IPESE Industrial Process and Energy Systems Engineering

Modeling and optimization of energy systems

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Project Description

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Introduction

The **energy system** of EPFL consists of systems supplying heating, cooling and electricity - however, the **heating** system is about to reach the end of its operating lifetime. The infrastructure management team is therefore looking for different options to replace it - each option should be assessed with regards to its energetic (efficiency), economic (investment and operating costs) and environmental (CO_2-emissions) performance. As an **energy consultant**, you were given the task of conducting this project, which consists of five main steps. Each is one part of the project:

1. analysing the energy (heating) demands on the EPFL site and classifying them,
2. selecting the utilities (heat pump, solar panel...) that can be integrated and calculating their annual operating costs,
3. assessing the possibilities for heat recovery from the EPFL data center and other sources,
4. developing heat pump models and deriving their performances based on given measurements,
5. put forward **your** suggestions and evaluate their benefits for different scenarios.

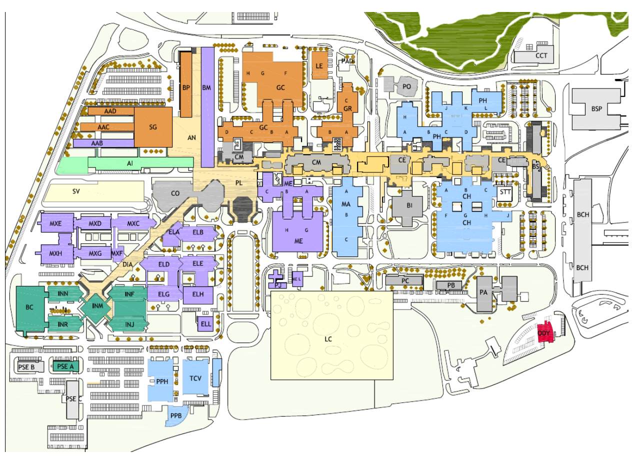


Figure 1: Map of EPFL campus

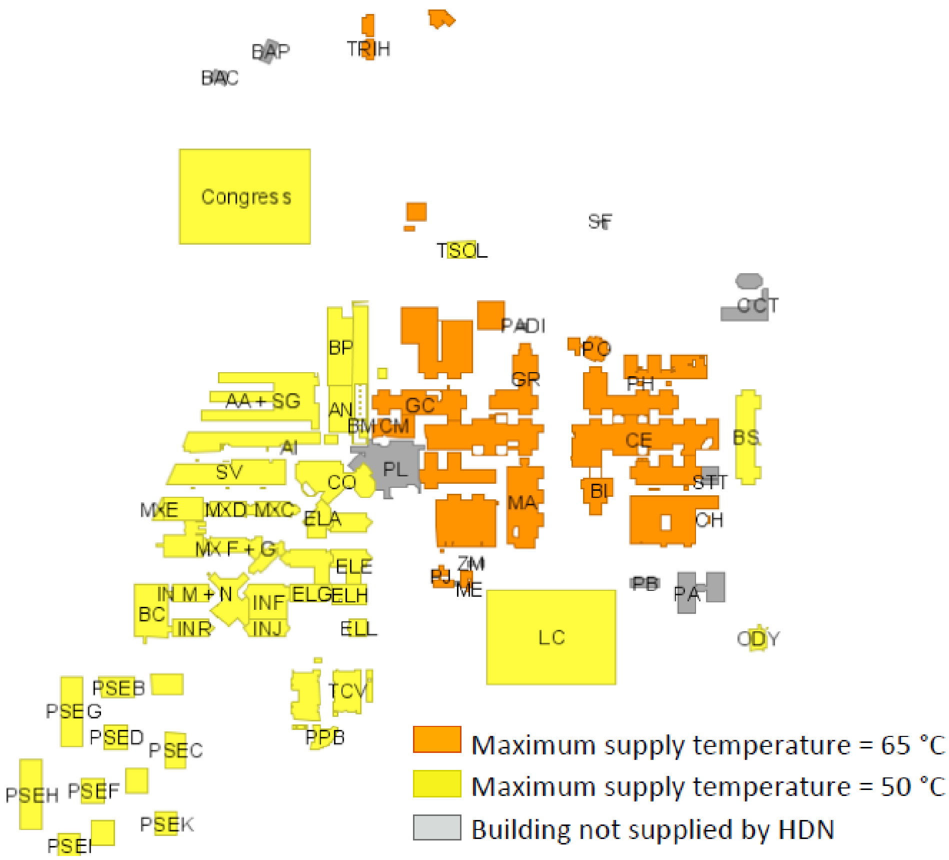


Figure 2: EPFL buildings with HDN sizing supply temperature

Part 1

Energy demand of the EPFL campus

Objectives

The main objective of this part of the project is to *analyze the energy demands of the EPFL campus*, with a focus on the heating demands and design characteristics of the various buildings on-site. Understanding the thermal design of the buildings (wall properties, heat gains, thermal losses) is important for a proper control of the amount of energy required to ensure thermal comfort throughout the year. To this end you are asked to:

- calculate the thermal gains from people and electronic appliances, based on the occupancy profiles of the buildings ;
- estimate the thermal properties of the buildings based on the annual heating demand;
- derive the hourly heating demand over the whole year for the buildings you were assigned;
- identify the most frequent and extreme working conditions (typical periods) that can represent the annual heating demand (Section 1.3).

Hint

For simplification, the analysis of the cooling demands and design of the cooling system are out of scope of the present study.

The main software to use for this part of the project is **Matlab**, and a **base-file** is given to start with.

1.1 General Overview

The campus consists of several buildings of different sizes (Figure 1). The buildings can be grouped based on their construction year, which also represents the level of insulation and the supply temperature for the heating demand (Figure 2). The building size (also: reference heated surface) and the annual demand of heat and electricity are presented in Table 1.1.
This next section aims to find the demand profiles from the annual values in Table 1.1. Therefore, Heating load calculations are carried out to estimate (1) the heat losses from the building to the environment (heat conduction through the walls and windows, ventilation for air renewal), (2) external heat gains (thermal radiation from the sun) and (3) internal gains from occupants and appliances. These calculations are usually performed assuming quasi steady-state conditions (hourly or daily basis). This simplified approach does not consider highly unsteady phenomena such as heat gains or losses due to heat accumulation in the walls, and

Table 1.1: EPFL Buildings

Building	Construction period[a]	Heated surface A_{th} [m^2]	Annual heat demand Q_{th} [kWh]	Annual electricity demand Q_{el} [kWh]
BC	2	17480	418,491	1,603,596
CO	2	11901	477,008	943,653
BP	2	10442	457,861	691,031
BS	2	10267	509,183	350,860
TCV	2	6095	318,209	2,067,675
IN	2	24073	1,260,041	1,889,430
GC	1	26586	1,465,755	1,978,120
CE	1	16655	1,003,313	1,200,598
ODY	2	4092	253,199	81,410
MA	1	14018	889,271	5,531,370
GR	1	9997	649,081	813,804
ME	2	17151	1,126,830	3,118,001
CM	1	18663	1,251,411	1,354,652
AA + SG	2	18389	1,306,603	1,231,934
BI	1	4496	345,679	413,651
EL	2	22127	1,728,630	1,447,090
PO	2	692	64,607	94,326
CRPP	2	10831	928,960	1,608,750
MX	2	25868	2,600,901	2,832,408
BM	2	19697	2,121,607	2,411,721
CH + STT	1	28,986	3,217,870	4,717,985
DIA	2	847	105,136	-
PH	1	23581	3,036,870	4,433,829
AI	2	17674	2,768,898	3,898,106

[a] Construction period 1 corresponds to medium temperature demand (65 °C) while period 2 is for low temperature demand (50 °C)

can be expressed explicitly with the following equation, which governs the thermal load for each building (Equation 1.1):

$$\begin{aligned} &\dot{\boldsymbol{Q}}_{\text{th}}(t) = A_{\text{th}} \cdot \left(\boldsymbol{k}_{\text{th}} \cdot (T_{\text{int}} - T_{\text{ext}}(t)) - \boldsymbol{k}_{\text{sun}} \cdot \dot{i}(t) - \dot{\boldsymbol{q}}_{\text{people}}(t)\right) - f_{\text{el}} \cdot \dot{\boldsymbol{Q}}_{\text{el}}(t) \\ &\text{if } \dot{Q}_{\text{th}}(t) \leq 0, \text{ cooling} \\ &\text{if } \dot{Q}_{\text{th}}(t) \geq 0, \text{ heating} \end{aligned} \tag{1.1}$$

where:

- A_{th}: reference heated surface (m^2);
- k_{th}: thermal losses and ventilation coefficient in ($\text{W/m}^2\text{/K}$);
- T_{int}: internal set point temperature equal to 21 °C;
- $T_{\text{ext}}(t)$: external ambient temperature (°C);
- k_{sun}: solar radiation coefficient $[-]$; [1]

[1] This coefficient takes into account the shape of the building (i.e. ratio between envelope and heated surface), the fraction of window surface and the transmittance of the glass

- $\dot{i}(t)$: solar global radiation per area (W/m^2), given in the project appendices ;
- $\dot{q}_{\text{people}}(t)$: heat gain due to the presence of people per unit area (W/m^2);
- f_{el}: share of electricity demand which is converted to heat appliances $[-]$; Based on the SIA regulations, about 70 to 90 %, depending on the type of buildings. Assume f_{el} equal to 0.8.
- $\dot{Q}_{\text{el}}(t)$: Electricity demand (W);

Hint

The bold symbols in Equation 1.1 are unknown and need to be calculated in the first part of the project with different levels of difficulty.

1.2 Hourly Demand Profiles

The main work in Part 1 of the project is to derive demand profiles. Therefore, this section is a guideline how to determine the unknown parameter in Equation 1.1.

1.2.1 Electricity demand

The electric appliances and lights are switched **ON** only from Mondays to Fridays and between 7 AM and 9 PM. Assume a uniform distribution of Q_{el} (Table 1.1)over the operating hours (3654 hours per year).

1.2.2 Heat gain due to people

For the occupancy profile, energy audits are usually based on the standard set schedule specified in SIA 2024:2015[2], as presented in Table 1.2 and Figure 1.1.

