Modeling and optimization of energy systems

Fall 2024

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 of the EPFL campus and classifying them,
2. Selecting the utilities (i.e. heat pump, solar panels) 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.

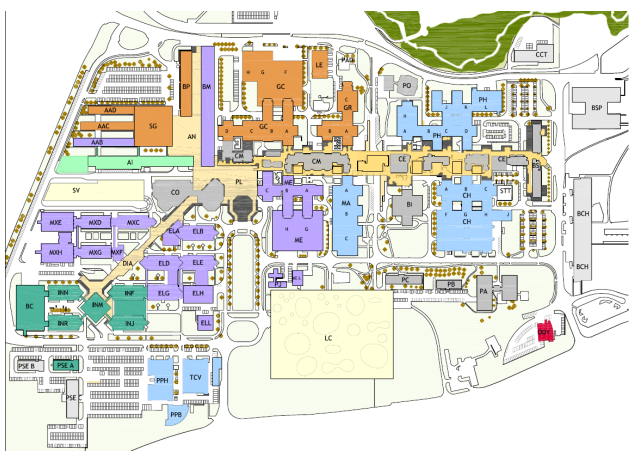


Figure 1: Map of EPFL campus

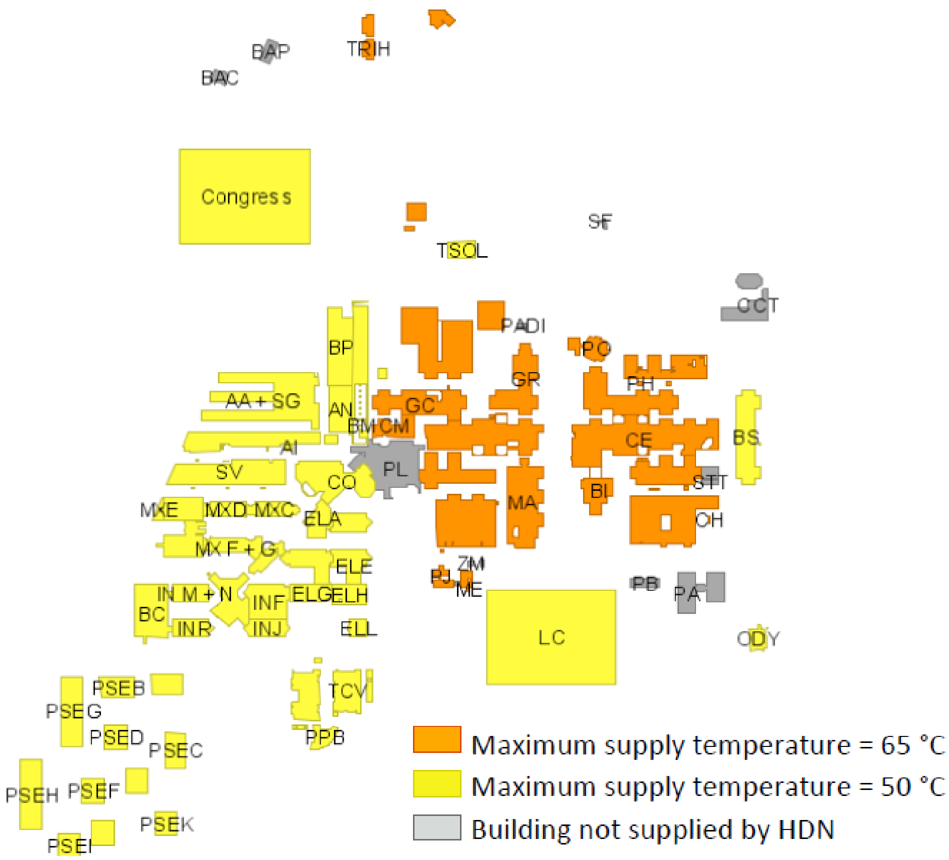


Figure 2: EPFL buildings with HDN sizing supply temperature

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 in the campus;
- 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.

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 can be expressed by the following equation, which governs the thermal load for each building (Equation

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	1	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)

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:

- t is the time interval of the analysis, e.g. minute, hour, day;
- 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 Eq. 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 energy demand profiles. Therefore, this section provides a guideline on how to determine the unknown parameters in Eq. 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 $\text{A}_{\text{type}}/\text{A}_{\text{th}}$
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:

