$ | |
| Parameters of the heat storage model | $\theta_{hs}$ | |
| Parameters of the energy conversion units model, if exist (e.g., CHP) | $\theta_{ec}$ | |
| Prediction of usage conditions of controllable loads, if applicable (e.g. temperature of the cold water supply in the domestic hot water tank | $d_{cont}$ | |

| | | |
|---|---|---|
| and profile of hot water usage) | | |
| Maximum power price | $c_{Pmax}$ | |
| Day-ahead prices | $c_{DA}$ | |
| Intra-day prices | $c_{ID,penal}$, $c_{ID,incentive}$ | |
| Requested intra-day service | $E_{grid}$ | |
| **Module outputs** | | |
| Profile of the energy exchange with battery/batteries storage | $E_{batt}$ | The value valid for the first sampling period is to be transmitted to the interface module |
| Profile of the energy command for controllable load actuation | $E_{cont\_load}$ | For controllable loads continuous energy commands are generated which are then transferred to on-off on the interface submodule |
| Profile of the energy conversion units actuation | $E_{ecu}$ | E.g., CHP command for electricity generation with heat as the side-product or vice versa |
| Local characterization of the value function of the optimization around the planned profile of controllable loads $E^{EL}$, $E^{H}$ | $J^*(E^{EL},E^{H})$ | This local characterization is transmitted back to the zone and central HVAC level |
| Energy exchange profiles with the grid and other data for the grid | $E_{grid}^{EL}$, $E_{grid}^{H}$, $E_{grid}^{gas}$, other conditions | Conditions obtained through optimization of the interaction with distribution grid/grids (Section 3) |
| Flexibility polytope with respect to the issued intra-day prices | $P_{flex}$ | Polytope that contains all energy exchange profiles acceptable to the building according to its current state, declared day-ahead schedule and intra-day prices |

Table 5.3.1 Table of input-output variables for the microgrid model predictive control module

| **Submodule for identification of battery parameters** | | |
|---|---|---|
| **Frequency of submodule calls: monthly or even seasonally** | | |
| **Variable name** | **Variable annotation** | **Variable description** |
| **Submodule inputs** | | |
| Historical profile of measured battery currents | $I_{batt}$ | |

| | | |
|---|---|---|
| Historical profile of measured battery and battery cells voltages | $U_{batt}$ | |
| Historical profile of measured battery cells temperatures | $T_{batt}$ | |
| **Submodule outputs** | | |
| Parameters of the battery/batteries model, if exist | $\theta_{batt}$ | |

Table 5.3.2 Table of input-output variables for the submodule of estimation of a battery model parameters

| **Submodule for estimation of battery state of charge** | | |
|---|---|---|
| **Frequency of submodule calls: every minute** | | |
| **Variable name** | **Variable annotation** | **Variable description** |
| **Submodule inputs** | | |
| Currently measured current of the battery | $I_{batt,0}$ | |
| Currently measured voltage of the battery and of the battry cells | $U_{batt,0}$ | |
| Currently measured temperatures of the battery cells | $T_{batt,0}$ | |
| **Submodule outputs** | | |
| Current state of charge estimate, prediction for the next sample, covariance and Kalman gain | $SOC_0$ | |
| | | |

Table 5.3.3 Table of input-output variables for the submodule of estimation of the battery state of charge

| **Submodule for prediction of the total non-controllable energy consumption on the microgrid level (off-line for model tuning and on-line for providing predictions)** | | |
|---|---|---|
| **Frequency of submodule calls: hourly or less (depends on the frequency of operation of the microgrid model predictive control)** | | |
| **Variable name** | **Variable annotation** | **Variable description** |
| **Submodule inputs** | | |
| Historical profile of relevant power meters | PM | |

| | | |
|---|---|---|
| data | | |
| <possibly other relevant data, as required> | other data | Posibly weather and time data |
| **Submodule outputs** | | |
| Parameters of the prediction model (off-lne) | $\theta_{pred\_microG}$ | |
| Predicted profile of the non-controllable electricity consumption, predicted profile of the non-controllable thermal load (on-line) | $E^{EL}_{non-controllable\_load}$ <br> $E^{H}_{non-controllable\_load}$ <br> $E^{gas}_{non-controllable\_load}$ | |

