SIMULATION FOR THE EVALUATION OF ENERGY MANAGEMENT ALGORITHMS AT THE DISTRICT LEVEL – EXAMPLE OF USE CASE FROM THE AMBASSADOR PROJECT

Patrick Béguery¹, Peter Pflaum¹, Nelly Rousset², Franck Bourry³, Audrey Wantier³
¹Schneider Electric, Grenoble, France
²Alten Technologies, Grenoble, France
³CEA-LITEN, National Institute of Solar Energy, Le Bourget du Lac, France

ABSTRACT
In the context of EU FP7 AMBASSADOR project¹, a simulation platform has been developed, as a support for the development and the deployment of energy management systems at the district level. The District Simulation Platform (DSP) includes both the models of the physical components and the models of the energy management algorithms and allows Software In the Loop (SIL) validation: the same algorithm code was first developed and tested on the DSP before being installed for real-time operation of the district.

The DSP can take into account various district configurations through user-defined configuration files. These configurations cover the field tests of the AMBASSADOR project, including the Lavrion experimental site from NTUA close to Athens (Greece), and the INCAS experimental district platform from CEA close to Chambery (France). The first one is detailed in this paper.

INTRODUCTION

Context
The fast development of distributed energy resources, combined with the liberalization of the electricity market, lead to the need for energy management systems. Such need exists for the different levels of energy systems, including the district level. In this context, the objective of the AMBASSADOR project is to develop energy management algorithms adapted for different energy systems of the district, and to deploy these algorithms to field tests. More precisely, the objective of the project is to study, develop and experiment systems and tools that aim to optimize the energy usage in the perimeter of a district by managing the energy flows, predicting and mastering energy consumption and energy production.

To achieve this global objective, the energy management system in the district will optimally control each component in the district (building, battery, production units,…) while respecting coupling constraints between them at district level.

More precisely the coupling constraint is a limitation on the global power consumed from the grid.

In order to develop such energy management algorithms, a simulation platform including both the models of the physical components from the district, and the models of the energy management algorithms to be deployed, was necessary. Consequently, in the frame of the AMBASSADOR project, a simulation platform denoted as “District Simulation Platform” (DSP) has been developed.

Simulation platform objectives
Several simulation software solutions exist for the simulation of the thermal and electric behavior of buildings. Energy+ and IDA ICE are examples of such building simulation solutions. However, the challenges addressed through the AMBASSADOR project lead to the need of a simulation tool which covers the whole range of thermal and electric components of the district, including not only buildings but also water distribution network, cogeneration plant, large energy storage, electric vehicle charging stations, etc. Also, the objective of the DSP is to be a support for the development of energy management algorithms. Consequently, the simulation platform has to be able to integrate the optimization algorithms using Software In the Loop (SIL) validation approach. The same algorithm codes were first developed by different project partners, integrated and tested on the DSP before being deployed for real-time operation of the district pilot sites. Regarding the district energy equipment models, such as a photovoltaic system model or building model, the platform was also able to integrate equipment models provided by different project partners.

Some published studies already mention simulation tools at the district level. For example, the energy management algorithms dedicated to HVAC operation, which are detailed in (Fong, 2006), are assessed using a simulation platform. Similarly, regarding district heating systems, (Benonysson, 1995) mentions a simulation platform used for developing and assessing the optimization algorithms. (Yamaguchi, 2007) describes simulation results for energy management at the district level, on a Japanese use-case. However, none of the existing studies or projects offer a simulation environment...
corresponding to the requirements of the AMBASSADOR project, especially the Software In the Loop support. Consequently, the decision to develop a new simulation platform based on Matlab Simulink environment was made. This open environment has already been used for a number of building simulation application (van Schijndel, 2014). It is interesting to note that the same decision (i.e. to develop a new simulation platform based on Matlab Simulink environment) has been made for other projects which are also related to energy management at district level: the e-hub project 2 and the Resilient project 3.