Table 1.2: Standard occupancy profile

Usage	Heat gain (W/m^2)	Share $A_{\text{type}}/A_{\text{th}}$
Office	5	0.3
Self-service Restaurant	35	0.05
Classroom	23.3	0.35
Others	0	0.3

1.2.3 Thermal characteristics k_{th} and k_{sun}

The building thermal characteristics can be described with the heat transfer coefficients k_{th} and k_{sun}. The former corresponds to the thermal losses through the building envelope and ventilation system, while the latter corresponds to the thermal gains by radiation.

$$k_{\text{th}} = U_{\text{env}} + \dot{m}_{\text{air}} \cdot c_{p,air} \tag{1.2}$$

where:

- m_{air} is the exterior air renewal (m^3/(m^2·h))
- $c_{p,\text{air}}$ is the air specific heat capacity in (J/(m^3·K))

[2]SIA 2024:2015 *Données d'utilisation des locaux pour l'énergie et les installations du batiment.*

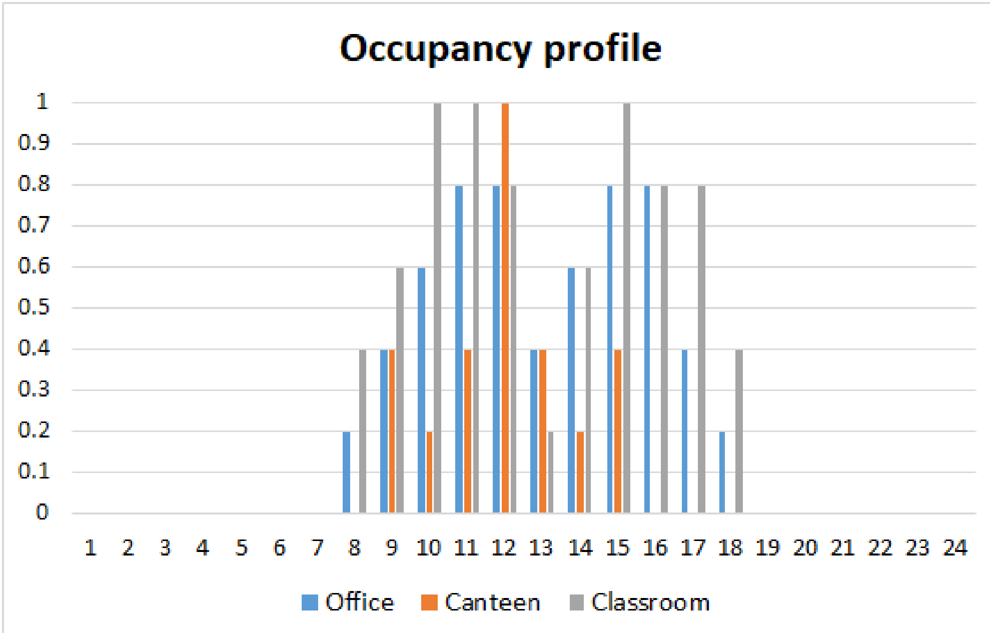


Figure 1.1: Occupancy profile per type of usage

- U_{env} is the overall heat transfer coefficient of the building envelope (W/(m^2·K)) (unknown)

Ventilation characteristics

- $m_{\text{air}} = 2.5$ (m^3/(m^2·h))
- $c_{p,\text{air}} = 1152$ (J/(m^3·K))

As there are two main unknowns remaining (k_{th} and k_{sun}), two equations are required to calculate the values of the two heat transfer coefficients. They can be deduced from the thermal load calculation (Equation 1.1). This equation considers that the external heating (or cooling) required should compensate the heat losses and gains, assuming that the building temperature is around the set point temperature, which is usually 21 °C.

At this **stage** you should **have and present**:

- the calculations of the heat gains from people ($\dot{q}_{\text{people}}(t)$) and appliances ($\dot{Q}_{\text{el}}(t)$) per hour, day and year;
- the calculations of the heat gains from solar radiation ($\dot{i}(t)$) per hour, day and year;

First equation - switching ON the heating system In practice, it is **not** necessary that the internal temperature is exactly 21 °C at all times. Studies show that the notion of 'thermal comfort' vary from one person to another, and a variation of $\pm$ 5°C around this set point can be accepted. In other words, the heating system *may* be turned ON only if the external temperature is below 16 °C (heating demand $Q^{+}_{\text{th}} \neq 0$), while the cooling system *may* be turned ON (cooling demand $Q^{-}_{\text{th}} \neq 0$) only if the external temperature is above 26 °C. These temperatures are named the *control cut-on temperatures*, while the range 16-26 °C is sometimes termed the *dead band* (Figure 1.2).

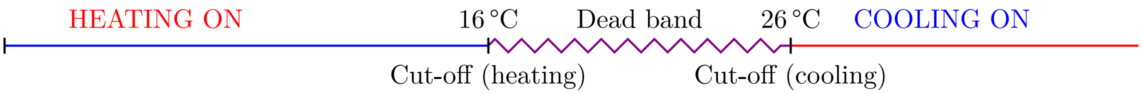


Figure 1.2: Cut-off temperatures of the heating and cooling systems

Therefore, for all the hours of the year in which the heating system *may* be ON and if the external temperature is lower than the cut-off temperature, the heat load can be expressed as (Equation 1.3):

$$\begin{aligned}
&Q_{\text{th}}(t) = \Delta t \left\{ A_{\text{th}} \cdot \left(k_{\text{th}} \cdot (T_{\text{int}} - T_{\text{ext}}(t)) - k_{\text{sun}} \cdot \dot{i}(t) - \dot{q}_{\text{people}}(t) \right) - f_{el} \cdot \dot{Q}_{\text{el}}(t) \right\} \\
&\forall t, \quad \text{if } T_{\text{ext}} \ \leq \ T_{\text{cut-off}} \\
&\text{if } Q_{\text{th}} \leq 0, \text{ cooling} \\
&\text{if } Q_{\text{th}} \geq 0, \text{ heating}
\end{aligned} \tag{1.3}$$

Hint

- Equation 1.3 is very similar than Equation 1.1. The validity range is different and the unit of the heat load Q_{th} is [Wh], Δt is one hour.
- You only may need heating during the time people are in the building, which is only from Mondays to Fridays and between 7AM and 9 PM.

Second equation - yearly heating demand In some cases, cooling of the building *may* be required ($\dot{Q}_{\text{th}}$ negative) for external temperatures below 16 °C if the heat gains from the solar radiation, electric appliances and people are significant (Equation 1.3). This implies that the demand of the heating system may be equal to 0 in some conditions, as the heating and cooling systems are **NOT** turned ON simultaneously.

$$Q^{+}_{\text{th}}(t) = \begin{cases} Q_{\text{th}}(t), & \text{if } Q_{\text{th}}(t) \geq 0. \\ 0, & \text{otherwise.} \end{cases} \tag{1.4}$$

The sum of the hourly heating demands over a year (N_p periods) corresponds to the total annual heating demand (Equation 1.5).

$$Q^{+}_{\text{th,year}} = \sum_{p=1}^{N_p} Q^{+}_{\text{th}}(t) \tag{1.5}$$

This second equation is *non-linear* and the Newton-Raphson method should therefore be applied for resolution.

Newton-Raphson Method As seen previously, the equation system constituted by the two relations presented before is non-linear, which is a common issue in heat transfer problems in buildings. Direct resolution by a linear solver to calculate k_{th} and k_{sun} is therefore not possible, and methods that address these non-linearities, such as the Newton-Raphson (NR) method, are required. You find more information about this method in the course material about "solving equations" on moodle. In the following, we provide you with some intermediate steps to help you setting up the method.

1. Hint Since the NR method allows you to find zero points in your function, we need to formulate our aim according to Equation 1.6 .

$$Q^{+}_{\text{th,year}} - Q_{\text{th}} = 0 \tag{1.6}$$

where:

- $Q^{+}_{\text{th,year}}$ is your calculated annual heatload Equation 1.5
- Q_{th} is the annual heatload given in Table 1.1

2. Hint Choose as variable either k_{th} or k_{sun} and formulate the derivative of Equation 1.6.

3. Hint For calculating the missing parameter (k_{sun} or k_{th}, depending on your choice in 2. Hint) use the assumption that the heat load is zero, if the cut off temperature is equal to ± 1 °C. You can assume mean values of irradiation, electricity demand and heat gain due to people for the time this condition applies.

$$0 = A_{\text{th}} \cdot \left(k_{\text{th}} \cdot (T_{\text{int}} - T_{\text{cut}}) - k_{\text{sun}} \cdot \dot{i}_{mean} - \dot{q}_{\text{people,mean}}\right) - f_{el} \cdot \dot{Q}_{\text{el,mean}} \tag{1.7}$$

4. Hint The following values are suggested for initialisation of the Newton-Raphson methods:

- Tolerance = from 10^{-4} to 10^{-6};
- Maximum number of iterations = from 10^{3} to 10^{6};
- $k_{\text{th},0}$ = from 1 to 10, and $k_{\text{sun},0}$ from 0.05 to 5.

At this **stage** you should **have and present**:

- the values of the heat transfer coefficients k_{th} and k_{sun} from the NR methods;
- the values of the building envelope coefficient U_{env};
- the number of iterations required and achieved accuracies;

The hourly heating demand can be calculated once the heat gains ($\dot{q}_{\text{people}}(t)$ and $\dot{Q}_{\text{el}}(t)$) and building properties (k_{th} and k_{sun}) are derived, following the equation1.1.

1.3 Typical periods

High-resolution data are highly valuable as they clearly show the relations between, on the one hand, the fluctuations in the environmental (external temperature and irradiation) and internal (occupancy and appliances) conditions, and, on the other hand, the actual heating loads. However, using such data may be impractical in preliminary feasibility studies because of the heavy computational load. It is therefore convenient to reduce a full year data set into a limited number of **typical periods** (Figure 1.3). Those should represent adequately the characteristics of the yearly profile while considering fewer time steps and variables.

Since the demand profiles are individual for each building on campus, the data clustering should be performed on **weather data**, in our case external temperature and irradiation. However, respect the fact that it makes no sense to have several typical periods accounting for the time the heating is switched off completely. It is **required** to apply at least two clustering methods and to compare the quality of the generated typical periods. It is your choice to select the preferred methodology to reduce the data.

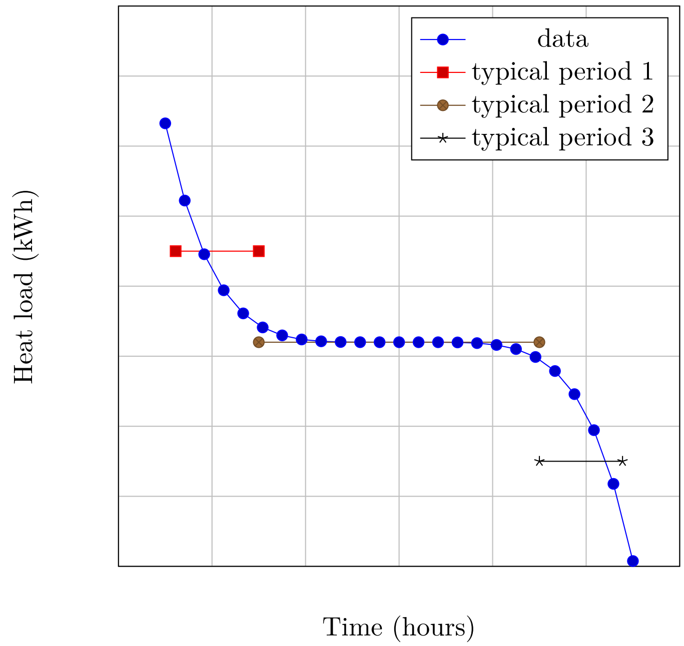


Figure 1.3: Example of clustering and typical periods for a heating duration curve

Numerical implementation of clustering methods

Several aggregation methods can be found in the literature to this purpose. For example, the most basic clustering method consists of selecting a typical period/day per week, month or season, and averaging the heat loads over this period. A more advanced tool is the k-means clustering method (implemented in Matlab, see: `https://ch.mathworks.com/help/stats/kmeans.html`), which classifies systematically the hourly data into a number of sets, in which each data point belongs to the set with the nearest average value.

Clustering indicators

The 'quality' of the clustering can be measured with the following indicators:

- the **profile deviation** for **each typical period**, which is defined as the difference between the original and typical period profiles;
- the **profile deviation** for **the entire year**, which is defined as the **total** deviation from the original load duration curve;
- the **maximum load duration curve difference**, which is defined as the relative difference in maximum loads between the original and typical periods;

Hints

- Be aware that the extreme working conditions (coldest ambient temperature, low sun irradiation) are important to define the size of your equipments and should be included as at least one typical period.
- It is highly recommended to normalize the data before clustering.

