MULTI-ZONE REDUCED BUILDING MODELS AUTOMATED GENERATION FOR DISTRICT SIMULATION

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ABSTRACT
This paper describes a process for automatic generation of building reduced models based on whole building simulation results. The data are used to identify a set of model parameters (one model per zone), analyze the model accuracy, generate C++ code that can be used in Matlab/Simulink and compile them. The resulting dll and additional contextual and physical data are then automatically built into a Simulink, multi-zone, building model.

INTRODUCTION
In the context of building control development, it is often needed to test the control software under development using building simulation. Most building simulation tools allow evaluation of simple control such as schedules or rules based control at component level. Softwares like TRNSYS or IDA-ICE offer opportunities to develop more complex, supervised control (Beguery, 2013). But even these more open environments are not sufficient when it came to the most advanced control strategy like model predictive control.

An obvious solution to achieve the above target is to use co-simulation. The building will be simulated using one of the existing whole building simulation software (DesignBuilder, TRNSYS, IDA-ICE, ...) and its control will be emulated in Matlab or Simulink.

This approach empowers to work with validated building simulation tools, most of them supplemented with an easy to use model design GUI. However, it also suffers a number of drawbacks, the most important one being complexity due to multiple tools management, more or less flexible coupling interface and large simulation time.

Another approach is to create a complete building model within Matlab, like the Simbad toolbox (Riederer, 2002). This removes a number of pain points of co-simulation, but, on another hand, brings some new ones such as model validity and easiness of model design.

A third solution, investigated in this paper, consists in the development of reduced models in Matlab. In that case, the main problems lie in the parameters identification and management of the learned model, especially in the case where a large number of zones is addressed. So, to be appropriate, the full process to move from whole building simulation results (or measured data) to reduced model must be automatized as much as possible. Schneider already has some work done in the automation of model identification based on real data for model predictive control application. In the scope of the AMBASSADOR project¹, this work has been extended to more complete building reduced model, whose parameters will be learned from detailed simulation results.

The first part of the paper describes the context in which takes place this work, e.g. validation of Model Predictive Control optimization at building and district level. The second part details the various steps of the Automatic Reduced Model Identification (ARMI) process. The third part presents results obtained and on-going work.

CONTEXT
AMBASSADOR project
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 because of 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.

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 dedicated simulation platform has been developed.

**District Simulation Platform (DSP)**

Several simulation software solutions exist for the simulation of the thermal and electrical behaviour 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 that covers the whole range of thermal and electrical components of the district. In addition, the objective of the DSP is to be a support for the development of energy management complex algorithms (Pflaum, 2014) developed by eight of the project partners. Furthermore, it was expected that the simulation platform should be able to propose Software In the Loop (SIL) feature. The same algorithm code is firstly developed and tested on the DSP before being deployed for real-time operation of the district. Regarding the district energy equipment models, such as a photovoltaic system model or building equipment models provided by different project partners.

As stated in (Bourry, 2015), a short review of existing software led us to opt for the development of a new simulation platform based on Matlab Simulink environment, an open environment already used for a number of building simulation application (Van Schijndel, 2014). It is interesting to note that other projects working on the same topic, namely e-hub project² and Resilient project³ had reached the same decision.

Besides developing energy management algorithms, another objective of the DSP is to assess the benefits of energy management at the district level. These benefits can be economic, environmental (for example in terms of CO2) or comfort-related. 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. For more details on the DSP, see (Bourry, 2015) and (Beguery, 2015).

Among the district components, one of the most difficult to integrate is the building model, especially as we want to control the building temperature to take advantage of their inertia in the district energy optimization.

One of the challenges of the DSP is to allow the validation of advanced, model based control. It is most common for such type of control to be evaluated through simulation using the same model in the control loop and in the physical model. This approach, which implies that we have captured the exact model of the system, is of course not very representative. It does not help to check the solution robustness and might leads to overestimated savings.

For this reason, it was decided in AMBASSADOR to develop, for the DSP, physical models that will be more detailed that the ones used by the model based control. For example, in a building with mechanical ventilation and 4-pipes Fan Coil Unit, the DSP physical models will use most of the input given in Table 1. At the same time, the model predictive control developed to leverage the building inertia contribution to district energy management will probably only use as input the outdoor temperature and the estimated heating/cooling power deliver to zone. By testing how the strategy proposed based on the simplest model behave when applied on the most detailed one, we can check how the control will react to representative disturbances as well as evaluating more precisely the overall control performance.