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

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

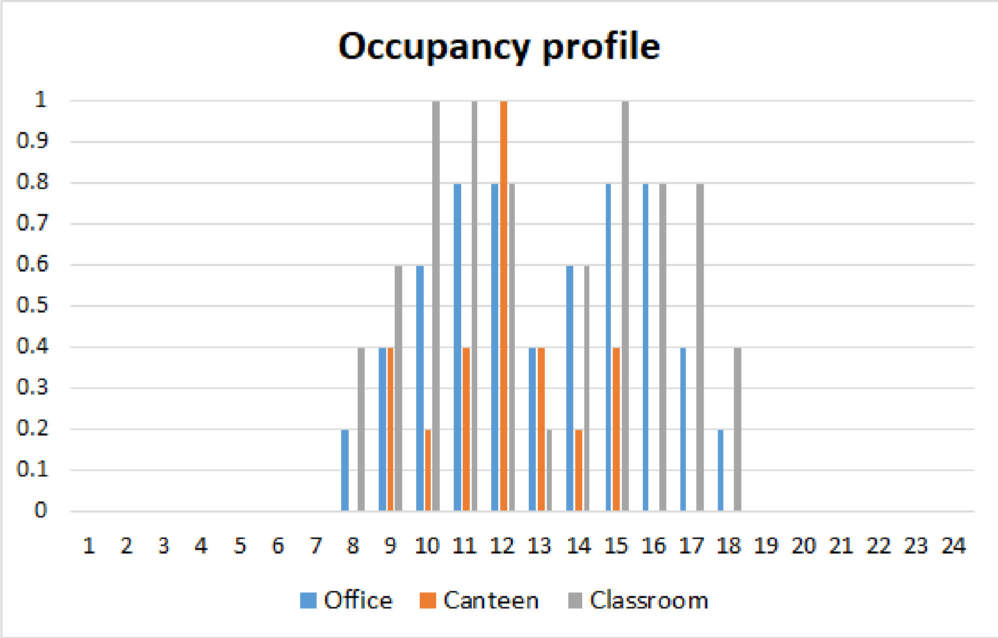


Figure 1.1: Occupancy profile per type of usage

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

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.

First equation - yearly heating demand 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 ± 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).

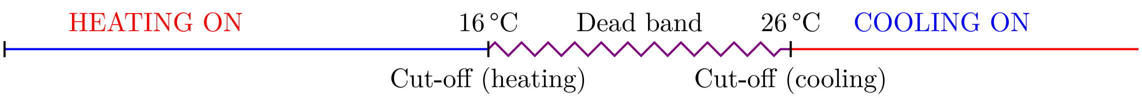


Figure 1.2: Cut-off temperatures of the heating and cooling systems

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**
>
> - Eq. 1.3 is very similar to Eq. 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.

Equation 1.4 ensures positive heating power values and set to 0 all negative values, when no heating or cooling are required. This equation is <u>non-linear</u> and the Newton-Raphson method should therefore be applied for resolution.

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

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

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

Second equation - Switching off the heating system In some cases, the demand of the heating system may be equal to 0 if the heat gains from the solar radiation, electric appliances and people are significant. You can assume that the heat load is zero if the cut off temperature is equal to ± 1 °C. Assume mean values of irradiation, electricity demand and heat gain due to people for the time this condition applies.

$$
0 = A_{\text{th}} \cdot \left(k_{\text{th}} \cdot (T_{\text{int}} - T_{\text{cut}}) - k_{\text{sun}} \cdot \dot{i}_{mean} - \dot{q}_{\text{people,mean}} \right) - f_{el} \cdot \dot{Q}_{\text{el,mean}} \tag{1.6}
$$

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 1.7 .

$$
Q_{\text{th,year}}^{+} - Q_{\text{th}} = 0 \tag{1.7}
$$

where:

- $Q_{\text{th,year}}^{+}$ is your calculated annual heatload Eq. 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 Eq. 1.7.

3. 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;
- $k_{\mathrm{th},0}$ = from 1 to 10 W/m^2/K, and $k_{\mathrm{sun},0}$ = from 0.05 to 5.

Hint

It may happen that you obtain negative k_{sun} values for some buildings. After analysing Eq. 1.1, one possible way of solving this issue is to reduce the share of electricity demand which is converted to heat f_{el}.

The hourly heating demand can be calculated once the heat gains ($\dot{q}_{\mathrm{people}}(t)$ and $\dot{Q}_{\mathrm{el}}(t)$) and building properties (k_{th} and k_{sun}) are derived, following the Eq. 1.1.

Bonus question: Once the hourly heating loads have been calculated, you can now determine the temperature profiles of the heating system, that is, the temperature of the heat supply $T_s(t)$ to the heat distribution system in the campus. A detailed explanation of this calculation can be found on slide 11 of lecture 1. Energy demand analysis: building modelling (*T1BuildingModel.pdf*). The heating curve obtained by identifying the supply temperature will be useful for the heat pump modelling in Parts 3 and 4.