At this **stage** you should **have and present**:

- the selection of typical periods (characteristics in terms of temperature, solar irradiation and heating demand);
- the analysis of their accuracy (profile deviation per day/year, maximum and relative differences).

1.4 Summary

At the end of the project:

Given:

- hourly external temperature $T_{\text{ext}(t)}$ (attached as .csv);
- hourly solar global radiation $\dot{i}(t)$ (attached as .csv);
- share of activity in terms of reference heated surface, occupancy profile and heat gain due the presence of people;
- annual electric consumption and profile for electric appliances and lights;
- air renewal flow rate $\dot{m}_{\text{air}}$;
- cut-off temperature T_{th};
- set schedule when the heating system could be switched ON;

You should **present** for each building you analyse:

- the estimations of the heat gains;
- the calculations of the building envelope properties;
- the hourly heat demands over the whole year;
- the derived typical periods representing the annual demand (not for each building).

You should be **able to**:

- conduct preliminary energy audits of buildings based on heat balances;
- apply Newton-Raphson methods for non-linear problems;
- apply clustering tools for creating typical periods and evaluate their quality.

Part 2

MILP Optimisation of Energy Systems

2.1 General Overview

In the second part of the project, you step from the building model to the model of the whole EPFL campus. The aim is not only to model the current energy system of EPFL but also to find the optimal energy system with new technological options (e.g. heat pumps, photovoltaics panels), taking into account their performance characteristics, capital and operating costs.
You are given a very basic but running model in algebraic modeling language AMPL. There are 3 file types for a complete AMPL model. The ".mod" files, containing the model equations , the ".dat" files containing the data for the parameters and sets and the ".run" file containing solver options, and displaying commands. For further details, see the presentation files of project part 2.
The files of the initial model are structured as follows: *moes.mod, moes.dat* and *moes.run* are the main model files. Each building and each utility (f.e. the photovoltaic panel) has to be added with their own model and data files (f.e. *moesPV.mod* and *moesPV.dat*). This makes it possible to share your building and technology models with other groups.
You are asked to develop this initial model. The next sections guide you through this development. First, the general model is explained, then you are asked to include your results of project part 1 and finally you are going to develop your own models of the energy equipment for the EPFL system.

2.2 MILP Formulation of Building Energy Systems

The base of the MILP formulation is given in the project files. Table 2.1 gives an overview about sets, parameters and variables used in the equations.

> Hint
>
> - The presented equations are marked with the same tag than in the ampl model to help you understanding the MILP formulation.
> - Figure 2 in project description part 1 gives an overview, which building belongs to which temperature level.

2.2.1 Nomenclature

The energy demand of the campus is defined by the set of Time ($t \in \mathbf{T}$) representing different time segments of operation and the set of Buildings ($b \in \mathbf{B}$) which is composed of buildings heated by medium temperature water loop ($mb \in \mathbf{MB}$) and buildings heated by low temperature loop ($lb \in \mathbf{LB}$), thus ($\mathbf{B} = \mathbf{MB} \cup \mathbf{LB}$). The set of Technologies ($tc \in \mathbf{TC}$) represents the energy conversion systems that satisfy the demand of the campus by using resources (e.g. natural gas, electricity) represented by the set of Layers ($l \in \mathbf{L}$). In addition to the technologies, energy can be supplied through the grid, which is defined by the set of Grids ($g \in \mathbf{G}$). The technologies and grid units are aggregated into the set of Utilities ($u \in \mathbf{U}$). The utilities are grouped with respect to their type using the set UtilitiesOfType ($ut \in \mathbf{UT}_{ty}$) and with respect to the resource generated and consumed by using the set UtilitiesOfLayer ($ut \in \mathbf{UL}_l$). The types of the utilities are defined in the set $\mathbf{TY} = \{$'Heating', 'Electricity'$\}$.

Table 2.1: Description of sets, parameters and variables in MILP

Set	Description
$\mathbf{T}$	Set of timesteps
$\mathbf{B}$	Set of buildings
$\mathbf{LB}$	Set of buildings heated by the low temperature loop
$\mathbf{MB}$	Set of buildings heated by the medium temperature loop
$\mathbf{TC}$	Set of technologies
$\mathbf{L}$	Set of layers (resources)
$\mathbf{G}$	Set of grid units
$\mathbf{U}$	Set of utilities
$\mathbf{UT}$	Set of utilities of a certain type (heating and/or electricity)
$\mathbf{UL}$	Set of utilities using a certain resource layer
$\mathbf{TL}$	Set of temperature level
Parameter	**Description**
$\mathrm{t^{op}}$	Operating time per year [h].
$\mathrm{C^{op1}_{u,t}}$	Fixed operating cost [CHF/h]
$\mathrm{C^{op2}_{u,t}}$	Variable operating cost [CHF/h]
$\mathrm{C^{inv1}_{u}}$	Fixed investment cost [CHF/year]
$\mathrm{C^{inv2}_{u}}$	Variable investment cost [CHF/year]
$\mathrm{f^{min}_{u}}$	Minimum sizing factor [-]
$\mathrm{f^{max}_{u}}$	Maximum sizing factor [-]
$\mathrm{q^{hs}_{u}}$	Reference heating supply from a utility [kW]
$\mathrm{m^{in}_{u}}$	Reference flow into a utility [various]
$\mathrm{m^{out}_{u}}$	Reference flow out of a utility [various]
$\mathrm{\dot{Q}mt^{-}_{t}}$	Total heating demand at medium temperature level [kW]
$\mathrm{\dot{Q}lt^{-}_{t}}$	Total heating demand at low temperature level [kW]
$\mathrm{\dot{E}^{-}_{t}}$	Total electricity demand [kW]
$\mathrm{\dot{Q}^{heating}_{b,t}}$	Heating demand of a building [kW]
$\mathrm{\dot{E}_{b,t}}$	Electricity demand of a building [kW]
Variable	**Description**
y	Binary variable to use the utility or not [-]
f	Sizing factor of the utility [-]
$h_{u,t,tl}$	Sizing factor of a utility for heating at temperature level tl [-]

2.2.2 Main Equations

The objective function of the optimization is the total annual cost of the system, comprising operating and investment costs, as given in Equation (obj).

$$\min \mathrm{TOTEX} = \mathrm{OPEX} + \mathrm{CAPEX} \tag{obj}$$

$$\mathrm{OPEX} = \sum_{u}^{\mathbf{U}} \sum_{t=1}^{\mathbf{T}} (\mathrm{C}^{\mathrm{op1}}_{\mathrm{u,i,t}} \cdot y_{u,t} + \mathrm{C}^{\mathrm{op2}}_{\mathrm{u,t}} \cdot f_{u,t}) \cdot \mathrm{t}^{\mathrm{op}}(t)) \tag{oc\_cstr}$$

$$\mathrm{CAPEX} = \sum_{u}^{\mathbf{TC}} (\mathrm{C}^{\mathrm{inv1}}_{\mathrm{tc}} \cdot y_u + \mathrm{C}^{\mathrm{inv2}}_{\mathrm{tc}} \cdot f_u) \tag{ic\_cstr}$$

The continuous decision variables of the problem are f_u and $f_{u,t}$, which determine the purchased size of the utilities and the capacity at which they are used at time segment t. The discrete (i.e. binary) variables of the problem are y_u and $y_{u,t}$ determine the existence of utilities and whether they are used or not at time segment t, respectively. Equation (size_cstr1&2) and (size_cstr3&4) links the continuous and discrete variables of the problem. Once a utility is purchased, it can be used at the purchase size or lower, which is ensured by Equation (size_cstr5).

$$\mathrm{f}^{\mathrm{min}}_{\mathrm{u}} \cdot y_u \leq f_u \leq \mathrm{f}^{\mathrm{max}}_{\mathrm{u}} \cdot y_u \quad \forall\ u \in \mathbf{U} \tag{size\_cstr1\&2}$$

$$\mathrm{f}^{\mathrm{min}}_{\mathrm{u}} \cdot y_{u,t} \leq f_{u,t} \leq \mathrm{f}^{\mathrm{max}}_{\mathrm{u}} \cdot y_{u,t} \quad \forall\ u \in \mathbf{U}, t \in \mathbf{T} \tag{size\_cstr3\&4}$$

$$f_{u,t} \leq f_u \quad \forall\ u \in \mathbf{U}, t \in \mathbf{T} \tag{size\_cstr5}$$

The problem is constrained by energy and mass balances, which are represented as heating, electricity and resource balances in the formulation. There are two heating networks on campus. There is a low temperature and a medium temperature heating network. Equations (MT_balance) and (LT_balance) are the heat balance equations for the medium temperature and low temperature loops respectively.

$$\dot{\mathrm{Q}}\mathrm{mt}^{-}_{\mathrm{i,t}} = \sum_{u}^{\mathbf{UT}_{ty}} h_{u,t,tl} \cdot \mathrm{q}^{\mathrm{hs}}_{\mathrm{u}} \quad \forall\ t \in \mathbf{T} : T_{mt} \leq T_u,\ ty =\ 'Heating' \tag{MT\_balance}$$

$$\dot{\mathrm{Q}}\mathrm{lt}^{-}_{\mathrm{i,t}} = \sum_{u}^{\mathbf{UT}_{ty}} h_{u,t,tl} \cdot \mathrm{q}^{\mathrm{hs}}_{\mathrm{u}} \quad \forall\ t \in \mathbf{T} : T_{lt} \leq T_u,\ ty =\ 'Heating' \tag{LT\_balance}$$

The continuous variable h is defined to determine the heat flowing from the utilities to each temperature level of heating, and $\mathrm{q}^{\mathrm{hs}}_{\mathrm{u}}$ represents the reference heat flow of the unit. The size of the utility is then determined by summing up h over the set of temperature levels (tl $\in$ $\mathbf{TL}$) by using Equation (heating_mult_cstr). For example if a boiler supplies 300kW to the medium temperature level and 200kW to the low temperature level, the size of the boiler must be 500kW.

$$\sum^{\mathbf{TL}} h_{u,t,tl} = f_{u,t} \quad \forall\ u \in \mathbf{U}, t \in \mathbf{T} \tag{heating\_mult\_cstr}$$

For electricity and other resources, flow into and out of utilities is calculated by Equation (inflow_cstr) and (outflow_cstr).

$$\dot{M}^{\mathrm{in}}_{\mathrm{u,t}} = f_{u,t} \cdot \mathrm{m}^{\mathrm{in}}_{\mathrm{u}} \quad \forall\ t \in \mathbf{T} \tag{inflow\_cstr}$$

$$\dot{M}^{\mathrm{out}}_{\mathrm{u,t}} = f_{u,t} \cdot \mathrm{m}^{\mathrm{out}}_{\mathrm{u}} \quad \forall\ t \in \mathbf{T} \tag{outflow\_cstr}$$

with $\mathrm{m_u^{in}}$ and $\mathrm{m_u^{out}}$ the reference resource flows in and out of the unit. The balances for electricity and other resources are then introduced by Equation (electricity_balance) and (balance_cstr) respectively.

$$\dot{\mathrm{E}}^{-}_{\mathrm{t}} + \sum_{u}^{\mathbf{UL}_l} \dot{M}^{\mathrm{in}}_{\mathrm{u,t}} = \sum_{u}^{\mathbf{UL}_l} \dot{M}^{\mathrm{out}}_{\mathrm{u,t}} \quad \forall\, t \in \mathbf{T} : l = \ '\mathit{Electricity}' \tag{electricity\_balance}$$

$$\sum_{u}^{\mathbf{UL}_l} \dot{M}^{\mathrm{in}}_{\mathrm{u,t}} = \sum_{u}^{\mathbf{UL}_l} \dot{M}^{\mathrm{out}}_{\mathrm{u,t}} \quad \forall\, t \in \mathbf{T} : l \neq \ '\mathit{Electricity}' \tag{balance\_cstr}$$

2.3 MILP Optimisation of the EPFL Energy System

The following section guides you through the development of the MILP model. The MILP model is the center of the whole project, meaning that the results of the other parts are used in the MILP model. You already have the results of project part 1. Before you model your own utilities, you have to initialize the model by using the building and weather data from part 1 of the project.