Table 5.3.4. Table of inputs and outputs for the submodule for prediction of non-controllable consumption of electricity and heat

| **Submodule for prediction of the photovoltaic array production (off-line for model tuning and on-line for providing predictions)** | | |
|---|---|---|
| **Frequency of submodule calls: hourly or less (depends on the frequency of operation of the microgrid model predictive control)** | | |
| **Variable name** | **Variable annotation** | **Variable description** |
| **Submodule inputs** | | |
| Historical profile of relevant power meters data | PM | |
| <possibly other relevant data, as required> | other data | Posibly weather and time data |
| **Submodule outputs** | | |
| Parameters of the prediction model (off-lne) | $\theta_{pred\_PV}$ | |
| Predicted profile of the photovoltaic array production (on-line) | $E^{PV}$ | |

Table 5.3.5. Table of inputs and outputs for the submodule for prediction of photovoltaic array production

| **Module for issuing commands towards the storage power converter based on the commanded energy exchange signals** | | |
|---|---|---|
| **Frequency of module calls: hourly or less (depends on the frequency of operation of the microgrid model predictive control)** | | |
| **Variable name** | **Variable annotation** | **Variable description** |
| **Module inputs** | | |
| Current SOC | $SOC_0$ | |
| Battery parameters | $\theta_{batt}$ | Posibly weather and time data |
| Commanded energy exchange | $E^{batt}$ | |
| **Module outputs** | | |

| | | |
|---|---|---|
| Commanded battery current | $I_{batt}$ | |

Table 5.3.6. Table of inputs and outputs for the module for battery actuation based on issued energy flow command

| **Submodule for identification of the controllable load** | | |
|---|---|---|
| **Frequency of module calls: periodically, e.g. once in a year** | | |
| **Variable name** | **Notation** | **Description** |
| **Module inputs** | | |
| Historical controllable load measured state | $x_l$ | E.g. temperature in rooms with electrical heaters or temperature of the water in domestic hot water boilers |
| Historical controllable load energy commands | $E_l$ | Previous commands |
| **Module outputs** | | |
| Simplified model of the controllable load | $\theta_l$ | Model to be used in MPC on the microgrid level |

Table 5.3.7. Table of inputs and outputs for the submodule for identification of the controllable loads model

| **Submodule for interfacing towards the controllable load** | | |
|---|---|---|
| **Frequency of module calls: minute-level** | | |
| **Variable name** | **Notation** | **Description** |
| **Module inputs** | | |
| Controllable load measured state | $x_l$ | E.g. temperature in rooms with electrical heaters or temperature of the water in domestic hot water boilers |
| Simplified model of the controllable load | $\theta_l$ | Controllable load parameters |
| Controllable load energy command from the microgrid MPC module | $E_l$ | Command from the MPC |
| **Module outputs** | | |
| On-off actions on the controllable load | $u_l$ | On-off actions for controllable loads |

Table 5.3.8. Table of inputs and outputs for the submodule for interfacing towards the controllable loads model

# 6. Steps of the modules and submodules development procedure

Steps of a module/submodule development procedure are:

1. Derivation of the procedure for the module/submodule execution (documenting and development environment)
    a. Derived procedure on the concept level is followed by transnational training to transfer the planned procedure to other consortium members (development partners, pilot leaders and pilot buildings hosts), discuss about the procedures and their application to environments of different pilots
2. Testing of the developed module/submodule on a simplified scenario (simplified building model, simplified modelling of different system elements)
3. Implementation of the module/submodule in Python (Python could be the development environment which would be beneficial to merge steps 2 and 3, but it is not that easy as Matlab has a larger number of options)
    a. Transnational training is organized to introduce the consortium members (development partners, pilot leaders and pilot buildings hosts) with the module and the procedure for its installation within the EMS.

# 7. Conclusion

This deliverable provides the 3Smart energy management system concept for buildings. It explains the main levels in its hierarchical architecture and the modules/submodules constituting these levels. It also shows the presumed interaction with the grid-side energy management system.

Functional requirements for EMS introduction in buildings are given as well as the basic IT architecture proposed for EMS implementation.

Finally, information interfaces of the different constituting submodules of the platform are provided as a basis for further individual development of modules and submodules.

# Bibliography

[1] Technology state-of-the art analysis and potential barriers identification. 3Smart deliverable from the activity 3.1 Analysis of the current technology needs and constraints for Energy Management Systems on the building and grid side in Danube region. D3.1.1, June 2017. Final draft available on http://www.interreg-danube.eu/approved-projects/3smart/section/deliverables.