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 accuracy values;
- The hourly heating demand of the EPFL campus for the whole year.

1.2.4 Impact of renovation and indoor temperature

Now that the heat transfer coefficients k_{th} and k_{sun} of each building have been estimated, one can study the impact of their variation on the building energy consumption.
As these coefficients characterize the leakage losses and the solar gains respectively, the renovation of the building can have an important impact on them. It is asked from you to present some claims on what could be the impact of renovation.
In a first step, discuss the different possibilities to vary the heat transfer coefficients of a building:

- In which direction could each coefficient be improved ?
- What does it mean to increase k_{sun} ? How can it be achieved ?
- What are the constraints on k_{th} ? Think about the ventilation requirements; does there exist some norms to comply with ?
- How can one vary the U_{env} parameter?
- Draw conclusions about the heat losses due to air renewal (Eq. 1.2).

Then, propose a brief quantitative analysis. As an example, suggest a xx % increase in k_{sun} (improved admission of solar gains) and assess the impact on the annual heating demand. Present some graphical results to support your findings. Pay particular attention to the physical units implied.
Energy sobriety is a hot topic due to energy shortages. Assess the impact of the indoor temperature on the annual heat demand of EPFL.

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 first 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.
As a second approach to the data clustering, include the heating demand profiles as a third attribute in addition to the external temperature and solar irradiation. Compare the results with the previous one and choose your typical periods for the rest of the project.

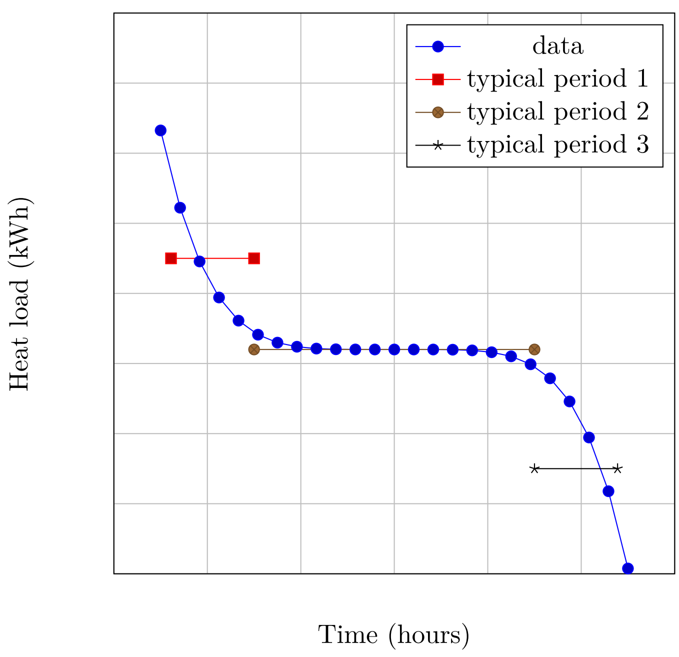


Figure 1.3: Example of clustering and typical periods for a heating duration curve

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 Python with libraries such as Scikit-learn, see: `https://scikit-learn.org/stable/modules/generated/sklearn.cluster.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 equipment size 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 Help for the following parts

To ensure that your group is not stuck on part 1, we provide you one possible solution for the weather and building data. This solution is not the only correct one. For the final report, you are expected to use your own results.

Weather data

The clustered weather data (Table 1.3) has to be the same for all buildings. This means we distinguish between two types of typical timesteps.

- 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.

Table 1.3: 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

Building data

In Parts 2 and 4, you will use the building data generated in Part 1. Table 1.4 gives an overview of the needed parameters from project part 1. We advise you to use a csv file with the following headers: FloorArea, specElec, k_th, k_sun and specQ_people.

Table 1.4: Time-depend and time-independent Building Parameter

Parameter	**Name**	**Description**	**Unit**
A_{th}	FloorArea	Reference heated surface	m^2
k_{th}	k_th	Thermal losses and ventilation coefficient	kW/m^2/K
k_{sun}	k_sun	Solar radiation coefficient	–
$for\dot{q}_{people}$	specQ_people	Average heat gain from people per unit area	kW/m^2
$\dot{e}_t^-$	specElec	Specific electricity demand per unit area	kW/m^2

Hints

- All data expressed in the unit "Watt (W)" has to be converted to "**kilo**watt (kW)". This applies even to building parameters like k_{th}, which has to be converted to kW/m^2/K.

1.5 Summary

At the end of Part 1:

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.

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 gains 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};
- Schedule when the heating system could be switched ON.