At this stage

- you should be able to run the basic model you have received

2.3.1 Initialization of MILP model

This section explains how you can use your project results of part 1 in the MILP model.

Hint

All data connected to the unit "Watt" has to be transferred to "**Kilo**watt". This applies even to building parameter like k_{th}, which has to be converted to kW/m^2/K.

Weather data

This section explains how you include the solution of the weather data clustering in the MILP model. To ensure that all groups come to the same result, we provide one possible solution in Table 2.2. This solution is not the only correct one. However, for the presentation and discussion in class, please use Table 2.2. For the final report in the end, you are free to use your own result of the clustering in project part 1.

Table 2.2: Solution of weather clustering, project part 1.

Type	**Temperature** [°C]	**Irradiation** [kW/m^2]	**Operating time** [h]
A	0.15	0.067	473
A	6.62	0.057	693
A	10.99	0.404	535
A	12.56	0.088	543
B	16.0	0.097	6515
Extreme	-9	0	1
Total	—	—	8760

The clustered weather data has to be valid and the same for all buildings. This means we distinguish between two types of typical timesteps with the same criteria for all buildings.

- Type A) timesteps were the buildings are used (Monday to Friday 7am to 9pm) and the external temperature is below the cut off temperature of 16 °C.
- Type B) the exact opposite of type A leaving the timesteps when the buildings are not used (night, weekend) and the external temperature is greater than 16 °C.

We provide 4 typical timesteps of type A for external temperature and irradiation. Furthermore, there is 1 typical timestep of type B were the external temperature set to 16 °C to ensure the heating system is switched off. During summer, when the heating system is switched off, there is the situation where the buildings have electricity demand and the photovoltaic panels would generate electricity. To be able to model this situation, the irradiation of this 1 typical timestep of type B is the average irradiation during this time. Additionally, there is the coldest hour of the year as extreme timestep. The weather data and the operating time of the typical timesteps have to be added in file *moes.dat*.

Hint

- Remember to also change the set for defining the timesteps in the very beginning of file *moes.dat*.
- At this stage the model does NOT run, you have to adjust the building data to the timesteps first. (next section)

Building data

The heating demand for each building is modelled similarly to project part 1. The calculation can be found in the file *moes.mod*. Each building is included with its own ".dat" file, for example "moesb1.dat". In this file, the first lines add the specific building to the set of buildings and choose the temperature level of the connected heating network. Construction period (Table 1.1) and Figure 2 show which building is connected t which network. The remaining part of the file is defining parameters to characterize the electricity and heat demand of the building. These parameter can be divided into time-dependent and time-independent parameter. Table 2.3 gives an overview of the needed parameters from project part 1.

Table 2.3: Time-depend and time-independent Building Parameter

Parameter	**Description**	**Unit**
A_{th}	Reference heated surface	m^2
k_{th}	Thermal losses and ventilation coefficient	$kW/m^2/K$
k_{sun}	Solar radiation coefficient	–
$\overline{\dot{q}_{people}}$	Average heat gain due to the presence of people per unit area	kW/m^2
$\dot{e}_t^-$	Specific electricity demand per unit area	kW/m^2

Create all building data files and include the buildings in the model. You should use the data provided by Table 2.4. You have to calculate the average heat gain $\overline{\dot{q}_{people}}$ and the specific electricity demand $\dot{e}_t^-$ with the help of data in the project description part 1.

Hint

- Do not forget to load the building data in the *moes.run* file
- The average heat gain due to the people's presence is only used in timesteps of Type A and Extreme. And therefore can be considered as time-independent. Additionally, the value should be the same for all buildings due to our assumptions in project part 1.

At this stage

- The typical timesteps and weather data are included in the model
- You should have calculated the average heat gain due to peoples presence $\overline{\dot{q}_{people}}$
- All Building models of EPFL Campus are included in the model
- The model is converging to an optimal solution.

Table 2.4: Solution of building parameter, project part 1.

Building	$\dot{E}_t^-$ **type A** [kW]	$\dot{E}_t^-$ **type B** [kW]	k_{th} [$\mathbf{W}$/m^{2}K]	k_{sun} [-]
BC	438.9	94.9	5.65	0.11
CO	258.3	55.9	3.31	0.07
BP	189.1	40.9	4.49	0.08
BS	96.0	20.8	8.55	0.15
TCV	565.9	122.4	4.83	0.09
IN	517.1	111.8	4.27	0.07
GC	541.4	117.1	4.88	0.09
CE	328.6	71.1	9.71	0.01
ODY	22.3	4.8	6.59	0.07
MA	1513.8	327.4	9.85	0.18
GR	222.7	48.2	2.97	0.01
ME	853.3	184.5	3.61	0.05
CM	370.7	80.2	3.57	0.06
AA	337.1	72.9	8.25	0.00
BI	113.2	24.5	4.21	0.07
EL	396.0	85.6	3.66	0.10
PO	25.8	5.6	4.93	0.10
CRPP	440.3	95.2	5.25	0.12
MX	775.2	167.6	4.84	0.15
BM	660.0	142.7	7.05	0.11
CH	1291.2	279.2	7.11	0.15
DIA	0.0	0.0	7.69	0.15
PH	1213.4	262.4	6.34	0.21
AI	1066.8	230.7	11.79	0.22

2.3.2 Energy Conversion Technologies

After the model is initialized in the previous section, the next step is to include appropriate models of utilities. The current heating system of the EPFL campus consists of ammonia-based heat pumps and oil-fired gas turbines. The gas turbines are used as auxiliary systems, while the heat pumps take the heat from lake Geneva and deliver it to the buildings via two hot water loops:

- Medium temperature loop: Hydronic distribution system with temperatures up to 65°C
- Low temperature loop: Hydronic distribution system with temperatures up to 50°C

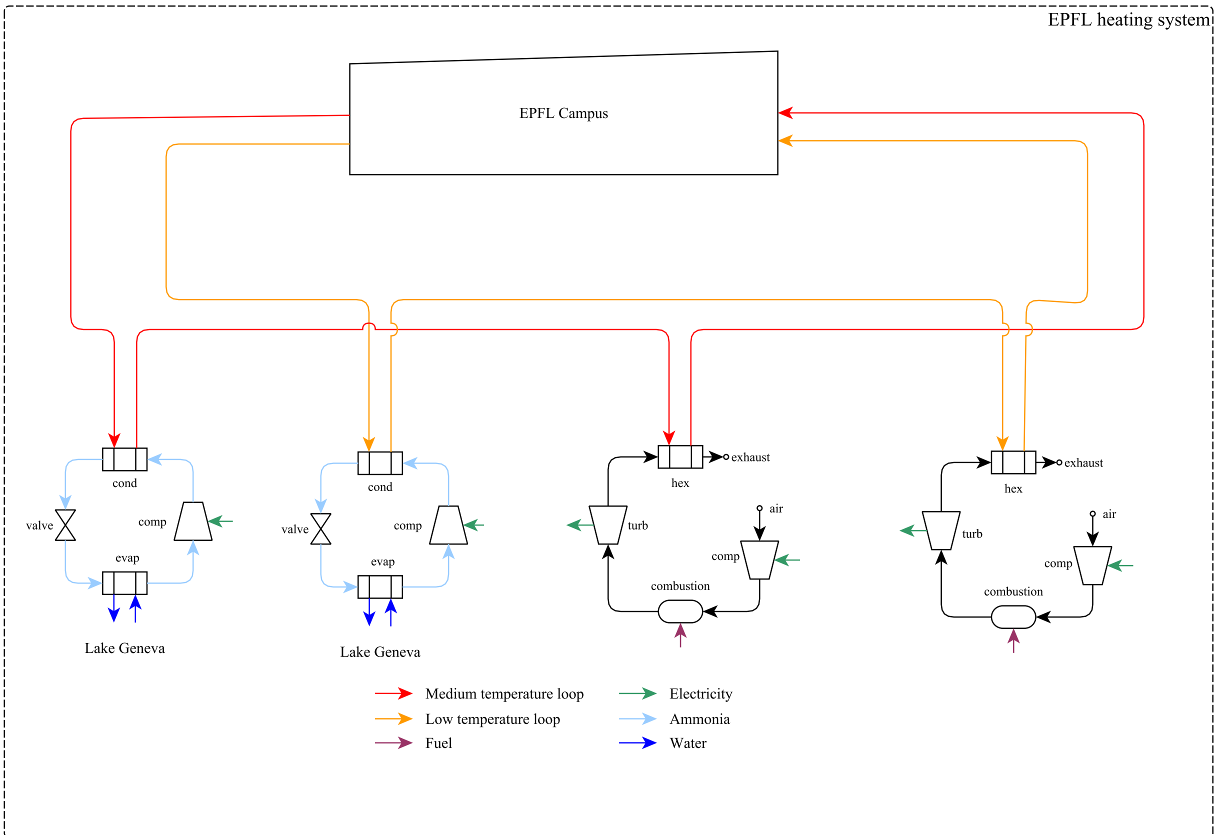


Figure 2.1: Current heating system of EPFL

Although the technologies to supply heating might change, since the rest of the heating system (i.e. piping in the buildings) will not change, the medium and low temperature loops will be kept. Hence, the new energy system still needs to able to supply heat to the hot water loops in place at EPFL. The technologies that are selected to be evaluated by EPFL are as follows:

- Boiler
- Two 1-stage heat pumps - one for low and and one for medium temperature loop
- **2-stage heat pump**
- Geothermal cogeneration system
- Cogeneration engine
- **Solid oxide fuel cell**

- Photovoltaic panels

The initial model already contains basic models of the photovoltaic panels and the boiler. Carry out a literature review to find at least appropriate values for the cost parameter of the two models. You can also further improve the models and change performance parameter (this is optional). It is obligatory to include the two technologies in bold (2-stage heat pump and Solid oxide fuel cell) since they will be analyzed in detailed in Part 4 of the project.
Each group should select 4 more technologies from the list or propose other technologies and integrate them to the optimization. Carry out a deep literature review for the 4 technologies selected for your group. Find the parameters required to integrate the utilities to the MILP model.
It should be highlighted that the efficiency of heat pumps depends on the ambient temperature. Table 2.5 gives the temperature levels of the Lake of Geneva, serving as the heat source for the EPFL heat pumps. These data are necessary to be integrated into your model for **one-stage heat pump**.

Table 2.5: Water temperature of Lake of Geneva

Type	**Temperature** [°C]
A	8
A	9
A	11
A	13
B	14
Extreme	5

Hint

- The water temperature of Lake of Geneva serves only for 1-stage heat pump. For the two stage heat pump, you do not need to integrate these data; for this stage, make realistic assumptions for the two stage heat pump, and also for SOFC, knowing that these assumptions will be replaced later by your results from the Part 4 of the project.

At this stage you should have

- included at least 6 utilities in the energy system
- obtained and evaluated the optimization results

2.4 Summary

You should **present** for the energy system on campus

- the low temperature heat demand, medium temperature heat demand and electricity demand for each of the 6 timesteps.
- the economic and performance indicators of the chosen utilities
- the evaluation of the optimization results including: the investment and operational expense of your solution, the influence of the extreme period, the analysis of the electricity generated on campus

You have learned:

- How to formulate MILP optimization programs for building energy systems.
- How different data reduction strategies influence the optimal solution.
- About different energy conversion units as part of an energy system.

