Automatic Control Laboratory
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EHCM Toolbox

Documentation

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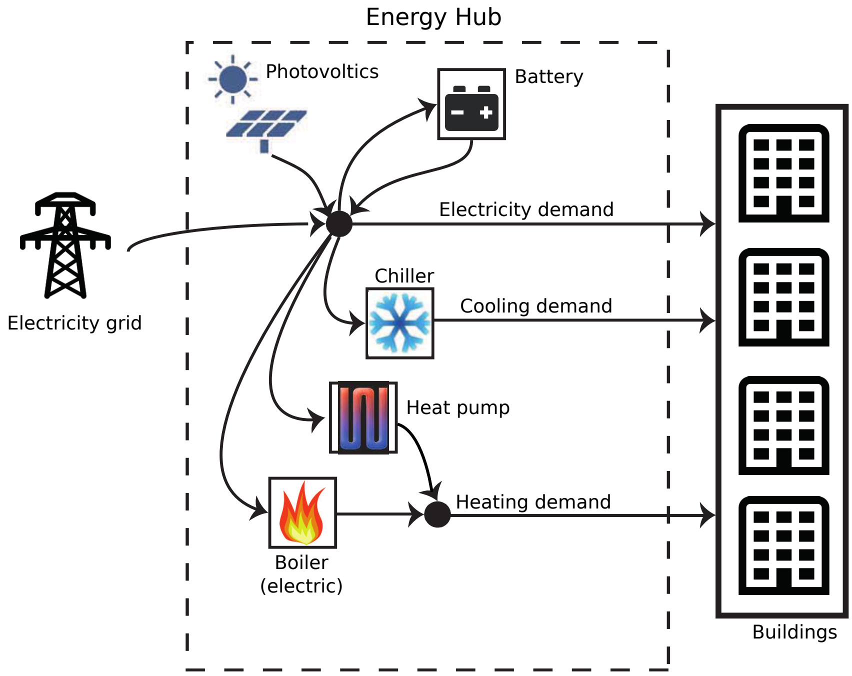

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1 Introduction

Building energy management is an active field of research since the potential in energy savings can be substantial. Nevertheless, the opportunities for large savings within individual buildings can be limited by the flexibility of the installed climate control devices and the individual construction characteristics. The energy hub concept allows one to manage a collection of buildings in a cooperative manner, by providing opportunities for load shifting between buildings and the sharing of expensive but energy efficient equipment housed in the hub, such as heat pumps, boilers, batteries. Typically, control design for the buildings and the energy hub are done separately, underutilizing the potential flexibility provided by the interconnected system. To address these issues, we developed the energy hub component modelling (EHCM) toolbox as a unified framework for controlling the operation of the energy hub and the buildings it connects to. The EHCM Toolbox uses simplified modelling techniques, and modular models built from libraries of commonly used component descriptions, to encourage the adoption of more advanced building control methods [1].

2 Installation and First Steps

The EHCM Toolbox can be installed using the `tbxmanager` [2]. It should be noted that an integral part of the EHCM Toolbox is the BRCM Toolbox which is used to model the building dynamics. It is, therefore, advised that the BRCM Toolbox installation be preceded the one of the EHCM Toolbox. The following steps will guide you through the installation of the EHCM Toolbox,

1) Install tbxmanager as described in www.tbxmanager.com.

2) Install the BRCM Toolbox by typing in matlab,

   `tbxmanager install brcm`

3) Install the EHCM Toolbox by typing in matlab,

   `tbxmanager install ehcm`

As a first step, it is recommended to have a look at the heavily commented `EHCMDemoFile.m` file, which guide step by step through the toolbox functionality. The auxialiary functions that are called in the `EHCMDemoFile.m` file, are considered structural components of the EHCM Toolbox and great notice should be paid to their functionality.