Part 2

NLP Optimisation of Energy Systems

2.1 General Overview

In this task, we will have a closer look at the heat supply of EPFL and how it could be improved regarding the heat recovery potential.
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). The investment cost of heat exchangers depends predominantly on their heat transfer area, which on the other hand depends on the temperature characteristics of the streams.
Therefore, the goal of Part 2 is to determine the technical and economic benefits of different heat recovery solutions in EPFL's heating system. The analysis involves determining the optimal minimum temperature difference (ΔT_{min}) in the new heat exchangers, their corresponding heat transfer areas, and quantifying the economic feasibility considering both investment and operation costs.

In **Part 2** you are expected to

Present flowsheets that fully characterize the four systems depicted in Figures 2.1 through 2.4). Each flowsheet **must** include at least the following data about the process and its streams:

- Arrangement of the pieces of equipment and stream connections;
- Stream mass flow rates, temperatures and compositions;
- Equipment sizes;
- Heat loads.

2.2 Reference scenario

Figure 2.1 depicts the reference scenario, which corresponds to the current heating concept of the EPFL campus composed of a heat pump (HP) that supplies hot water at 65 °C to the medium-temperature network of the campus with lake water at 7 °C. The hot water at the return side of the HP is at 30 °C. Lake water leaves the evaporator at 3 °C.

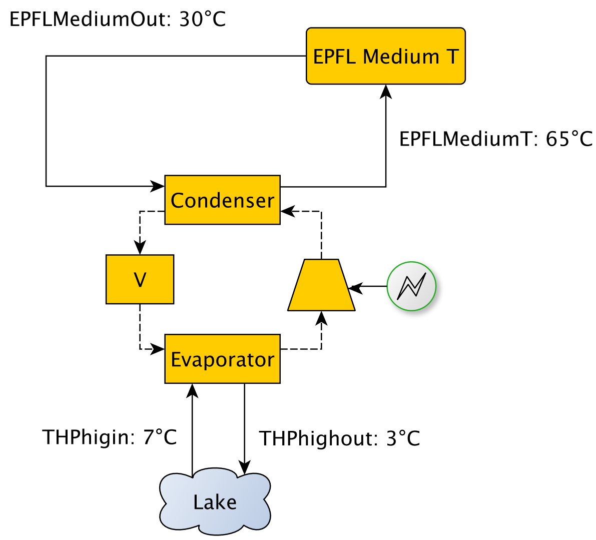


Figure 2.1: Reference scenario for heat supply

As a starting point, you are given a model in algebraic modeling language AMPL, which is running but it is still incomplete. In this first part, you are asked to complete this model and use it to evaluate the current heating concept of EPFL. The files of the initial AMPL model are structured as follows:

- *.mod*: contains the model equations;
- *.dat*: contains the data for the parameters and sets;
- *.run*: contains solver options and displaying commands.

The heat requirements and the operating time of the typical time steps have to be added to the corresponding *.dat* file. Concerning the heat requirements, you can use Eq. 1.3 with A_{th} being the sum of the heated surfaces. Pay attention to consider only the buildings heated at 65°C (medium-temperature demand). 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). For further details, see the presentation files of project part 2.

What do you have to do in the AMPL models

- 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 solution.

At this stage

- You should develop the flowsheet of the reference system;
- You should complete the AMPL model for the reference scenario. Some assumptions and/or relevant information are available in section 2.7;
- You should calculate and present the current energy bill.

Now that we know more about the reference scenario, we are interested in analyzing potential heat recovery options. For the evaluation of each of them, you should use and modify the provided AMPL code. Be aware that AMPL will only be able to solve what you insert as constraints. In other words, AMPL is not 'smart' and, even though you know that a temperature T_2 is higher than T_1, AMPL doesn't! This is why you must be very meticulous about the way in which you define the constraints.

Do not forget Polya's 4 steps when addressing a problem. Do not skip any of them! They help you structure the problem:

Polya's 4 steps

- **Analyse -** The energy recovery scheme is given for the 4 scenarios. What and where will the trade-offs be? Any initial thoughts?
- **Plan -** Constraints are suggested and commented. Pay attention to the units (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?

2.3 Data Center heat recovery

The first option for heat recovery you should analyze is the integration of the data center. The data center at EPFL generates 574 kW of heat, which has to be removed. In order to recover it, a heat exchanger is being considered. The intended configuration as well as some variables and parameters are depicted in Figure 2.2. As in the reference scenario (section 2.2), you are given 3 AMPL files: A *NLP_DC.mod* file that contains the model description; a *NLP_DC.dat* file that contains a part of used data; and a *NLP_DC.run* file that loads both .mod and .dat files, specifies the solver and displays specific variables.