Part 3

NLP Optimisation of Energy Systems

3.1 General Overview

In order to reduce the energy demand of industrial processes, heat recovery represents an attractive solution. Typical heat recovery is performed by placing a heat exchanger between a hot and a cold stream (i.e. a process stream which has to be cooled down and a process stream which has to be heated up, respectively). This decreases both the operating cost and the environmental impact of the process, but additional equipment has to be installed (e.g. a new heat exchanger). Investment costs of heat exchangers depend predominantly on their exchanging surface. Therefore, the goal of this exercise is to define the optimal minimum temperature difference (ΔT_{min}) in such heat exchangers, their area and quantifying the economic potential of the investment.
For the reference scenario consider Figure 3.1, as well as the information it contains.

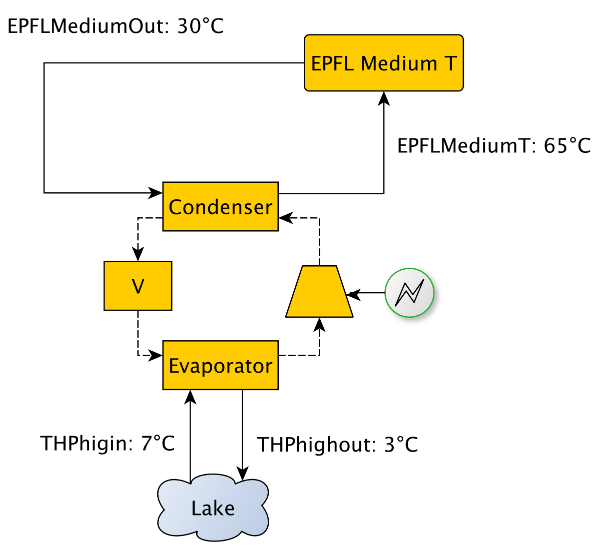


Figure 3.1: Reference scenario for heat supply

What do you have

- Open the NLP_Ref.mod file and identify the variables and parameters in the diagram.
- Open the NLP_Ref.dat file and identify the values you need to input. Pay attention that in the present situation we are only interested in the medium temperature heat demand. **The values in the .dat file are an example and do not correspond to your data**.
- The AMPL model contains *a priori* all the required data. Every parameter, variable and constraint are commented in order to guide you through the problem resolution.

At this stage

- You should develop the AMPL model for the reference scenario (current situation). Some assumptions and/or relevant information are available in section 3.6.
- You should calculate and present the current energy bill.

EPFL is concerned with integrating potential waste heat into the current energy system. To do it, engineers suggested 3 potential scenarios. You should evaluate each one of them. To do so you will keep on using AMPL. Please be aware that AMPL will be only able to solve what you insert and constraint. In other words, AMPL is not 'smart' and although you know T2 is higher than T1, AMPL doesn't!

Do not forget Polya's 4 steps when addressing a problem. Try not to skip them! They help you structuring the problem.

Polya's 4 steps

- **Analyse** - The energy recovery scheme is given for the 3 scenarios. What and where will the trade-off be? Any initial thoughts?
- **Plan** - Constraints are suggested and commented. Pay attention to the units used (they must be consistent).
- **Execute** - Implement the constraints as suggested. Try to run the model. Error messages will guide you identifying the mistake.
- **Look back** - What is the objective? Try to change and see how your solutions change. Is the investment worth it? Could we have done it differently?

3.2 Data Center heat recovery

Integration of the database centre into the heating loop: data centres at EPFL generate 574 kW of heat, which has to be removed. In order to recover it, an heat exchanger is being considered. The intended configuration is depicted in Figure 3.2, as well as some variables and parameters.
You have access to 3 files, with the same structure as in the MILP part. A NLP_DC.mod file that contains the model description; a NLP_DC.dat file that contains a part of used data; NLP_DC.run file that loads both .mod and .dat files, specifies the solver and displays specific variables. In this section we are solving a non-linear problem (NLP), so a non-linear solver is needed (snopt, baron or minos can be used).

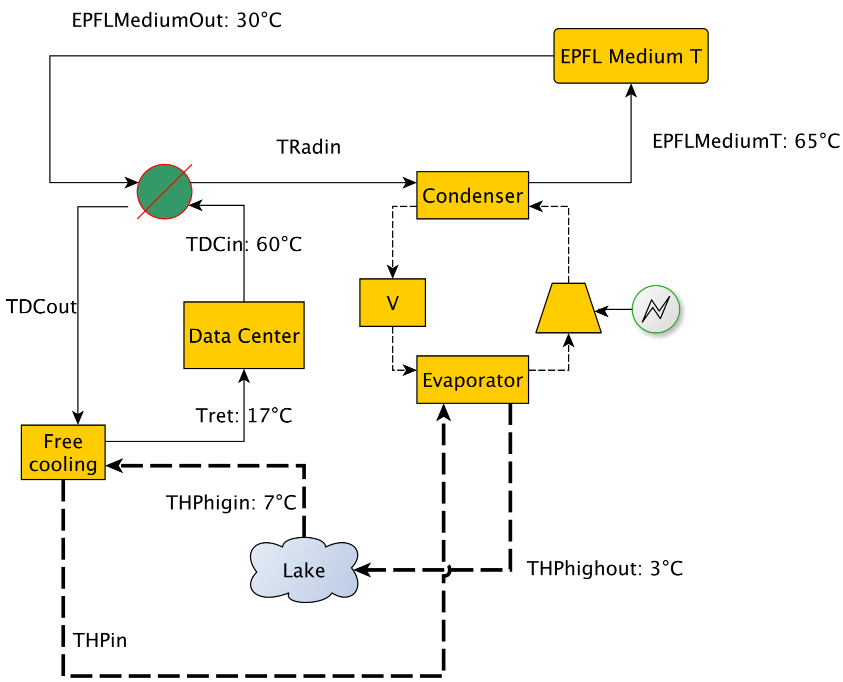


Figure 3.2: Heat recovery from data center

Hint

- Open the NLP_DC.mod file and identify the variables and parameters in the diagram.
- Open the NLP_DC.dat file and identify the values you need to input. Again we are only interested in the medium temperature heat demand. **The values in the .dat file are an example and do not correspond to your data**.
- Consider that the (in place) data centre free cooling system is able to cope with changes in the load, and that there is no cost associated.
- The AMPL model contains all the required information. Every parameter, variable and constraint are commented in order to guide you through the problem resolution.
- You have to model the heat exchanger in green, that affects the amount of heat needed to be supplied by the default heat pump. Furthermore, it is suggested to pre-heat the lake water that is entering the default heat pump evaporator.

At this stage

- Take Polya's 4 steps. You should develop the AMPL model for Data center recovery. Some assumptions and/or relevant information are available in section 3.6.
- You should be able to calculate the new energy bill (if you decide to make use of the DC heat), the new heat exchanger area, cost, pay-back time as well as the optimal ΔTmin. Insert any other metrics you think of interest.

3.3 Air ventilation heat recovery

Integration of the air ventilation into the heating loop: considering the specifications given in the first part of the project, the incoming air ventilation flow ($T = T_{ext}$) can be preheated by the outgoing air ventilation flow (leaving the building at $T = T_{int}$ =21°C). By preheating the air ventilation flow, the heat demand (and consequently the operating cost) reduces according to (see Equation 3.1):

$$Q(t) = A_{th} \cdot \{U \cdot (T_{int} - T_{ext}(t)) + m_{air} \cdot c_{p,air} \cdot (T_{int} - T_{ext_new}(t)) - k_{sun} \cdot Irr(t) - Q_{people}(t)\} - Q_{el}(t) \quad (3.1)$$

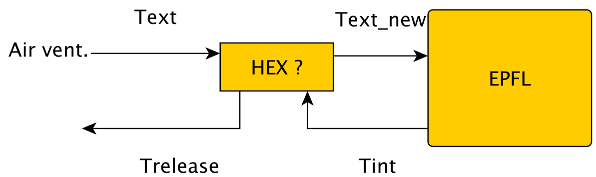


Figure 3.3: Heat recovery from air ventilation

Similarly to the previous section there are 3 files, NLP__vent.mod, NLP__vent.dat and NLP__vent.run

Hint

- Only based in the hypotheses presented initially are you able to comment *a priori* on the viability of this kind of heat exchanger?
- Heat demand is no longer a parameter but a variable, that depends on the external temperature.
- When computing the logarithmic mean temperature, you may want to consider another equation (why?). Check equation 3.2.

$$\Delta T_{ln} = \frac{\Theta_1 \cdot \Theta_2^2 + \Theta_2 \cdot \Theta_1^2}{2}^{1/3} \quad (3.2)$$

At this stage

- Take Polya's 4 steps. You should develop the model allowing you to take conclusions. Some assumptions and/or relevant information are available in section 3.6.
- You should be able to size the ventilation heat recovery (if it is profitable), indicating the area and optimal ΔTmin of the installed heat exchanger. You should also provide the costs, pay-back time and any other metric you think of interest.

3.4 Air ventilation with Heat pump integration

Another possibility is to use the recover the exiting air ventilation heat as heat source for an HP evaporator (Figure 3.4).

Similarly to the previous section there are 3 files, NLP__vent__HP.mod, NLP__vent__HP.dat and NLP__vent__HP.run

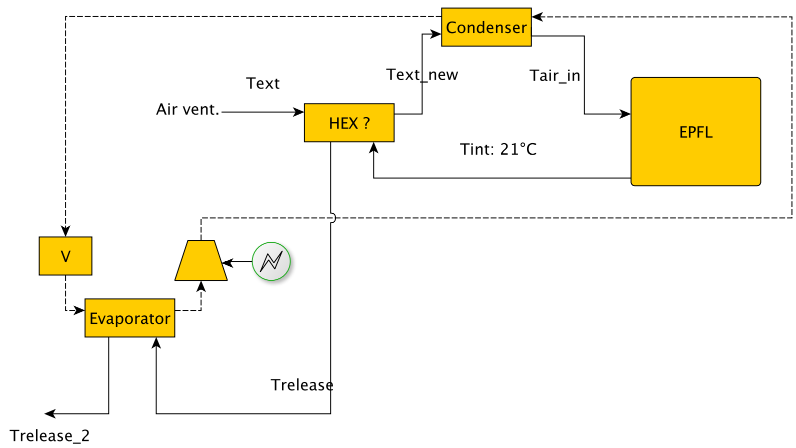


Figure 3.4: Ventilation and heat pump integration

Hint

- The connections between variables are extremely sensitive in this model.
- Make some extra assumptions, if needed, but be able to justify them.

At this stage

- Take Polya's 4 steps. Develop the model to take conclusions. Some assumptions and/or relevant information are available in section 3.6.
- You should be able to provide operating and investment costs, as well as pay-back time for the ventilation HEX (if profitable) as well as its size.

3.5 Summary

You should **present** for the heat recovery system on campus

- The optimum ΔTmin for the Data Center heat recovery and the ventilation recovery units (if implemented), the heat recovered in each of them and the corresponding area.
- **All** the relevant economic and performance indicators.
- Connect to the main MILP model by creating a technology that is able to provide heat with a given investment cost, thus reducing the overall energy bill of EPFL.

You have learned to:

- Formulate NLP optimization programs for several heat recovery scenarios.
- Interpret results and provide economic indicators to assess their viability.