Besides developing energy management algorithms development, another objective of the DSP is to assess the performances of energy management at the district level. These performances can be evaluated in terms of economic, environmental (for example in terms of CO2) or comfort-related criteria. The simulation platform is designed to be generic in order to consider different district configurations. More precisely, the DSP can take into account district configurations which are defined by the user through a configuration file. These configurations can be different from the field test configuration, and consequently, the DSP offers the possibility to simulate the operation of much wider range of district than the ones proposed for the field tests.

DISTRICT SIMULATION PLATFORM

General specification

Taking into account the targeted usages, the following guidelines have been decided during the initial stage of the platform development:

• DSP will use Matlab/Simulink, with no additional toolboxes to maximise its potential re-use.
• The platform will include automatic model building feature that creates a Simulink model based on a district configuration file.
• Simulation will run at a fixed step-time of 5 minutes.
• Data exchange between models will follow strict interfaces and will use only SI units.
• Electrical grid model is not detailed. Electrical consumptions are defined by power only.
• Water distribution network model considers pressure, but in a simplified manner (this simplified model is still under development and will not be presented in this paper).
• Weather data, time data and energy prices are shared resources, loaded from files and delivered to models through GoTo blocks.

• Forecast values needed by the model’s predictive control are also provided. By default, they are given for every quarter of the next 24 hours. At this time the forecast are ideal ones, but noise can be easily added later to check the optimization algorithm robustness.
• The physical and control models will be clearly separated to facilitate Software In The Loop algorithm integration. Thus, the DSP will include two main functional blocs: the District Energy Management system model and District Physical model.

Energy management

In general, the local objectives of the different district actors are to minimize the operational cost for delivering the required service (in case of a consumer) or to maximize the revenue (in case of a producer). The resulting optimization problem, which needs to be solved at each decision instant, is a large-scale optimization problem which would be computationally intractable in real-time, especially if the number of district components exceeds a certain level. For this reason the District Energy Management structure proposed in AMBASSADOR is based on the concept of Distributed Model Predictive Control (DMPC), where the objective is to design local predictive controllers (called xMS for Management System for component x) that are responsible for local decision making. Through an iterative communication scheme the local controllers are able to recover the optimal solution of the centralized problem or at least to find a relevant sub-optimal solution. Figure 1 illustrates the DMPC concept, for which more information can be found in the result part of this paper and in (Pflaum, 2014).

This distributed optimization approach enables the possibility to integrate different optimization algorithms for the different xMS of the district. This is particularly interesting in the context of the AMBASSADOR project where several partners may provide xMS for a given district. The integration of different complex optimization systems coming from different contributors is a challenge for the reliable operation of the test sites; thus a simulation platform able to test the integration of multiple xMS combined

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with the DEMIS is a solution to pre-validated the global solution.
The DSP is organized to host these different levels of District Energy Management system:

- The top level District Energy Management Information System (DEMIS) acts as coordinator of the xMS;
- Intermediate levels are available in xMS, which are related to the main components of the District physical model; for example, a Building Management Systems (BMS) is related to a building model in the District Physical model;
- Local controllers directly control the physical actuators. They can work as a typical component control (with no optimization algorithm) or receive variable set points defined by the xMS.

Figure 2 summarizes the main architecture of the DSP. The black line represents the bus of physical measures that are delivered to the control systems. In cooperation with the DEMIS, each xMS compute some set points; the local controllers then apply or transform these values into actuators set points that are delivered to the physical models.

Figure 2 - Overview of the architecture of the District Simulation Platform (DSP).

Model libraries

All available models of the DSP are stored according to their type in Simulink libraries. This allows adding new models without changing the DSP framework. Figure 4 shows the battery physical models library.

The global district framework is composed of an assembly of physical models, local controllers and xMS. In order to connect them together, each of them have to follow some interface (inputs/outputs) specifications. All interfaces must use Simulink buses with specific variable names. This facilitates the integration of models developed by different partners, as well as allow easier management of the data for the debugging process. For each kind of district actor, the interfaces have been fixed and a model empty template is proposed in each library. Figure 3 represents the empty template for the battery physical model.