4) To update the EHCM Toolbox, the following command can be used,

   `tbxmanager update ehcm`

3 Combined building/hub energy management

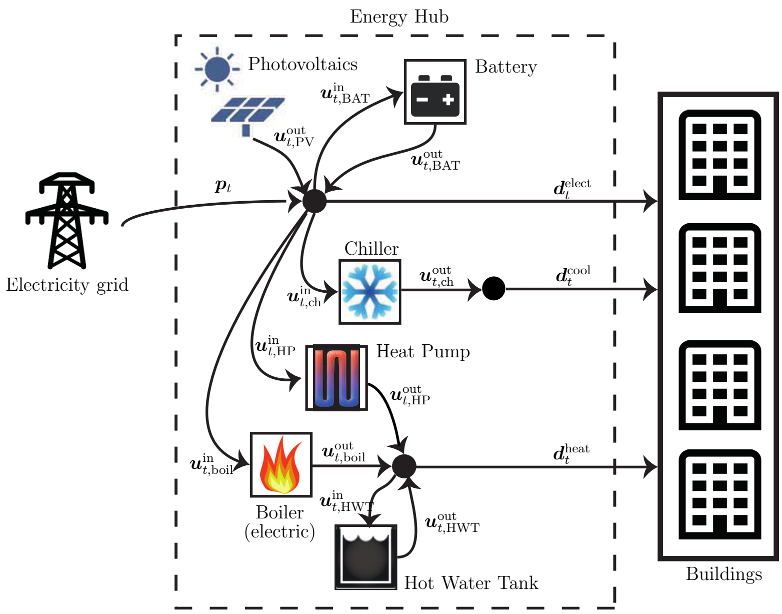

Figure 1: *Energy hub and Building configuration*

The structural components of an energy hub are the following,

a) Generation units (e.g. photovoltaics)

b) Storage units (e.g. batteries, hot water tank)

c) Conversion units (e.g. heat pump, chiller, boiler)

An examplary energy hub, that contains at least one element of each category, is depicted in Fig. 1.

We consider a generic model that captures the dynamical behavior of the i-th energy hub component,

$$\begin{aligned} \boldsymbol{x}_{t+1,i} &= A_i \boldsymbol{x}_{t,i} + B_i^{\text{in}} \boldsymbol{u}_{t,i}^{\text{in}} + B_i^{\text{out}} \boldsymbol{u}_{t,i}^{\text{out}} + C_i \boldsymbol{\xi}_t, \\ &(\boldsymbol{x}_{t,i}, \boldsymbol{u}_{t,i}^{\text{in}}, \boldsymbol{u}_{t,i}^{\text{out}}, \boldsymbol{\xi}_t) \in \mathcal{C}_{t,i}, \end{aligned} \tag{1}$$

where

$\boldsymbol{x}_{t,i}$	: states (e.g. battery charging states)
$\boldsymbol{u}_{t,i}^{\text{in}}, \boldsymbol{u}_{t,i}^{\text{out}}$	: control variables (e.g. power flows)
$\boldsymbol{\xi}_t$	: disturbances (e.g. ambient temperature)
$\mathcal{C}_{t,i}$	: operational constraints (e.g. demand satisfaction, operation limits)
$A_i,\ B_i^{\text{in}},\ B^{\text{out}},\ C_i$	: time-invariant matrices of proper dimensions (e.g. examples 1,2,3)

The following examples that model several energy hub components of Fig. 1, demonstrate the versatility of the proposed model,

Example 1. *Battery Dynamics*

$$\boldsymbol{x}_{t+1} = \begin{pmatrix} 0.51 & 0.22 \\ 0.47 & 0.78 \end{pmatrix} \boldsymbol{x}_t + \begin{pmatrix} 0.61 \\ 0.25 \end{pmatrix} \boldsymbol{u}_t^{in} + \begin{pmatrix} -0.83 \\ -0.39 \end{pmatrix} \boldsymbol{u}_t^{out},$$

Example 2. *Photovoltaics*

$$0 \leq \boldsymbol{u}_{t,PV}^{out} \leq 0.1655 - 0.0066\boldsymbol{\xi}_{t,Amb.Temp.} + 7.8\boldsymbol{\xi}_{t,Solar(S)},$$

Example 3. *Coefficient of Performance*

$$\boldsymbol{u}_{t,chiller}^{out} = 0.7\boldsymbol{u}_{t,chiller}^{in},$$

$$\boldsymbol{u}_{t,boiler}^{out} = 0.7\boldsymbol{u}_{t,boiler}^{in},$$

$$\boldsymbol{u}_{t,HP}^{out} = 3\boldsymbol{u}_{t,HP}^{in},$$

The interconnection of the various energy hub components is performed using balancing nodes. A balancing node is analogous to a throughput node of an electricity grid where the sum of incoming energy streams to the node equals the sum of outgoing streams from the node. In the running example of Fig. 1, we distinguish three balancing nodes, namely, the electricity, the heating and the cooling. The balancing equations will be as follows,