3.6 Notes and assumptions

Besides the usual hypotheses, consider the following list that might be useful.

Hypotheses

- Investment cost equation: Purchase cost (ref. year 2000) $C_p = a_{unit} A^{b_{unit}}$ [CHF], $a_{unit} = 1200$ [CHF/m^2], $b_{unit} = 0.6$
- Overall heat transfer coefficient of the heat exchanger (air-air): $U_{ex} = 0.025$ kW/m^{2}K , (air-water): $U_{ex} = 0.15$ kW/m^{2}K , (water-refrigerant): $U_{ex} = 0.75$ kW/m^{2}K
- Interest rate: 6 %
- Life time of units: 20 years
- Chemical engineering plant cost index (2000): 394.1
- Chemical engineering plant cost index (2015): 605.7 (at the time of purchase)
- Bare module factor: 4.74 for heat exchanger

Part 4

Modeling and reconciliation of a combined heat pump

4.1 Introduction

The **energy system** of EPFL consists of systems supplying heating, cooling and electricity. The novel centralized heating system of the EPFL campus buildings consists of an advanced 2-stage heat pump (HP, Figure 4.1) and a solid oxide fuel cell (SOFC) combined heat and power (CHP) unit. The HP is the **main heating utility** and the SOFC is **solely operated** when the HP cannot supply the demand (maximum capacity of the HP is $6\,\mathrm{MW_{th}}$).
The two systems are not isolated from the medium voltage distribution grid, and the electricity produced by the SOFC is **not** used to run the compressors of the HP since both systems may not always be run simultaneously.

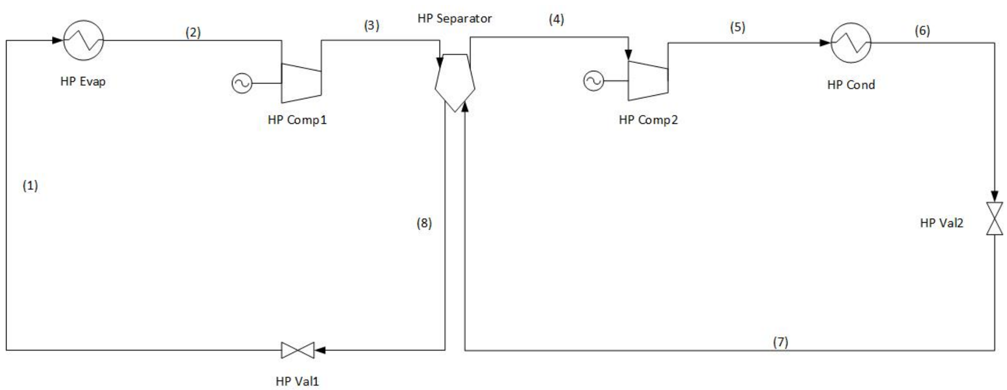


Figure 4.1: Process flow diagram (PFD) of a heat pump (HP)

The present document presents the data required for this **task** and the steps that can be followed.

Objectives

The main objective of this part of the project is to *conduct an energy audit of a novel heat pump-SOFC system for heating of the EPFL campus*, with a focus on the modelling, simulation and data reconciliation of the system. To this end, **you** are asked to:

- build a preliminary model of a heat pump in a process simulation software (Section 4.2);
- compare the properties of refrigerants in heat pumps and select two, considering their thermo-physical properties and possible environmental impacts (Section 4.3);
- calculate the resulting performance (ideal and real) of the heat pump layouts (Section 4.4);
- couple the heat pump and SOFC models to satisfy the heating demands of your buildings (Section 4.5);
- use measurement data for performing degrees of freedom and data reconciliation analyses of the heat pump - SOFC model (Section 4.6).

4.2 Modelling of a two-stage heat pump

A gas turbine model is given in the baseline file attached to the project description for inspiration. It will be used later in the project when building the combined heat pump and gas turbine model. The **goal** for now is to build a working model of the heat pump, which you can adapt at a later point of time for different refrigerants. The software to use is named Belsim VALI, for which the installation procedure, a short description and hints are given in Appendix 4.8.

Hint

Do **NOT** attempt to build all the model first (i.e. putting all components), then to include the parameter data (e.g. pressures and temperatures) and finally to run it and solve your convergence issues. This will definitely create problems when running the model (e.g. missing data, convergence, unstability) and may be challenging to debug. Follow instead the following tips:

1. Choose one component that you want to model (e.g. a compressor);
2. Read the corresponding documentation (help tool of Belsim Vali) for this specific component;
3. Determine the parameters that should be entered (e.g. inlet/outlet pressure) based on the help topics available in Vali and a degrees of freedom analysis;
4. Make a reasonable assumption of these parameter values, based on a literature review, manufacturing data, etc.;
5. Run the software for your component - if it works, proceeds with the next one, if not, check whether data is missing (did you, for example, forget to enter the component efficiency?) or if whether it runs, but does not converge (did you set a pressure at the outlet of a compressor higher than the inlet one? do you have liquid at the inlet?).

In the provided file, open the PFD named (HP) and build there your model. It is suggested to fix the following parameters in your model:

- the flow rate (mass) at point (1), i.e. before the evaporator;
- the temperature at points (2) and (6), i.e. the evaporation and condensing temperatures;

- the compression ratio for one of the compressors.

As a start, you can consider water as your heat pump working fluid, and use the dataset you are provided with as a reference for the input values of your models. The software convergence may be improved using a CATVAL unit in close cycles (e.g. along streams (1) or (7)). It is suggested to use the same names in the model as in the figures (Figure 4.1).

At this **stage** you should **have**:

- a working model of a basic two-stage heat pump, not **yet** calibrated.

4.3 Selection of heat pump working fluids

The selection of a working fluid for a heat pump is a complex task, as several factors (energetic, economic and environmental) need to be considered. For example, refrigerants such as chlorofluorocarbons (CFCs) such as R-12 used to be some of the most common working fluids for heat pump applications, but got banned or restricted with the adoption of the Montreal protocol, which prohibits refrigerants with high impact on the ozone layer.

- thermophysical properties:
  - freezing point;
  - critical temperature;
  - critical pressure;
  - latent heat of vaporization;
  - density;
- economic properties:
  - specific cost;
  - availability;
- possible safety issues (ASHRAE);
  - flammability;
  - toxicity;
  - corrosivity;
- possible environmental impact:
  - global warming potential (GWP);
  - ozone depletion potential (ODP);
  - eutrophication;
  - acidification.

In the rest of this project, you will proceed with two refrigerants, whose choice is up to your own decisions. You may want to base and defend your choice based on the criteria above-mentioned. The goal is now to **calibrate** your HP model to the fluids you chose, meaning:

- modify the working fluid in your simulation file (Thermod);

- correct the pressure ratio of the compressors (the high-pressure level should correspond to the saturation pressure for the desired condensation temperature);
- adjust the flowrate so that the heat pump has a heating capacity of 6000 kW (the maximum capacity of the heat pump is in this magnitude);
- repeat the same procedure, in a different file, for a different working fluid.

At this **stage** you should **have**:

- a model of a two-stage heat pump adapted (flow rates and pressure levels) tailored for two working fluids;

4.4 Performance of heat pumps

The thermodynamic performance of heat pumps can be assessed by calculating their energy efficiency (coefficient of performance) (Equation 4.1).

Coefficient of performance

$$\begin{aligned} \mathrm{COP}_{\mathbf{heating}} &= \frac{\dot{Q}_{\mathrm{th}}}{\dot{W}} \\ \mathrm{COP}_{\mathbf{heating,max}} &= \frac{T_h}{T_h - T_c} \end{aligned} \tag{4.1}$$

where:

- $\mathrm{COP}_{\mathbf{heating}}$: coefficient of performance of a heat pump (heating purposes), also named 1st-law efficiency of heat pumps;
- $\dot{Q}_{\mathrm{th}}$: heat supplied by the heat pump, in W;
- $\dot{W}$: power consumption of the heat pump, in W;
- $\mathrm{COP}_{\mathbf{heating,max}}$: maximum coefficient of performance of a heat pump (theoretical), also named Carnot efficiency of heat pumps;
- T_h: temperature at which heat is required, in K;
- T_c: temperature at which heat is removed, in K;

At this **stage** you should **have**:

- the calculation of the theoretical and real coefficients of performance of your heat pumps, for your two refrigerants, based on your models;

4.5 Modelling of a HP+SOFC system for heating buildings

The heat pump and SOFC models can now be coupled to assess the global system performance for heating of the buildings under study. A ‘control’ model is also implemented to actviate and deactive the heat pump and SOFC systems when necessary - apart from the heat pump control unit, this model is ready-to-use.

4.5.1 SOFC

The SOFC model is already given and does **not** need to be modified - it consists of a black box model that converts fuel to electricity.

4.5.2 Buildings

The buildings model is already given and does **not** need to be modified. It includes the heating demand of each building for each considered time period.

4.5.3 Control

The control model is currently deactivated, and should be activated to enable the operating constraints of the models. It should consist of three FLEXLIB units and a BBXVAL unit:

- DH_CONTROL sets the 'dh_heating' stream (in BUILDINGS) off if the heating demand is lower than 10 kW (the heating demand is negligible for all buildings).
- SOFC_CONTROL sets all the units of the SOFC model off if the heating demand is lower than 6001 kW (all the heating demand is satisfied by the heat pump).
- HP_CONTROL sets all the units of the HP model off if the heating demand is lower than 10 kW (the heating demand is negligible, no heat pump operation).
- SAFETY is a blackbox that is activated when the demand is lower than 10 kW. This unit prevents the Vali model from crashing in case the heating demand is small.

The control units of the turbine and the building are implemented and ready to use. For the heat pump, you are asked to activate the control unit and implement the code that cuts off the operation of the heat pump for any heat demand smaller than 10 KW. In order to do so, use the flex code tab in the control unit and call the heat load of the building. In an *if*-branch, set off the components of the heat pump. You can use the flex code integrated in the other control units as inspiration and find missing commands in the vali help for the flex code description.

Hint

Activate one unit at a time and debug it first (if necessary). Each unit calls different tags (variables or parameters) - check that the tag names that are called in the code are equal to the tag names that you defined (for example, how did you call the tag corresponding to the 'dh_heating' (heating demand) load? Is it the same in both the FLEX code, dataset and component tag?

At this **stage** you should **have**:

- a fully working model HP+SOFC;

4.6 Data reconciliation

Measured process data inevitably contain some inaccurate information. The reason behind the existence of errors in any observation is the use of imperfect instruments which have their own accuracy. In general, measurement errors can be categorized into two types:

- A systematic error (an estimate of which is known as measurement bias) is associated with the fact that a measured value contains an offset. It is a component of error that remains constant or depends on some other quantity.

- A random error is associated with the fact that when a measurement is repeated, it will generally provide a measured value that is different from the previous value. It is said to be random because its next measured value cannot be predicted exactly from previous realizations.

While the first type of error is due to the intrinsic sensor accuracy, the systematic errors, also known as gross errors, are due to sensor calibration or faulty data transmission. Data reconciliation theory assumes that errors are the sum of many factors and that are normally distributed.

4.6.1 Degrees of Freedom analysis

The data reconciliation technique generally requires redundancy of the process measurements. For example, for a separator (Figure 4.2), the flowrate at point (a) can be deduced from the mass balance if the flowrates at points (b) and (c) are measured. The measurements are therefore not redundant.