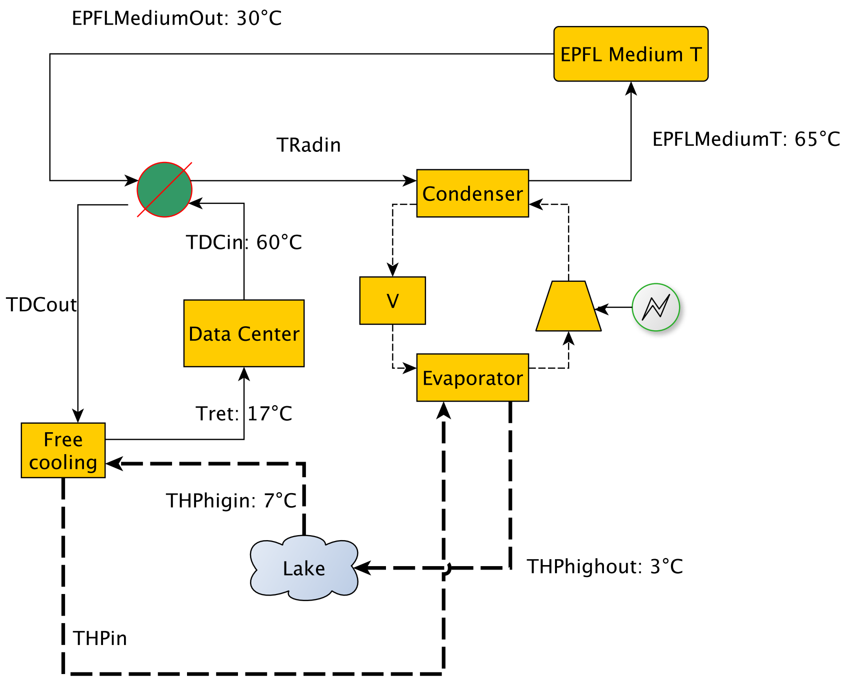


Figure 2.2: Heat recovery from data center

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 need to model the green heat exchanger in Figure 2.2, which affects the amount of heat that needs to be supplied by the heat pump. Furthermore, it is suggested to pre-heat the lake water that is entering the heat pump evaporator (both shown in the Figure).

At this stage

- Take Polya's 4 steps. You should develop the AMPL model for data center waste heat recovery. Some assumptions and/or relevant information are available in section 2.7;
- 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, the payback time as well as the optimal ΔTmin. Insert any additional metrics you judge being of interest.

2.4 Air ventilation heat recovery

Before you model the air ventilation heat recovery illustrated in Figure 2.3, you have to initialize the model by using the weather data from Part 1 of the project. Default values of the buildings data have already been added to the model. First, build your model and make sure it is running with the default values. Then, using Quarto, send the data from your .csv file to AMPL.

Hint

- Once you move from AMPL to Quarto, comment the solve command in AMPL. We will send the solving instructions via Quarto;
- Pay attention to attribute the right building to the right temperature level using the two sets med_T_id and low_T_id. Construction period (Table 1.1) and Figure 2 show which building is connected to which network;
- The average heat gain due to the people's presence is only used in time steps 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.

The heating demand for each building is modelled similarly to project Part 1 (Eq. 2.1). 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 Eq. 2.1. Due to air infiltration, you can assume an air mass flow loss of 20% between the air flow entering and exiting EPFL.

$$Q(t) = A_{th} \cdot \{U \cdot (T_{int} - T_{ext}(t)) + m_{air} \cdot c_{p,air} \cdot (T_{int} - T_{ext_{new}}(t)) - k_{sun} \cdot Irr(t) - Q_{people}(t)\} - Q_{el}(t) \quad (2.1)$$

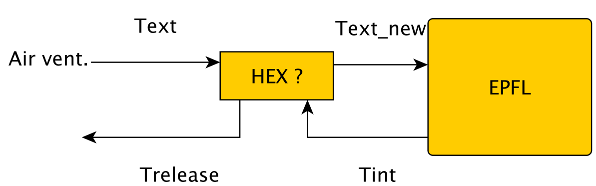


Figure 2.3: Heat recovery from air ventilation

Similarly to the previous section, there are 3 files: *NLP_vent.mod*, *NLP_vent.dat* and *NLP_vent.run*.

Hint

- Only based on the hypotheses presented initially, are you able to comment *a priori* on the viability of this kind of heat exchanger?
- The heat demand is no longer a parameter but a variable that depends on the external temperature;
- The logarithmic mean temperature difference equation is expressed by Eq. 2.2.

$$\Delta T_{ln} = \frac{\Theta_1 - \Theta_2}{ln(\Theta_1) - ln(\Theta_2)} \quad (2.2)$$

where $\Theta_{1,2}$ are the temperature difference at both side of the heat exchanger.