1. ***Electricity node***

$$\boldsymbol{p}_t + \sum_{i \in \mathrm{E}_+} \boldsymbol{u}_{t,i}^{\mathrm{out}} = \sum_{i \in \mathrm{E}_-} \boldsymbol{u}_{t,i}^{\mathrm{in}} + \sum_{i \in \mathcal{B}} \boldsymbol{d}_{t,i}^{\mathrm{elect}}, \quad \forall t \in \mathcal{T},$$

where $\mathrm{E}_+ = \{\mathrm{PV, BAT}\}$ and $\mathrm{E}_- = \{\mathrm{HP, chiller, boiler, BAT}\}$

2. ***Heating node***

$$\sum_{i \in \mathrm{H}_+} \boldsymbol{u}_{t,i}^{\mathrm{out}} = \sum_{i \in \mathrm{H}_-} \boldsymbol{u}_{t,i}^{\mathrm{in}} + \sum_{i \in \mathcal{B}} \boldsymbol{d}_{t,i}^{\mathrm{heat}}, \quad \forall t \in \mathcal{T},$$

where $\mathrm{H}_+ = \{\mathrm{HP, boiler, HWT}\}$ and $\mathrm{H}_- = \{\mathrm{HWT}\}$.

3. ***Cooling node***

$$\sum_{i \in C_+} \boldsymbol{u}_{t,i}^{\mathrm{out}} = \sum_{i \in \mathcal{B}} \boldsymbol{d}_{t,i}^{\mathrm{cool}}, \quad \forall t \in \mathcal{T},$$

where $C_+ = \{\mathrm{chiller}\}$

The buildings are modelled using the BRCM Toolbox [3], which provides a bilinear model for the i-th building connected to the hub of the following form,

$$\boldsymbol{x}_{t+1,i} = A_i \boldsymbol{x}_{t,i} + B_i \boldsymbol{u}_{t,i} + C_i \boldsymbol{\xi}_t + \sum_{j \in \mathcal{D}_i^{\mathrm{b}}} \left(D_{i,j} \boldsymbol{\xi}_t + E_{i,j} \boldsymbol{x}_{t,i} \right) \boldsymbol{u}_{t,i,j}, \tag{2}$$

where $\mathcal{D}_i^{\mathrm{b}} = \{\text{radiators, blinds position, AHU, TABS}\}$. The BRCM Toolbox is also providing the constraint set of the i-th building as follows,

$$F_{t,i} x_{t,i} + M_{t,i} u_{t,i} + L_{t,i} \xi_t \leq h_{t,i}$$

The constraint set defined above can be composed by both actuation limits that depend on the room temperatures and disturbances (e.g. air handling unit) and a comfort band for the room temperatures.

As it was already mentioned, the energy hub objective is to meet the demand for electricity, heating and cooling of the buildings. In our running example, the coupling of the energy hub and the buildings can be modelled as follows,

$$\begin{aligned}
\boldsymbol{d}_{t,i}^{\mathrm{elect}} &= \sum \boldsymbol{u}_{t,i,\mathrm{AHU}}, \\
\boldsymbol{d}_{t,i}^{\mathrm{heat}} &= \sum \boldsymbol{u}_{t,i,\mathrm{radiator}} + \sum \boldsymbol{u}_{t,i,\mathrm{TABS}}, \\
\boldsymbol{d}_{t,i}^{\mathrm{cool}} &= \sum \boldsymbol{u}_{t,i,\mathrm{TABS}},
\end{aligned}$$

Hence, the overall optimization problem that is formulated and solved by the EHCM Toolbox over a time horizon $\mathcal{T}$, is the following,