Figure 3 - Template of Battery physical model

In order to change the model configurations without modifying the Simulink block, all model parameters are defined as variables and called by their names in the Simulink blocks. To facilitate the management and modification of values, they are integrated in a Matlab structure, which is initiated through the configuration file and passed to the Simulink model as a mask parameter. This allows the background model to include multiple sets of parameters for the same model.

Building models

In AMBASSADOR, it was assumed that the buildings will use their flexibility to contribute to the district energy management optimization. More specifically, the solutions proposed by several partners aims to control the temperature set points at zone levels in order to benefit from the building inertia. This means that the building models should be sufficiently detailed in order to allow such type of zone level control simulation.

The proposed model is a multi-zone model connected
to a central HVAC system. The zone model include computation of all internal gains (mostly based on a schedule) and a black box thermal model with the inputs/outputs detailed in Table 1. Black box models are identified from more detailed building models developed in Energy+ or IDA-ICE. An automated process has been developed to enable the quick generation of Simulink model for complex multi-zone building based on IDA-ICE simulation results (Beguery, 2015).

Table 1

<table>
<thead>
<tr>
<th>Inputs/Outputs of reduced multi-zone thermal model</th>
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<tbody>
<tr>
<td><strong>Global input - Weather data</strong></td>
</tr>
<tr>
<td>Outdoor temperature</td>
</tr>
<tr>
<td>Global irradiance</td>
</tr>
<tr>
<td>Global irradiance by direction (4)</td>
</tr>
<tr>
<td><strong>Zone input data</strong></td>
</tr>
<tr>
<td>Thermal power produced by occupants</td>
</tr>
<tr>
<td>Artificial lighting power</td>
</tr>
<tr>
<td>Equipment power</td>
</tr>
<tr>
<td>Local unit electrical power</td>
</tr>
<tr>
<td>Heating Fan Coil Unit water flow</td>
</tr>
<tr>
<td>Heating Fan Coil Unit air flow</td>
</tr>
<tr>
<td>Heating FCU water inlet temperature</td>
</tr>
<tr>
<td>Cooling Fan Coil Unit water flow</td>
</tr>
<tr>
<td>Cooling Fan Coil Unit air flow</td>
</tr>
<tr>
<td>Cooling FCU water inlet temperature</td>
</tr>
<tr>
<td>Ventilation supply mass flow</td>
</tr>
<tr>
<td>Ventilation supply air temperature to zone</td>
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<tr>
<td><strong>Zone output data</strong></td>
</tr>
<tr>
<td>Zone temperature</td>
</tr>
<tr>
<td>CO2 concentration</td>
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<tr>
<td>H2O concentration</td>
</tr>
<tr>
<td>Global zone illumination</td>
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<tr>
<td>Heating FCU water outlet temperature</td>
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<tr>
<td>Cooling FCU water outlet temperature</td>
</tr>
<tr>
<td>Heating FCU return water mass flow</td>
</tr>
<tr>
<td>Cooling FCU return water mass flow</td>
</tr>
<tr>
<td>Ventilation return air temperature to zone</td>
</tr>
<tr>
<td>Ventilation return mass flow</td>
</tr>
<tr>
<td>Thermal power consumed by heating FCU</td>
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<tr>
<td>Thermal power consumed by cooling FCU</td>
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<tr>
<td>Electrical power consumed by heating FCU</td>
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<tr>
<td>Electrical power consumed by cooling FCU</td>
</tr>
</tbody>
</table>

*Note: output in italic have been provisioned for future development but are not used at this stage in the DSP framework.*

The HVAC model has to be manually defined for each building. A set of individual component (pump, boiler, chiller, tank, etc) has been developed to make this task easier. Also, every full HVAC system can be saved and easily reuse in other buildings. The HVAC model is connected to the zone by water and air distribution network. It can also be connected to the district hot water network.

Finally, the building model includes a simple electrical model that gathers all the building consumptions. It is also possible to add building energy sources (photovoltaic, wind turbine) and storage (battery). In that later case, it was considered that the battery shall be managed by the Building Management system itself, instead of an independent Battery Management System.

Figure 5 illustrates the various buildings of the AMBASSADOR pilot sites that were developed in IDA-ICE, and then imported to DSP. Additional typical buildings were also developed and added to the DSP libraries for virtual district simulation.