**REDUCED MODEL IDENTIFICATION**

**Building reduced model**

The proposal for reduced building model is based on a variant of the multi-zone thermal model developed for model predictive control purpose and described in (Lamoudi, 2012). For the AMBASSADOR project, the identification works with the set of inputs and outputs given in Table 1.

Figure 1 describes the global process for model reduction integration in the DSP. More specifically, the following steps must be observed:

- Produce time-series that describes the system behavior. If available, real data can be used. In our case, we rely on detailed whole building simulation to create the required time series.
- Execute the ARMI process to create compiled thermal model of each zones. For AMBASSADOR purpose, we produce both a complete reduced model for the DSP, and a simpler one (with less input/output) that will be used by the on-line optimization process.

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3. [http://www.resilient-project.eu](http://www.resilient-project.eu)
Integrate the thermal models and complete them with additional part like the HVAC production and distribution system which is, at this stage, manually developed.

The ARMI process is able to interpret the available data and adapt its input/output interfaces to match the specific building data flow. This feature is nice for control development optimization. In the case of the DSP, for simplicity of model integration, it was decided that the Simulink model will always have the same input/output. Management of the unused data is made both in the code generation part of the ARMI model and in the Simulink model automatic builder. The reason for this choice is to reduce the risk of mixing up data in the interface between the S-function and Simulink.

### Whole building models

For most building, data specified in Table 1 will not be easily available from real sensors. This was the case for AMBASSADOR pilot sites. Thus, to produce the detailed results needed for reduced model identification, whole building models were developed in IDA-ICE. Figure 2 presents the 3D-view of the various models developed for AMBASSADOR pilot sites. For residential blocks in Bedzed and office buildings in Lavrion, these models were calibrated based on audit data and energy invoices. For INCAS houses in Chambery, more precise tuning was achieved based on measurements and existing calibrated Energy+ models.

Once the detailed models tuned, simulation must be run and the right time series saved. For the reduced model identification, we need to record the input/output of each zone models in PRN result files, which is the output format for IDA-ICE simulation results.

An excel sheet must be produced with all the information about where the data can be found in the PRN files. This file will be used by a Matlab script that will import the data to the right format for the next step. The excel import file is the same for all IDA-ICE model with a given HVAC architecture. It must be checked and possibly adapted for every new architecture as the HVAC data can be stored in different PRN files.

There is no specific duration range for the simulation required to produce the data. However, we typically use full year simulation to improve the model robustness. Also, as any identification process, the ARMI will work better for input/output data with variable values. Any constant set point, or very simple schedule (often duplicated in whole building simulation tools to serve simultaneously the occupancy, lighting and equipment models) in the IDA-ICE are thus replaced by more dynamic, complex and individual signals.

### ARMI process

The Automatic Reduced Model Identification (ARMI) is a MATLAB project developed to identify automatically and at once all the existing zones of a building. Initially intended to provide models for model predictive control (Lamoudi, 2012), this process has been extended in the scope of AMBASSADOR to identify models for building simulation.

All the steps in the ARMI process are automatic. The data imported from IDA-ICE are the results of the simulation for each zone of the building and the associated weather data used for the simulation.
The building identification process loads the data into MATLAB from the result files and the identification starts. Each zone is identified independently. To do so, the process selects, based on the provided excel input/output file, the right IDA-ICE simulation inputs and outputs signals for the current zone. Main output is always the zone internal temperature. The thermal identification tool selects from the logged IDA-ICE data the ones that are inputs for the current zone (inputs can be different for each zone). The tool automatically creates the right state-space form (see below) and identify its parameters which are saved in a XML file.

This is done both for the DSP physical model (using all available data, up to the full list of Table 1) and for the control model (using a much limited list of input/output, depending on what the project partner feel can be achieved in a commercial approach, were few data are typically available).

Then, automatic code generation is used to produce executable code for each zone. For the control algorithm, the code generated is a compiled C-function that will be called by the optimization framework (a Matlab, class-based approach).

For the DSP, the model is embedded in a S-function wrapper and compiled to produce one dll per zone. As already mentioned, the S-function inputs and outputs are defined in a generic way. This generalisation simplifies the integration of the reduced thermal model in the DSP.

Thermal zone model

According to classical arguments that can be found in literature, a thermal dynamical model of a zone in a building can be expressed on the following discrete-time state-space form:

\[
\begin{align*}
    x(k+1) &= A \cdot x(k) + B \cdot u(k) \\
    y(k) &= C \cdot x(k) \\
    x(0) &= x_0
\end{align*}
\]

where:
- \( x \in \mathbb{R}^{nx} \) is the state vector of the model. Note that the states of the system using the representation do not need to have all a physical meaning;
- \( y \in \mathbb{R}^p \) is the output of the model and represents the measured temperature of the zone;
- \( u \in \mathbb{R}^{nu} \) represents the input vector of the model (both controlled inputs and disturbances);
- \( x_0 \) is the initial state of the system.