At this stage

- Take Polya's 4 steps. You should develop the model, analyse the results and make conclusions. Some assumptions and/or relevant information are available in section 2.7;
- You should be able to size the ventilation heat recovery and indicate the area and optimal ΔTmin of the installed heat exchanger. You should also provide the costs, the payback time and any other metrics you deem of interest.

2.5 Air ventilation with Heat pump integration

Another possibility is to recover the heat from the air leaving the ventilation system as heat source for a HP evaporator (Figure 2.4).

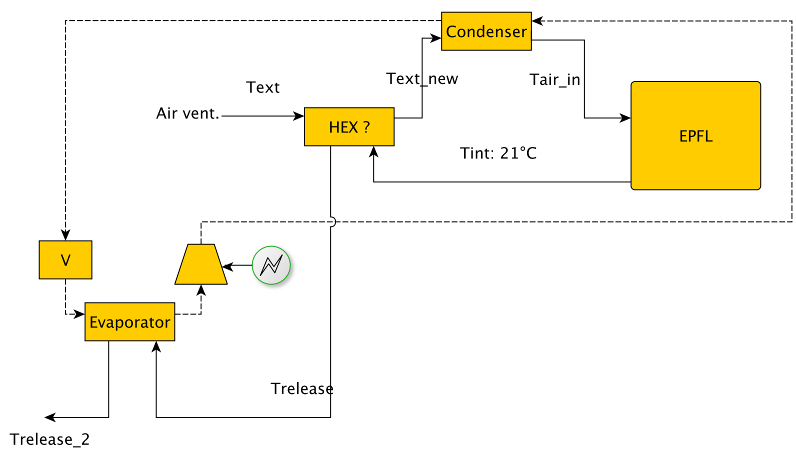


Figure 2.4: Ventilation and heat pump integration

Similarly to the previous section there are 3 files: *NLP_vent_HP.mod*, *NLP_vent_HP.dat* and *NLP_vent_HP.run*.

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 make conclusions. Some assumptions and/or relevant information are available in section 2.7.
- You should be able to provide operating and investment costs, as well as payback time for the ventilation HE as well as its size.

2.6 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;
- Detailed flowsheets of all analysed systems;
- **All** the relevant economic and performance indicators;
- Later, you will use the models and the results you obtained herein to connect to the main MILP model developed in Part 4 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 problems for different heat recovery scenarios;
- Interpret results and provide economic indicators to assess their viability.

2.7 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
- Annual 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 3

Modelling and reconciliation of a two-stage heat pump

3.1 Introduction

While Part 2 focused on heat recovery solutions for EPFL's centralized heating system, Part 3 delves into the modelling of the heat pump (HP) with its components (i.e. compressor, evaporator, condenser, valves) and working fluid.
The novel centralized heating system of EPFL will consist of an advanced **two-stage HP** with maximum capacity of 6 MW_{th}, as depicted in Figure 3.1. The main objective of this part of the project is to provide decision support to EPFL to choose a working fluid for the heat pump based on environmental and economic characteristics. To this end, you are asked to:

- Build a preliminary model of a HP in the process simulation software Belsim VALI by applying degrees of freedom (DOF) analysis for two working fluids (Section 3.3);
- Use measurement data for performing DOF and data reconciliation analyses of the HP (Section 3.4);
- Use the results of the data reconciliation to evaluate the economic and thermodynamic performances of the system (Section 3.5).

3.2 Modelling of a simple heat pump - Optional

This section proposes a hands-on practice in learning to use Belsim VALI, the software used in Part 3 to model the two-stage HP.
The **goal** for now is to build a working model of a simple HP following the video tutorial on how to build a HP from scratch that can be found on Moodle. The Appendix 3.7 provides a short description and hints for Belsim VALI. An empty file (HP.bls) is provided for you to build your model there.