**Auto-building of the Simulink district model**

A Simulink model is typically built manually by dragging and dropping the components from Mathworks and the user defined libraries. This can be a long and tedious work, especially when multiple test cases have to be developed and updated simultaneously.

In AMBASSADOR, it was decided to develop a single “background” Simulink model (see Figure 6). This model will include a number of common features for all districts, but for the main part, it will be configured automatically through a few Matlab scripts, based on a district configuration file.

The configuration file contains all information about models, controllers and xMS used for each district actors (model name and associated parameters file). Calendar, price and weather data are also defined in the configuration as well as data that will be used to run the simulation and post-process the result. All
this information is loaded from the configuration file into a global data structure. Based on this Matlab structure, a set of scripts build the Simulink district model. The models involved in both the District Energy Management system model and the District Physical model are selected into the libraries, placed in the Simulink background model and linked together. The models parameters are then set using the configuration file.

Despite compromising the flexibility of usage in Simulink, this configurable background approach has several benefits:

• An user can specify or modify a district only by setting the configuration file.
• Any generic features developed on the background model will be applied to all existing districts.
• Multiple districts/variants can be easily maintained and evaluated simultaneously.
• Finally, the configurable background model can easily be packaged with a few GUI to obtain an interesting tool for district design and optimization.

**Post treatment**

DSP model has a predefined set of signals that can be stored in a mat file. Several graphical user interface (GUI) offer the users the possibility to visualize the resulting time series. These interfaces enable the following:

i. Analyze the output time series by providing statistical information related to them (min, max and mean values, histogram, monotone curve and carpet plots);
ii. Visualize the different components on a map of the district, with a few global key criteria;
iii. Get a summary of the main parameters and most important signals for each component;
iv. Energy flow synthesis with features to replay "recorded" simulation. Figure 7 gives an example of this feature.

v. Focused view of the optimization process through a dynamic view of xMS strategies showing the time evolution of the forecasted optimal solutions (Note: this display can be activated in line for direct analysis of the optimization during the development and validation phase).

**RESULT**

**Description of the use-case**

The INES (Chambéry) pilot site has been described in (Bourry, 2015). In this paper, we considered another pilot site, located in Lavrion, situated in south-east part of Athens, Greece. This site is an old mine complex in which a number of buildings have been retrofitted and are now used by National Technical University in Athens (NTUA) and private companies. The district includes the following components:

• The Administrative building is an old villa converted into offices and meeting rooms for NTUA. It is a double-storeyed building with a global surface area of approximately 690m². The ground floor hosts a waiting area, four conference/seminar rooms, a computer room, toilets, a boiler room and a storage area. The first floor hosts a waiting area, four administration offices and two meeting rooms. In total, the building model has 15 thermal zones. Heating and cooling is achieved through four pipes with fan coil units connected to a gas boiler and electrical chiller. Heating/cooling system will be controlled by a local xMS developed by CSEM and Neurobat. The building will soon be equipped with a PV field as well as a 60 kWh battery.
• The H2SusBuild is another NTUA building. It has a ground floor with a surface area of 375 m² and an attic floor with an area of 150 m². The ground floor hosts a waiting area, a small kitchen, toilets, the control room and the main area. The attic hosts a waiting area, two offices and a meeting room. In total, there are 14 thermal zones in the building model. The H2SusBuild building covers its energy needs using renewable energy sources and hydrogen storage systems developed by Dappolonia. Locally produced electricity (see below) is converted into hydrogen by a 22 kW electrolyser. It can then be either converted back to electricity by a 20 kWel and 20 kWth fuel cell or burned in a 60 kWth boiler. Hot water produced is used to heat the building. As the hydrogen and building management systems are not developed by the same partner, the current proposal is to have two xMS that will separately report to the DEMIS.
• Three other buildings will also be considered as part of the smart district, even if they will not be controlled. Such components, unable to communicate with the DEMIS are called “dumb loads”. To allow the district optimization, the contribution of these components to the district forecasted consumption should be evaluated.
through appropriate profiling and predictive analytics.