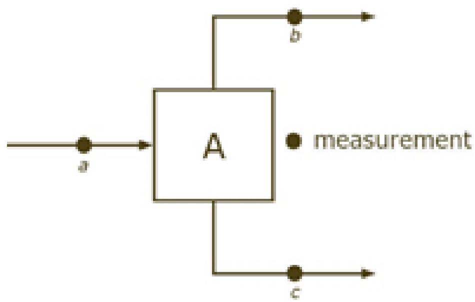


Figure 4.2: Schematic illustration of a separator for data reconciliation purposes

On the contrary, performing measurements of the mass flowrates at points (a), (b) and (c) is redundant, as the mass flowrate at (a) can be deduced from the two others. This redundancy is necessary for performing data reconciliation, as no measurement is exempt of random errors. This illustrates that, the more sensors are placed, and the more reliable the data reconciliation process is. Based on your Vali model, select a unit for each type (a HEX, a compressor etc.) from your Vali model and conduct a degrees of freedom analysis answering to these questions:

- for each component, how many measurements are needed for a mass balance?
- for an energy balance?
- how many are set as parameters?
- how many are calculated from the rest of the system?

At this **stage** you should **have**:

- a degrees of freedom analysis for each type of unit: a heat exchanger, a compressor, a throttling valve, a separator

4.6.2 Data reconciliation assessment

Once your models are properly running you are asked to perform the data reconciliation based on the provided measurements - note that there is a different dataset per refrigerant. Based on your Vali model, for the complete system, conduct, at first, a complete degrees of freedom analysis answering to these questions:

- how many measurements are needed for a mass balance?
- for an energy balance?
- how many are set as parameters?
- how many are calculated?
- what is the additional number of measurements you have?
- what is the redundant number of measurements you get?

Afterwards, an input file for each month should be prepared and called by Belsim Vali, meaning each group should deal with 24 text files. For each data reconciliation procedure, it is desired to know the performance of the heat pump (COP), and, if relevant, the SOFC efficiency.

At this **stage** you should **have**:

- 24 reconciled sets of data (12 per refrigerant, as there is one dataset per month);
- the calculations of the coefficient of performance of the heat pump and efficiency of the SOFC for each dataset;

4.7 Summary

At the end of the project:

Given:

- an initial model of a SOFC, building demand and control plant;
- a set of averaged operation data (for a month) for typical refrigerants;

You should **present**:

- the tailored models of two-stage heat pumps with SOFC and control units;
- the derivations of the ideal and real coefficients of performance for two refrigerants for the heat pump;
- a listing of the degrees of freedom of your problem (number of measurements - required and redundant);
- the calculations of these performance indicators after and before reconciliation, including the efficiency of the SOFC (if relevant) for each period (monthly basis).

You should be **able to**:

- build simple models of heat pumps;
- select and explain the reasons for your choice of working fluids;
- estimate the performance of combined heat pump/SOFC plants;
- perform degrees of freedom and data reconciliation analyses;

4.8 Additional information

4.8.1 Introduction to Belsim Vali

VALI is an equation-based data validation and reconciliation (DVR) software. It uses information redundancy and conservation laws to correct measurements and convert them into accurate and reliable information. VALI is used in upstream, refinery, petrochemical, chemical plants as well as power plants including nuclear power stations. VALI detects faulty sensors and pinpoints degradation of equipment performance (heat rate, compressor efficiency, etc.).
The plant measurements, including lab analyses, are reconciled in such a way that mass (on a component per component basis) and heat balances are satisfied. When necessary, L/V equilibrium and performance constraints can be added. Unmeasured values are calculated and VALI also quantifies the precision of reconciled values. Its sensitivity analysis tool shows the interdependence between the measurements. VALI can be used on-line or off-line and has been integrated in various control systems.
There are a large number of benefits due to data validation and reconciliation, and they include:

- improvement of measurement layout
- decrease of number of routine analyses
- reduced frequency of sensor calibration; only faulty sensors need to be calibrated
- on-line optimization tools work with more accurate information
- systematic improvement of process data
- early detection of sensors deviation and degradation of equipment performance
- correct plant balances for accounting and performance follow-up
- quality at process level

To understand the basic principles of DVR, one must first recognise that plant measurements (including lab analyses) are not 100% error free. When using these measurements without correction to generate plant balances, one usually gets incoherence in these balances.
Some sources of errors in the balances directly depend on sensors themselves:

- intrinsic sensor precision
- sensor calibration
- sensor location

A second source of error when calculating plant balances is the small instabilities of the plant operation and the fact that samples and measurements are not exactly taken at the same time. Using time averages for plant data partly reduces this problem. However, lab analyses cannot be averaged.
One must also realise that in some cases too many measurements are available whereas in some other cases some measurements are missing and must be back calculated from other measurements. The aspect of data redundancy is here an essential factor. It is because too many measurements are available that one can prove the fact that the measurements are somewhat inaccurate. For example, measuring all inlet and outlet flow rates of a plant (or of part of a plant), usually leads to some imbalance between the total inputs and total outputs.
The main idea of DVR is to use the data redundancy of the system as the source of information to correct the measurements. In fact, each measurement is corrected as slightly as possible but in such a way that the validated measurements match all the constraints (or balances) of the process.

4.8.2 Belsim Vali - installation

The provided virtual machines already contain a working version of the software Belsim Vali. However, it is possible to install the software in your own laptop by following the steps below (only for Windows users):

1. Make sure that you belong to the Vali group `https://groups.epfl.ch/`.

2. Get a copy of Belsim VALI at `https://documents.epfl.ch/groups/v/va/vali/private/`: Install the 4.9 version (ask if you are not sure) and any available updates.
   - Use your Gaspar credentials to log in
   - Select **VALI4900** folder (on 27/06/2014 this is the latest stable version)
   - Download **VALI4900__CDROM.zip** by simply clicking on it
   - Unzip downloaded file (anywhere, including a temporary folder)
   - Go to **\VALI4900__CDROM\Vali4Client** folder and double-click on Belsim VALI4
   - Follow installation steps. Specify User name and Organisation. Choose **C:\belsim** as the destination folder. Keep the rest of the settings as default.
3. Set up the license server
   - Open **Belsim.ini** file located in **C:\belsim\dat** and set the IPServer to *stilic5.epfl.ch* (e.g. for me: *IPServer=stilic5.epfl.ch*)
   - Enter your Windows user name at `https://moodle.epfl.ch/mod/questionnaire/view.php?id=941351` [1]. To retrieve your Windows session username, follow instructions below (4.8.3).
4. Next download, extract and replace the Vali files on your disc from the patch `https://documents.epfl.ch/groups/v/va/vali/private/VALI4700/Patch4702c.zip`. You can do this by replacing the *bin* and *dat* folders directly in **C:\belsim** (using merge folders).
5. Launch Vali Modeller and check that your username is set in the bottom of the windows. If it's written 'GUEST' there is an error with the username.

4.8.3 How do I find my Windows username?

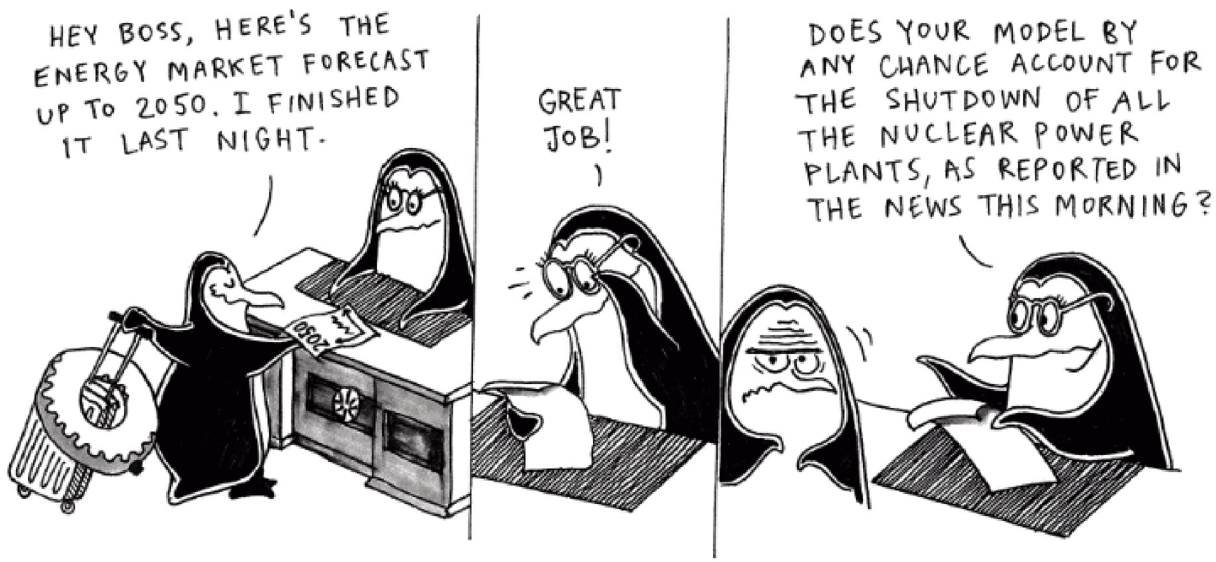
You can determine your Windows username as follow:

1. Press and hold the Windows key and press the letter R on your keyboard. The Run box will appear.
2. In the box, type cmd and press Enter. The command prompt window will appear.
3. Type echo %USERNAME% and press Enter.
4. Your current username will be displayed.

[1] This link works only if you are already logged into the moodle

Part 5

Scenario Analysis



by Outi Supponen

5.1 Introduction

The final part of the project aims at defining a new energy system for EPFL, considering various objectives (e.g. minimize the total costs and environmental impacts) and the resulting trade-offs (e.g. between lower CO_2-emissions and higher investment costs). You are given a working AMPL model of the problem formulated in **Part 2 - Optimisation of the EPFL energy system (MILP)** with simple technology models (e.g. photovoltaic panels). The given model may be adapted to your needs (or not used at all, depending on the state of your own MILP model).

Overview

The present part of the project builds on the results obtained along the semester, from the calculation of the building energy demands (**Part 1**) to the modelling of the campus (**Part 2**) and data reconciliation of the heating utilities (**Part 4**). In this part of the project, **you** are asked to:

- Adapt your current model (or use the one given to you) of the EPFL energy system with the results obtained in each part of the project (Section 5.2);
- Suggest at least three different new energy systems (combination of heat pumps, import of natural gas, etc.) for the EPFL campus (Section 5.3.1);
- Conduct a multi-objective optimisation, analysing the trade-off between different design objectives (e.g. lower investment costs against higher penetration of renewable energy) (Section 5.3.2);
- Assess the sensitivity of your solutions to variations in e.g. the natural gas and electricity prices (Section 5.4).

5.2 MILP Optimisation of the EPFL energy system

If you decide to use your current MILP model, what you need to change in the model is:

- the 2-stage heat pump characteristics in the MILP (change the Carnot efficiency and temperature levels in the MILP model based on the Vali results (**Part 4**));
- the SOF characteristics (change the values of the electrical and thermal efficiencies based on the Vali results (**Part 4**));
- integrate emission factors for the imported electricity (c_{elec}) and natural gas (c_{ng}) in the MILP program;
- add the following constraint on the CO_2 emissions, reflecting that the total emissions of CO_2 equal the annual sum of the CO_2 associated with the fuel consumption

$$CO_2 = \sum(c_{ng} * m_{ng} + c_{elec} * E_{elec}) \tag{5.1}$$

The given MILP model of the EPFL energy system is essentially the same as the one you have developed, with the data on the typical hours given in the description of **Part 2**. The things to adapt in the given model are the same as mentioned above, with the following differences:

- you may want to change the data on the typical periods (irradiation and external temperatures) based on your results of **Part 1**;
- you may want to add additional energy technologies that you have developed in **Part 2** or to change the values of some parameters such as the PV efficiency.