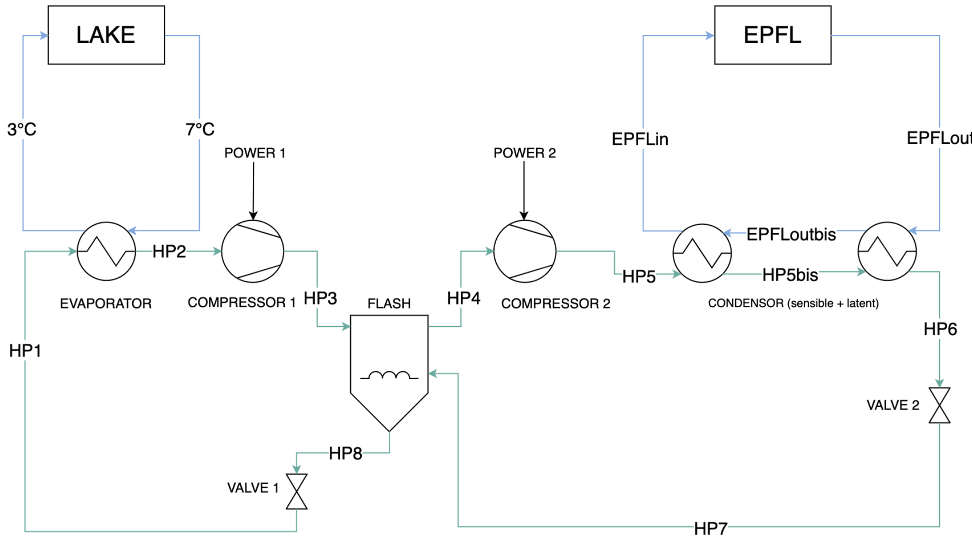


Figure 3.1: Process flow diagram (PFD) of the two-stage heat pump

Hint

Do **NOT** attempt to build the whole system first (i.e. adding all components) and only then include the parameter data (e.g. pressures and temperatures). This will definitely create convergence issues and instability when running the model, which may be challenging to debug. Instead, follow the following tips:

1. Choose one component and add it to the model. For instance, a compressor;
2. Read the corresponding documentation (help tool of Belsim VALI) for this specific component;
3. Determine the parameters that should be given as input (e.g. inlet/outlet pressure) based on the help topics available in VALI and a DOF analysis;
4. Make a reasonable assumption of these parameter values based on literature review, manufacturing data, etc.;
5. Add the appropriate values to the component in the model and solve it;
   (a) If it works, proceed to adding the next component until the whole system is completed;
   (b) If it does not work, check for missing data (for example, did you forget to enter the component efficiency?) or convergence issues (did you set a pressure at the outlet of a compressor higher than the inlet one? Do you have liquid at the inlet?).

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

- A working model of a simple heat pump in Belsim VALI.

3.3 Modelling of a two-stage heat pump

A working, yet not calibrated, model of the two-stage heat pump depicted in Figure 3.1 is given to you for each working fluid listed in Table 3.1 (file name: fluid-name_empty.bls). The models have all tags set to OFF and the working fluid set to water.
The default working fluid is **R-290**. Your **task** for this part is to:

- Carry out a DOF analysis to determine which tags should be activated in the VALI model R-290_empty.bls. A csv file named DOF.csv, containing 5 different combinations of sets, is given to help you in the analysis (only one combination is correct);
- Open the R-290_empty.bls file in VALI and activate the correct tags. Do **not** change any values, just change the set in the accuracy tab from OFF to CST (constant);
- Modify the working fluid by first loading the appropriate fluid (Compound) and then creating a Thermod for it;
- Set the new Thermod for the correct flows;
- Make sure the model is properly running without convergence issues;
- Repeat steps 2, 3 and 4 for a second working fluid of your choice. Note that you should use the corresponding model for the chosen working fluid.

Hint

You can find the flowsheet of the two-stage heat pump that was already created in Figure 3.1 in the Appendix A, together with a list of relevant tags and explanations in Tables A.2 and A.4.

3.3.1 Degrees of Freedom analysis

A csv file containing 5 different combinations of activated tags is given to you, in which only one combination is correct. Your task is to deduce the correct combination of CST tags in order to be able to run the simulation. This can be done by following the DOF analysis unit-by-unit and comparing with the given options. For example, for a separator (Figure 3.2), 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.

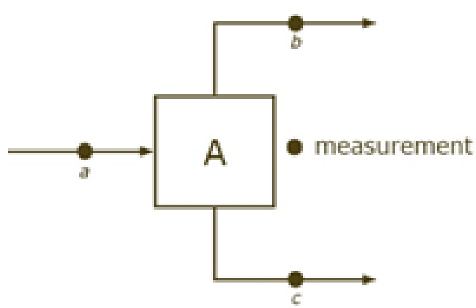


Figure 3.2: Schematic illustration of a separator for data reconciliation purposes

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. Based on your VALI model, select a unit for each type (i.e. a HEX, a compressor etc.) and conduct a DOF analysis answering the following questions:

- For each component, how many measurements are needed for a mass balance?

- For each component, how many measurements are needed for an energy balance?
- How many measurements are set as parameters?
- How many values 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;
- A working model of the two-stage heat pump running without convergence issues for the working fluid R-290.

3.3.2 Selection of heat pump working fluids

Having determined a feasible combination of tags, your current task is to repeat the procedure for a second working fluid of your choice.
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, chlorofluorocarbons (CFCs) refrigerants, such as R-12, used to be some of the most common working fluids for heat pump applications, but their use was 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);
  - Lifetime in the atmosphere (τ);
  - eutrophication;
  - acidification.