- 475 m² of photovoltaic panels (47kW) and 6 wind turbines (36kW). Their production will be forecasted by a weather forecast service provider.

- A public lighting system (14.6 kW) with schedule based control.

Physical models for all the Lavrion district components were developed in the DSP framework, together with the existing local controllers. The two detailed building models were calibrated based on real site consumptions. For the other buildings, real power profiles were used when available, or replaced by typical forecasted schedules. Modelling of the detailed hydrogen chain and H2susBuild HVAC systems is based on a pre existing TRNSys model developed by NTUA.

![Lavrion (Greece)](image)

**Figure 8 - Lavrion pilot site layout.**

**Energy management objectives**

The distributed optimization approach applied in the Ambassador project is based on dual decomposition. The coupling between the different systems in the district comes from the fact that a global limit on the consumed power in the district needs to be respected. Hence the global optimization problem for the entire district can be written as follows:

Minimize \( \sum_{i=1}^{n_s} J_i(x_i, p_i) \)

subj. to: \( \sum_{i=1}^{n_s} p_i \leq P_{\text{max}} \)

local component constraints

where \( x_i \) are local variables associated with sub-system \( i \) and \( p_i \) is its power consumption profile which appears in the coupling constraint with the global power limitation profile \( P_{\text{max}} \). \( n_s \) is the number of sub-systems in the district and \( J_i \) is the objective function of the \( i \)-th sub-system.

It is due to the coupling constraint that the local optimization problems cannot easily be solved separately. However dual decomposition provides a way to distribute this large-scale optimization problem which would be otherwise intractable.

By building the so-called Lagrangian where the coupling constraint is transferred into the objective term by introducing the dual variables \( \lambda \), the problem becomes decomposable into \( n_s \) sub-problems and one coordinator problem.

\[
\sum_{i=1}^{n_s} J_i(x_i, p_i) + \lambda \left( \sum_{i=1}^{n_s} p_i - P_{\text{max}} \right)
\]

The i-th sub-problem is then:

Minimize \( \sum_{i=1}^{n_s} J_i(x_i, p_i) + \lambda \cdot p_i \)

local component constraints

It is advantageous that the dual variables \( \lambda \) behave in the same manner as the energy tariff at the subsystem level.

For any detail concerning the coordinator problem readers are referred to (Pflaum, 2015). The principle steps of the distributed optimization algorithms are the following:

- The sub-systems solve their local optimization problems in parallel for an initial \( \lambda \) (also called “virtual tariff”) and return their results - the predicted power consumption profile \( p_i \) to the coordinator

- The coordinator updates the virtual tariff and sends it to all sub-systems.

- The previous two steps are repeated 10-15 times. If sub-systems’ local problems are strictly convex, then the solution is the one of the initial large-scale problem with the coupling constraint being respected.

In the following section the xMS of a building and a battery are described in greater detail:

**Building xMS:**

The building’s model which is incorporated in its local optimization problem is a bilinear model which can be represented in state-space form as follows:

\[
\begin{align*}
\dot{x} &= A \cdot x + B \cdot [y \cdot w]\cdot u + F \cdot w \\
y &= C \cdot x + D \cdot [w \cdot u]
\end{align*}
\]

The cost function to be minimized is as follows:

Minimize \( J^f(p(u)) + J^c(y(u,w)) \)

where \( J^f \) is the energy criterion, i.e. the cost for the consumed energy over the prediction horizon and \( J^c \) represents the relaxed comfort constraint in the building. More precisely, when the temperature in the building zones lies outside the comfort bounds, a strong linear penalization on this constraint violation makes the cost function increase. This ensures the feasibility of the problem. Figure 7 illustrates the comfort criterion cost function shape.