$$\begin{aligned}
J(x_1) = \min \; & \mathbb{E} \left(\sum_{t \in \mathcal{T}} c_t \boldsymbol{p}_t \right) \\
\text{s.t.} \; & \left.\begin{aligned}
& \boldsymbol{x}_{t+1,i} = A_i \boldsymbol{x}_{t,i} + B_i^{\mathrm{in}} \boldsymbol{u}_{t,i}^{\mathrm{in}} + B_i^{\mathrm{out}} \boldsymbol{u}_{t,i}^{\mathrm{out}} + C_i \boldsymbol{\xi}_t, \\
& (\boldsymbol{x}_{t,i}, \boldsymbol{u}_{t,i}^{\mathrm{in}}, \boldsymbol{u}_{t,i}^{\mathrm{out}}, \boldsymbol{\xi}_t) \in \mathcal{C}_{t,i} \\
& \boldsymbol{p}_t + \textstyle\sum_{i \in \mathrm{E}_+} \boldsymbol{u}_{t,i}^{\mathrm{out}} = \sum_{i \in \mathrm{E}_-} \boldsymbol{u}_{t,i}^{\mathrm{in}} + \sum_{i \in \mathcal{B}} \boldsymbol{d}_{t,i}^{\mathrm{elect}} \\
& \textstyle\sum_{i \in \mathrm{H}_+} \boldsymbol{u}_{t,i}^{\mathrm{out}} = \sum_{i \in \mathrm{H}_-} \boldsymbol{u}_{t,i}^{\mathrm{in}} + \sum_{i \in \mathcal{B}} \boldsymbol{d}_{t,i}^{\mathrm{heat}} \\
& \textstyle\sum_{i \in C_+} \boldsymbol{u}_{t,i}^{\mathrm{out}} = \sum_{i \in \mathcal{B}} \boldsymbol{d}_{t,i}^{\mathrm{cool}} \\
& \boldsymbol{x}_{t+1,i} = A_i \boldsymbol{x}_{t,i} + B_i \boldsymbol{u}_{t,i} + C_i \boldsymbol{\xi}_t + \sum_{j \in \mathcal{D}_i^{\mathrm{b}}} \left(D_{i,j} \boldsymbol{\xi}_t + E_{i,j} \boldsymbol{x}_{t,i} \right) \boldsymbol{u}_{t,i,j}, \\
& F_{t,i} x_{t,i} + M_{t,i} u_{t,i} + L_{t,i} \xi_t \leq h_{t,i} \;\; \forall i \in \mathcal{B} \\
& \boldsymbol{d}_{t,i}^{\mathrm{elect}} = \textstyle\sum \boldsymbol{u}_{t,i,\mathrm{AHU}}, \;\; \boldsymbol{d}_{t,i}^{\mathrm{heat}} = \sum \boldsymbol{u}_{t,i,\mathrm{radiator}} + \sum \boldsymbol{u}_{t,i,\mathrm{TABS}} \\
& \boldsymbol{d}_{t,i}^{\mathrm{cool}} = \textstyle\sum \boldsymbol{u}_{t,i,\mathrm{TABS}}, \;\; \forall i \in \mathcal{B}
\end{aligned}\right\} \forall t \in \mathcal{T}
\end{aligned} \tag{3}$$

4 Model Generation

The EHCM Toolbox was designed in an object oriented fashion, as depicted in Fig. 2,

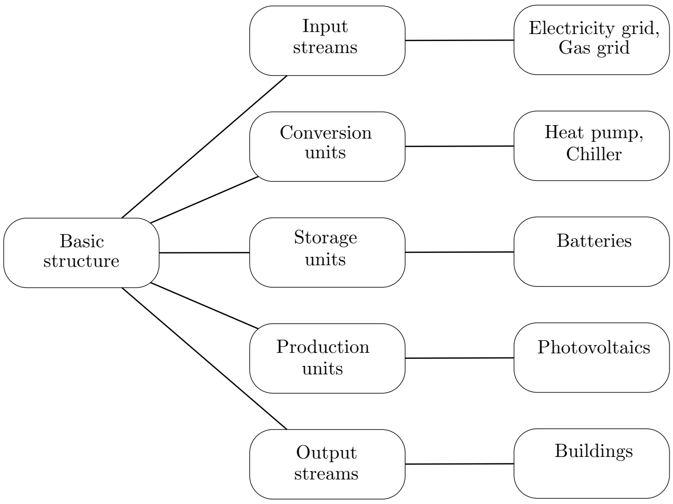

Figure 2: *Object oriented structure of EHCM Toolbox classes*

The ”Basic structure” class is inherited by all the other classes of the toolbox, and enables the automated interconnection of the various energy hub components in order the optimization problem (3) to be formulated. Moreover, the actual components of the energy hub (e.g. batteries, heat pump) inherit the methods of their parent class, which can be one of the following,

1. Input streams
2. Conversion units
3. Storage units
4. Pruduction units
5. Output streams

In the remaining of this section, we provide the basic information regarding the build in classes that are currently supported by the EHCM Toolbox, namely,

a) Conversion units

b) Battery units

c) Building units

The users are highly adviced to thoroughly check the demo file `EHCMDemoFile.m` for a detailed analysis of the various features and functions included in the toolbox.