The study of the usual response of zone leads us to identify that building usually have two time constants leads to adopt the 2-order state space representation as model.

For the identification, the algorithm uses cross validation to break up the data interval in two separate intervals. The identification works on the first interval and the validation of the identified model operates on the second ones. The identification method mixes several algorithms and results in a meta-heuristic adapted to the problem. The principal components are the fixed point algorithm and the simplex algorithm.

To conclude, the ARMI is an automatic process of thermal building identification that creates from IDA ICE model simulation data:
- An XML file with all the identified parameters.
- Source code and compiled block of the model in Matlab function format (for the optimization
Integration in the District Simulation Platform

The reduced thermal zone models identified by the ARMI process are then integrated in whole building models in the DSP Simulink environment. This whole building models are made of three main parts, which are:

- **The HVAC model** includes all the production, storage and distribution component needed to deliver hot/cold water and air to zones. It is potentially linked with the District Hot Water Network (DiHWN): the building receives the water input temperature and maximum flow available, and return the output temperature and used flow.

- **The multi-zones block** is composed of one subsystem for each zone, which contains the S-Function provided by the ARMI process and additional models as occupancy pattern and internal loads profiles. These blocks are automatically configured using specific parameters defined in a configuration file.

- **The electricity network** sums the electricity consumption of HVAC and zones models. It may include local renewable energy sources and storage. It delivers the net electrical power exchanged with electrical grid.

Each of this sub-system can receive control from the Building Management System and return sensor data in the Bui_Data output.

The diversity and complexity of buildings imply a non-generic model creation. Some parts as the heating, ventilation and air conditioning (HVAC) or the electricity network are very different from one building to another. In the DSP, the HVAC and electricity network models are manually built using simplified models of system as heat pump, air-heating unit for the HVAC and battery, photovoltaic models for the electricity network. A library of simplified HVAC components models is available in the DSP. The work consists on select and configures them according to the building systems.

With the use of S-Function, the parts of code that implements the reduced thermal model can be quickly integrated in the complete building model. There are numerous ways to improve the integration process, by adding more emitters, as well as integration of the HVAC production. Nevertheless, as it is, the process allows us to quickly create complete buildings in the DSP, using the full set of simulation data.

**RESULT**

**Model validation**

Two indicators, automatically computed by the ARMI process on the validation interval, help to validate the performance of the model. They compare the value of the model simulation output with the measured output (in our case, the IDA-ICE simulation results are used in place of the real measurements). The ARMI process utilizes Cross Validation to certify the model. The validation interval and the identification interval are independent and do not share common values.

The indicators are computed from the absolute error vector. It is the normalized absolute difference between the real measure of the temperature and the simulated temperature for each step of the interval. The mean of the error vector offers a good estimation of the model performances, giving an estimation of the error between the time series used to identify the model and the model output (in our case, this is the error between the detailed model and the reduced one). The lesser this indicator is, the more representative the reduced model is.

The standard deviation of the error vector is associated to the mean. The standard deviation helps...
to understand the repartition of the error. The model is better with a small standard deviation.

The correlation of the two indicators grants to the ARMI process the possibility to evaluate the model’s performances and to validate it.

In the context of AMBASSADOR project, the ARMI process was used several times to identified reduced building models of pilot’s sites. The Administrative building at Lavrion is one of them. It is an old villa converted in offices and meeting rooms for the National Technical University in Athens. In each room, there is a four pipes fan coil unit connected to a gas boiler and electrical chiller. In this case, the ARMI process get no information for local electric heater and mechanical ventilation as they do not exist on this site. The reduced model has been adapted to the available input. The Simulink model will have the corresponding input/output displayed but not used (NaN constant input and terminator will be use to manage them).

In IDA-ICE, the Administrative building detailed model is composed of 15 thermal zones. For each of this room, the ARMI process allows identifying the reduced thermal model with less than 1°C of mean error. The following validation report was obtained for one of these zones at the end of the ARMI process (Figure 5 gives the full time series and statistical distribution of the temperature error).

These good results, which are obtain in most of the cases, clearly validate the model for the planed usage. Results can be worst for zone with no or very little heating/cooling needs. In that case, the global impact on the energy is probably low, but we might decide to find better result, for example by increasing the information level in the detailed model schedules.

Indeed, as already mentioned, the quality of the identification depends on the model excitation. If model inputs are correlated or have small variations, the reduced model will not be well learnt and the error will be high.