In order to solve this non-linear optimization problem, a fixed-point algorithm as mentioned in (Lamoudi, 2012) seems to be very efficient.
Battery xMS:
The battery xMS is based on a linear model of the battery with different charging- and discharging efficiencies:

\[ b^+ = b + \eta(p_b) \cdot p_b \]

where \( b \) is the state of charge, \( p_b \) is the charging/discharging power and \( \eta(p_b) \) is the efficiency defined as:

\[ \eta(p_b) = \begin{cases} 
\eta^+ & \text{if } p_b \geq 0 \\
\frac{1}{\eta^+} & \text{if } p_b < 0 
\end{cases} \]

The objective of the battery xMS is purely economic, i.e. to maximize the revenue by conveniently buying and selling energy. Moreover, the battery’s optimal behavior is determined by the variations in the tariff profile. During periods of low tariff, the battery has the intention to charge in order to be able to supply power to the district during high tariff periods. The corresponding optimization problem is as follows:

Minimize \((\Gamma + \lambda)p_b\)

Subj. to: \[ 0 \leq p_b^+ \leq p_b \leq \overline{p}_b \]

\[ p_b = p_b^+ - \overline{p}_b \]

\[ b \leq b \leq \overline{b} \]

\[ b^+ = b + \eta(p_b) \cdot p_b \]

where \( \Gamma \) is the base tariff profile and \( \lambda \) the virtual tariff profile obtained from the coordinator. The constraints in the problem are the upper and lower bounds on charging- and discharging power, the bounds on the state of charge and the battery’s dynamic model.

Simulation results
In this part, some simulation results illustrating the functionality of the applied distributed optimization scheme are presented, with a focus on the battery management. The considered district is a simplified version of Lavrion district where the hydrogen storage system is never used. The coordinator plays the role of an aggregator who coordinated all components of the district in order to minimize the cost from the electricity export/import to/from the grid and maximize the auto-consumption.

In Figure 10, the first plot shows the power consumption in the district. By adjusting the virtual tariff (red curve in the second graph), the battery adjusts his charge in such a way that the over production is stored in the battery instead of be given to the grid. In the third plot one can see that the battery charge when the virtual tariff is low and discharge when it is high.

In order to evaluate the benefits of the distributed optimization for the simplified Lavrion district, a comparison between three simulation cases are realized (see Table 2):

1. A first case consists in simulating the district operation with basic rules.
2. A second case consists in simulating the operation of the district with uncoordinated optimization. Each sub-system solves his local optimisation problems without coordination. In that case, the battery has no access to knowledge on the renewable energy production and will be used only to buy energy when price is low and deliver it back when price is high. There is a clear benefit in term of cost (-15%). However, simultaneously, more energy is injected into the grid, as the battery the battery controller might decide to discharge its stored energy even if renewable local production is available.
3. A third case consists in simulating the district operation with the distributed optimization. This time, the district controller will coordinate the building needs, local production and storage. Taking into account the virtual tariff, the battery xMS will store more energy when renewable production exceed district consumption. This
allows a reduction of energy injected into the grid of -35%. At the same time, the global district cost saving rise to 17%.

The following table summarizes the obtained simulation results on a one-month simulation. They clearly show the benefits of the distributed optimization in terms of cost and auto-consumption.

Table 2 - Synthesis of january simulation on Lavrion site.

<table>
<thead>
<tr>
<th>Performance indicators</th>
<th>Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No optimization (reference case)</td>
</tr>
<tr>
<td>Electrical energy cost (€)</td>
<td>1977</td>
</tr>
<tr>
<td>Energy injected on grid (kWh)</td>
<td>1416</td>
</tr>
</tbody>
</table>

CONCLUSION

This paper presents the District Simulation Platform (DSP) which has been developed in the context of the AMBASSADOR project. The DSP is a support for Software In the Loop (SIL): the same algorithm code is first developed and tested on the DSP before being deployed for real-time operation of the district. The DSP can take into account various district configurations through user-defined configuration files. The DSP is now operational, and the paper presents the first simulation results obtained with the use-case of the Lavrion pilot site (Greece). The site will host by the end of 2015 the energy management algorithms that are developed using the DSP. These first results validate the objectives of the DSP, i.e. optimization algorithm development and validation, and energy management performance evaluation. In the next steps, the DSP will be used in to evaluate the sensitivity of cost profile, component sizing or control granularity on the global performance of the AMBASSADOR solution. These studies will be performed on the pilot sites, but also on more representative virtual districts that can be easily developed thanks to the flexibility of the DSP.

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