5.3 Scenarios analysis and multi-objectives optimisation

5.3.1 Scenario analysis

Scenario analysis is a process of examining and evaluating possible events that could take place in the future by considering various feasible results or outcomes. Mathematical models have to be flexible enough to allow decision makers to quickly change the assumptions of the models and reflect important changes that may have taken place in regard to the system's operations. Such changes or unforeseen events could be due to shifts in the economy, to the enforcement of new environmental requirements or to any other specific issues. Scenario-building is therefore designed to allow improved decision-making by allowing deep consideration of outcomes and their implications [3].

With all this in mind, you are now asked to **suggest at least three different new energy systems (combination of heat pumps, import of natural gas, etc.) for the EPFL campus**. You can consider different objectives for the three designs you suggest, and some possible scenarios are listed hereby:

- Scenario 1: EPFL has very little money to invest at present and wants to minimize the costs of installing new technologies.
- Scenario 2: EPFL has a very large budget this year, but due to the financial crisis, expects to have much less money in the coming years and wants to minimize the operating costs.
- Scenario 3: EPFL has enough money to cover most costs at present, and most likely in the coming years, and just wants the best economical solution in terms of the whole life span of equipments.
- Scenario 4: Winter is coming and the price of natural gas is striking. EPFL prefers to import as little natural gas as possible in the future.
- Scenario 5: EPFL wants to be as independent as possible from imports of energy, whether it is electricity or gas (self-sufficiency).
- Scenario 6: EPFL wants to become a greener university and wants to minimise the total equivalent carbon emissions.
- Scenario 7: The CO2 levy in Switzerland was 96 CHF/t in 2018 for purchases of thermal fuels. Does it have an impact in the investment or/and operational strategies of energy supply for EPFL? how about the sensitivity of the system to the CO2 tax?

At this stage you should:

- **have** at least three different new energy system proposals for the EPFL campus, based on the scenarios listed above or other ones you deem more interesting;
- **present and explain** the differences in terms of utility use and sizes between all these proposals, and justify why some technologies are preferred/discarded over others.

5.3.2 Multi-objective optimization

After having analysed some of the given objectives in a singular manner you are now asked to compare them simultaneously. This can be achieved by performing multi-objective optimization, also known as Pareto optimization.

Multi-objective optimization deals with the simultaneous optimisation of multiple objectives (for example, trying to minimise at the same time the environmental impact and operating costs of a new energy system). These objectives may be conflicting - for example, gas boilers may be the cheapest units to install (low investment costs) but require the consumption of natural gas (high CO_2-emissions). There is therefore no single solution with both minimum emissions and minimum investment costs.

In that case, the objective functions are said to be conflicting and in a trade-off to each other. There exists a (possibly infinite) number of "Pareto-optimal" solutions that present this trade-off (Figure 5.1). A solution is called "Pareto-optimal" if none of the objective functions can be improved in value without degrading some of the other objective values. For example, the direct CO_2-emissions of the new EPFL energy system can be decreased by shutting down completely gas boilers, and installing photovoltaic panels and import electricity from wind farms. This solution is optimum from an environmental perspective, but not from an economic one.

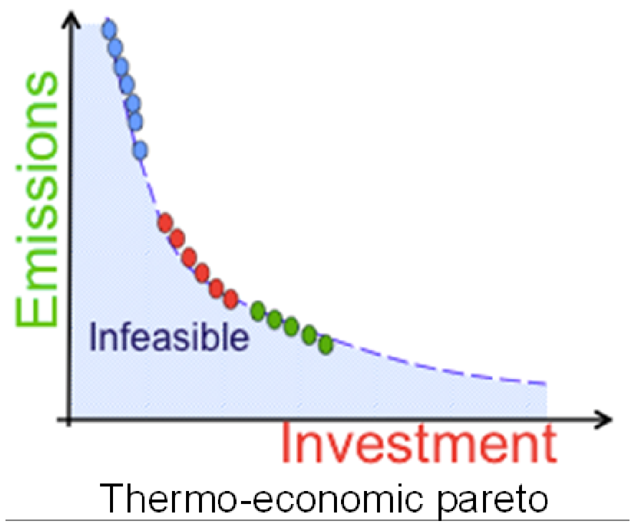


Figure 5.1: Example of Pareto front (trade-off environmental impact/investment costs) (`https://ipese.epfl.ch/ipese-research/ipese-process_design/`)

Without additional subjective preference information, all Pareto optimal solutions are considered equally good. The final goal of MOO is therefore to find a representative set of Pareto optimal solutions and analyse a single or multiple solutions that can satisfy the subjective preferences of the decision maker [2].

You are now asked to select two contrasting objectives (e.g. investment and operating costs, total costs and emissions, etc.) and to draw the trade-off between those, as in Figure 5.1. In practice, you can obtain this Pareto frontier by (in the case of emissions/investment trade-off):

- first, run your AMPL model with the objective of minimizing investment costs (this gives you the highest emissions and lowest investment costs, point located on the top-left of Figure 5.1);
- secondly, re-run your AMPL model with the objective of minimizing the total CO_2-emissions (this gives you the lowest emissions and highest investment cost, point located on the bottom-right of Figure 5.1);
- re-run your AMPL model with different values of the investment costs (for example, if the annualised investment costs are at least 3,000 CHF/year, run the model with a target value of 4,000 CHF/year, calculate the associated emissions, and run again the model for another target value of 5,000 CHF/year, etc.).

Which are the configurations (Pareto optimal solutions) most representative of your Pareto set? Can you explain why? Please select at least 3 solutions and discuss them into details (which technologies are implemented? what are their sizes?).

At this stage you should:

- **have** a Pareto frontier (e.g. minimise emissions and investment costs);
- **present** the differences between at least three different points located on this Pareto frontier;

5.4 Sensitivity analysis

Predicting an "exact" outcome or a "perfect" optimum solution is not realistic in practice, as many factors are likely to vary in the future (Figure 5.2).

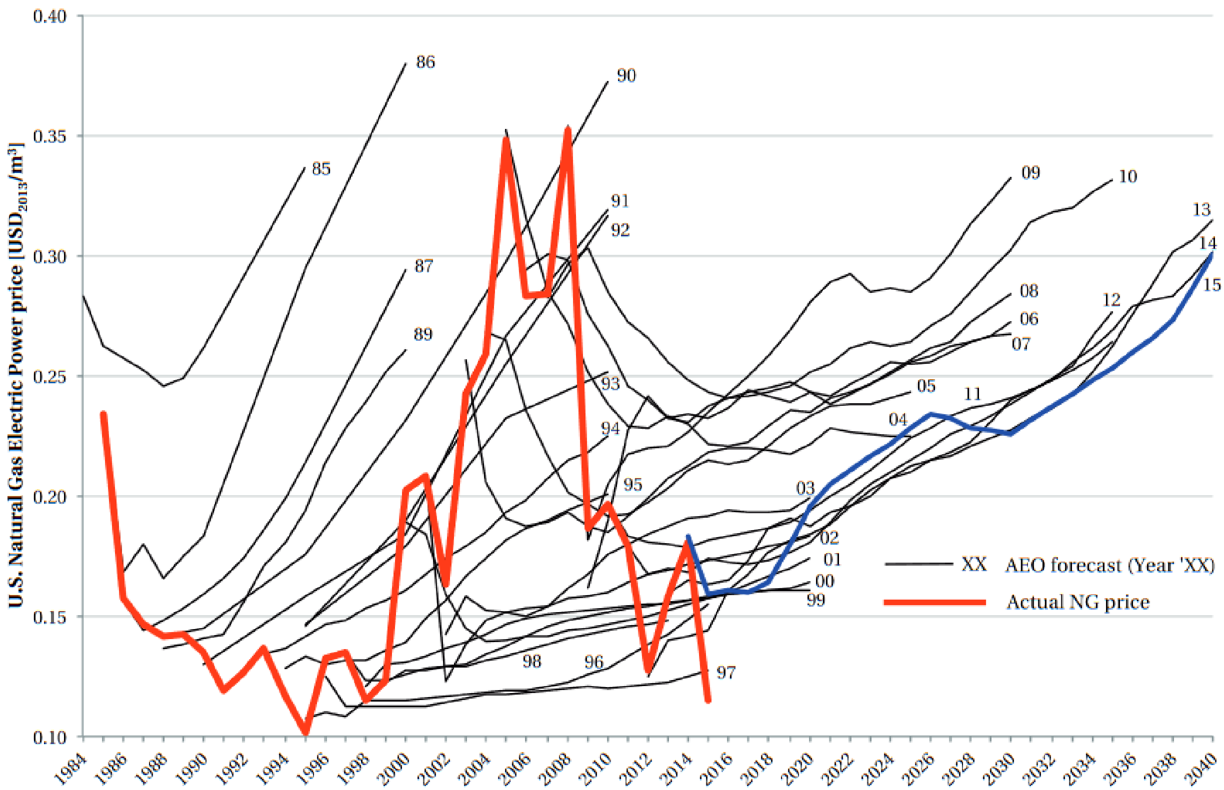


Figure 5.2: Example of differences between predictions and actual variations (natural gas price) [1]

Some examples of parameters that may vary are:

- the natural gas price;
- the electricity price;
- the emissions associated with the electricity source (if the electricity is imported from France, are the emissions the same as if it you import electricity from Italy?)

You are now asked to **vary at least one of these parameters** and estimate how the total costs vary with those, and how the Pareto frontier derived in the previous section changes.

At this stage you should:

- estimate how the system costs vary when modifying a factor;
- give two Pareto frontiers for the same trade-off as investigated in the previous section (e.g. minimise emissions and investment costs), but for two different values of the gas and electricity price;

5.5 Summary

Overview

The present part of the project builds on the results obtained along the semester, from the calculation of the building energy demands (**Part 1**) to the modelling of the campus (**Part 2**) and data reconciliation of the heating utilities (**Part 4**). In this part of the project, **you** are asked to:

- Adapt your current model (or use the one given to you) of the EPFL energy system with the results obtained in each part of the project (heat pump and SOFC characteristics (Section 5.2));
- Suggest at least three different new energy systems (combination of heat pumps, import of natural gas, etc.) for the EPFL campus;
- Conduct a multi-objective optimisation, analysing the trade-off between different design objectives (e.g. lower investment costs against higher penetration of renewable energy);
- Assess the sensitivity of your solutions to variations in e.g. the natural gas and electricity prices.

You should present:

- 3 possible layouts of the EPFL energy system, that you selected based on different objectives (minimum investment costs, minimum consumption of natural gas, etc.);
- 1 Pareto frontier for a trade-off you decided to analyse (e.g. emission vs. CAPEX or OPEX or totalcost);
- 1 Pareto frontiers with different CO_2-emissions associated to natural gas or electricity prices.
- 1 Pareto frontiers with totalcost associated to different level of CO2 taxes, and analyze the differences of the installation/operational strategies.

References

[1] Stefano Moret. *Strategic energy planning under uncertainty.* Tech. rep. EPFL, 2017.

[2] *Multi-objective optimization.* en. Page Version ID: 891509579. Apr. 2019. URL: https://en.wikipedia.org/w/index.php?title=Multi-objective_optimization&oldid=891509579 (visited on 05/06/2019).

[3] *Scenario analysis.* en. Page Version ID: 883790048. Feb. 2019. URL: https://en.wikipedia.org/w/index.php?title=Scenario_analysis&oldid=883790048 (visited on 05/06/2019).