**Pilot site models**

The ARMI process was successfully used to create the reduced model of all the buildings in the Lavrin and Chambey pilot sites. The validation of the complete model in the DSP was realized using the monthly energy consumption comparison with IDA-ICE results. Results obtained for the Administrative building are summarised in the following table.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Mean Absolute error</th>
<th>Mean error</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>F.Office_room</td>
<td>0.19116°C</td>
<td>0.0060118°C</td>
<td>0.24208°C</td>
</tr>
</tbody>
</table>

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Table 2

| Monthly energy comparison between IDA-ICE and the DSP for the Administrative building |
|----------------------------------------|--------|--------|
| Monthly electrical energy (kWh)       | IDA-ICE| DSP    |
| January                               | 729.3  | 680    |
| February                              | 646.8  | 615.1  |
| March                                 | 675.7  | 658.6  |
| April                                 | 689.8  | 644.7  |
| May                                   | 588.7  | 572.4  |
| June                                  | 575.6  | 549.4  |
| July                                  | 1638   | 1573   |
| August                                | 1598   | 1545   |
| September                             | 950.3  | 958.7  |
| October                               | 586.4  | 572.4  |
| November                              | 675.9  | 660.4  |
| December                              | 678.6  | 629.7  |
| Total                                 | 10033.1| 9659.4 |

With a global error of less than 5%, the quality of the reduced model is considered to be sufficient for the purpose of the energy flow management at the district level.

Compared to the whole building models, the reduced model run much faster. For a full year simulation, at a step time of 5 minutes, we are able to run a small district simulation in less than one hour as long as we use classical control.

**Future development**

The DSP is currently used to validate the optimization algorithm developed for Chambéry and Lavrion test sites. Most of the partner algorithms are first tested on specific sandbox (a district with only the model of component controlled by the partner), before being integrated in the full validation case. For more details on these sites and the optimization algorithms considered, readers are referred to (Bourry, 2015) and (Beguery, 2015). The last pilot site, Bedzed (England) requires building to be connected with simplified district hot water distribution models, which is one of the project next steps.

As the pilot sites are not very representative of a real district (few buildings of a given type with large experimental energy production and storage), it has been decided to use the DSP to create some virtual districts on which the energy management should be demonstrated. The virtual districts will include more building models of different types (residential, office, school, retail...). To populate this district, it is planned to use some of the pilot site buildings and to develop, through the ARMI process, additional typical buildings from various sources. For example, a few reduced models based on the DOE Reference Building (Deru, 2011) database will probably be developed in the next months.

From the detailed building models, the ARMI process provides the thermal model in a very efficient way. Time needed to integrate the model in the DSP is mostly due to the manual development of specific HVAC models. One improvement will be to develop a library of typical HVAC systems with automatic sizing/tuning. This will not be addressed in AMBASSADOR but might be considered in future works.

**CONCLUSION**

This paper has described an automatic process to create reduced multi-zone models based on whole building simulation results. Initially developed for Model Predictive Control application, this process has been adapted to implement complete detailed district in a Matlab/Simulink platform.

The proposed solution combined some interesting features:

1. The reduced building models are automatically defined from a set of available input/output measurement. Their parameters are identified and code generation is used to produce executable blocks, both in typical C and C S-function.

2. The same process is applied both for identification of a very simple model that will be used by models-based control solutions and for the physical, more realistic, model.

3. If not available, the data set can be produced by a detailed model of the building, developed and calibrated using a commercial whole building simulation tool like IDA-ICE.

4. For already developed HVAC system, the integration process of a new building, starting from available data, is no more than a few hours. This time is not dependant on the building zone number. For new HVAC system, more time will be needed as the excel sheet and Simulink HVAC model have to be manually adapted.

In the scope of AMBASSADOR project, this process is very useful. For pilot site, it allows us to start working before any data were available on pilot site, and to perform the on-going pre-validation of the optimization algorithm on a representative case prior to deployment on real site. It will also be very helpful in virtual district investigation, where multiple typical buildings have to be easily developed with their respective optimal control strategy.

In commercial approach, such a pre-validation process might not be easily feasible due to the typical time needed to design and calibrate a building model. However, there is a current trend for systematic use of building simulation, not only at design stage but also during the whole life cycle of the building. In that case, if an updated building model exists, the ARMI process could contribute to a fast and reliable estimation of potential savings by advanced, model-based, control solutions. Furthermore, if deployment of such a solution is decided, the model produced from the ARMI process could be use as a starting point, to be adapted when real signals is available.
ACKNOWLEDGEMENT

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