4.1 Conversion units modelling

A conversion unit is modelled using the following discrete-time dynamical model,

$$\begin{aligned} x_{t+1} &= Ax_t + Bu_t^{\text{in}} \\ u_t^{\text{out}} &= Cx_t + Du_t^{\text{in}} \end{aligned} \tag{4}$$

and the constraint set,

$$F_x x_t + F_u u_t \leq g \tag{5}$$

where the matrices, A, B, C, D, F_x, F_u are properly defined by the user and capture the dynamical behaviour and constraints of the conversion unit. Moreover, the user should define the nodes to which the conversion unit is connected to.

The matlab code that is used to define a conversion unit in the EHCM Toolbox is as follows,

```
obj = EHConverter(convName, inputNode , outputNode ,A,B,C,D,Fx,Fu,g)
```

4.2 Battery units

Lead-acid batteries were chosen as an efficient solution for electric power storage of buildings [4]. The EHCM Toolbox is providing built in classes that uses the simplified model developed in [5] to sufficiently capture the dynamics of a lead-acid battery. In our running example, a 5kW lead-acid battery was used and the produced model is as follows,

$$\begin{pmatrix} \boldsymbol{x}_{t+1}^1 \\ \boldsymbol{x}_{t+1}^2 \end{pmatrix} = \begin{pmatrix} 0.51 & 0.22 \\ 0.47 & 0.78 \end{pmatrix} \begin{pmatrix} \boldsymbol{x}_t^1 \\ \boldsymbol{x}_t^2 \end{pmatrix} + \begin{pmatrix} 0.61 \\ 0.25 \end{pmatrix} \boldsymbol{u}_t^{\text{in}} + \begin{pmatrix} -0.83 \\ -0.39 \end{pmatrix} \boldsymbol{u}_t^{\text{out}},$$

$$\begin{pmatrix} -1 & -1 \\ 1 & 1 \\ 0 & 0 \\ -0.61 & -0.26 \\ 0.73 & 0.73 \end{pmatrix} \begin{pmatrix} \boldsymbol{x}_t^1 \\ \boldsymbol{x}_t^2 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \boldsymbol{u}_t^{\text{in}} \\ \boldsymbol{u}_t^{\text{out}} \end{pmatrix} \leq \begin{pmatrix} -1 \\ 5 \\ 8 \\ 0 \\ 4.39 \end{pmatrix}$$

The matlab code used to generate the above battery model in the EHCM Toolbox is the following,

```
obj = EHBattery(batteryName,nomBat,nodeIO)
```

4.3 Building unit

The building dynamics as these are given by the BRCM Toolbox will be,

$$\begin{aligned} & x_{t+1} = Ax_t + B_u u_t + B_v v_t + \sum_{i=1}^{n_u} \left(B_{vu,i} v_t + B_{xu,i} x_t \right) u_{i,t} \\ & F_{x,t} x_t + F_{u,t} u_t + F_{v,t} v_t \leq f_t \end{aligned} \tag{6}$$

where x_t denotes the states (temperatures of rooms or wall/floor/ceiling layers), u_t the inputs (e.g. heating power or blinds position) and v_t the predicted disturbances (e.g. solar radiation or ambient temperature) at prediction time step t. $F_{x,t}$, $F_{u,t}$, $F_{v,t}$ and f_t denote the potentially time-varying constraint matrices and vectors at time step t. Note that the above model is in total agreement with the generic model (2) with a slight change in notation to be compatible with the output model of the BRCM Toolbox. Moreover, the buildings are serving their demand through the ouput streams of the energy hub, therefore, the user should provide the name of the node at which the building is connected to. The matlab code to generate a building unit in the EHCM Toolbox is given as follows,

```
obj = EHBuilding(modelName, pathName, nodeName)
```

where the variable `nodeName` denotes the output node of the energy hub at which the building is connected to. For detailed analysis of the building dynamics and actuation units, the interested reader is strongly recommended to advice the online documentaion of the BRCM Toolbox [3].

References

[1] G. Darivianakis, A. Georghiou, R. S. Smith, and J. Lygeros. A Stochastic Optimization Approach to Cooperative Building Energy Management via an Energy Hub. *IEEE Conference on Decision and Control,*, 2015.

[2] *The Toolbox Manager.* www.tbxmanager.com.

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[5] E. Vrettos and S. Papathanassiou. Operating policy and optimal sizing of a high penetration res-bess system for small isolated grids. 26(3):744–756, 2011.