Table 3.1: Selected refrigerants for the study. R-12 is added for comparison.

ASHRAE number	Name	Group	GWP	ODP	Lifetime τ [yr]	Safety Group
R-290	Propane	HC	3.3	0	12	A3
R-600	Butane	HC	4	0	12	A3
R-600a	Isobutane	HC	3	0	12	A3
R-717	Ammonia	N	0	0	0.02	B2L
R-1234yf	Tetrafluoropropene	HFO	4	0	0.03	A2L
R-1234ze	Tetrafluoropropene	HFO	6	0	0.05	A2L
R-1270	Propylene	HO	1.8	0	12	A3
R-12	*Dichlorodifluoromethane*	*CFC*	*10'900*	*1*	*100*	*A1*

From the heat pumps manufacturer catalogue, you have the choice between 6 different working fluids (Table 3.1). In the rest of this project, you will proceed with two refrigerants, the R-290 and another one of your choice. It is important that you properly justify your choice based on the above-mentioned criteria.

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

- A working model of the two-stage heat pump running without convergence issues for the working fluid of your choice.

3.4 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 known as measurement bias) is associated with the fact that any 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 one. It is said to be random because its next measured value cannot be predicted exactly from previous realizations.

While random errors are due to the intrinsic sensor accuracy, systematic errors are due to sensor calibration or faulty data transmission. Data reconciliation theory assumes that: (i) errors are the sum of many factors and, (ii) errors are normally distributed.
The data reconciliation technique generally requires redundancy of the process measurements. This redundancy is necessary since no measurement is exempt of random errors. This illustrates that, the more sensors are placed, the more reliable the data reconciliation process is.
From the DOF analysis in the simulation and the working model, measurements for different numbers of periods and temperature levels are provided to you in the project data. Once your models are properly running, your **task** is to perform the data reconciliation based on the provided measurements, and obtain the reconciled files from VALI that will be used in the next section to determine the performance of the heat pump.
Each refrigerant has been evaluated for two temperature levels (LT - low temperature and MT - medium temperature) and for a different number of measurements (from 6 to 11). You are responsible for identifying the relevant measurement files based on your selection of working fluids and temperature levels.
Each measurement file called by VALI generates one reconciled file. You should obtain as many reconciled files as there are measurements for the working fluids and temperature levels you are working with. Note

that there must be a folder called **Reconciled** in the folder of your VALI model. The reconciled files will be automatically saved there.

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

- Reconciled sets of data files (6-11 per refrigerant);

3.5 Performance evaluation and decision support

You are asked to perform thermodynamic performance and cost calculation for different working fluids of the heat pump in order to support the decision making. Your **task** is to perform the analysis for the two working fluids you are working with (the R-290 and the working fluid of your choice) using the AMPL models provided.

3.5.1 Carnot factor regression analysis

The **Coefficient of Performance** (COP) is a measure of the heat pump's performance. It represents the ratio of useful heating $Q(t)$ provided by the heat pump to the energy input required, typically in the form of electricity $W(t)$, in any given time t. For the heat pump models you are expected to develop in **Part 4**, it is important to have an accurate estimation of the $COP(t)$ that takes into account the impact of external influences, such as varying ambient temperatures $T_{ext}(t)$. Therefore, in this section you will improve the assessment of the heat pump's performance by developing a regression model based on the **Carnot factor**.

In the context of heat pumps, the **Carnot factor** $C_{carnot}(t)$ is the ratio of the actual performance $COP(t)$ to the theoretical maximum COP based on the Carnot cycle $COP_{carnot}(t)$, as expressed by Eq. 3.1. It thus indicates how closely a real system approaches its theoretical efficiency limit as it operates between two temperature levels corresponding to the lower-temperature heat source $T_{evap}(t)$ and the higher-temperature heat sink $T_{cond}(t)$.

$$C_{carnot}(t) = \frac{COP(t)}{COP_{carnot}(t)} = \frac{Q(t)}{W(t)} \cdot \frac{T_{cond}(t) - T_{evap}(t)}{T_{cond}(t)} \tag{3.1}$$

where $T_{cond}(t)$ and $T_{evap}(t)$ are the absolute temperatures in Kelvin of the heat sink and source, respectively.

The reconciled data files consist of 6 columns, which are described in Table A.3. Each of these sets contains all measurements and their reconciled values, plus other operational conditions that were recorded during the data reconciliation process. With the reconciled tag values, you are asked to complete the AMPL model (.dat file). Then, you must derive a regression curve that calculates the Carnot factor $C^*_{carnot}(t)$ (Eq. 3.2) as a polynomial function of the ambient temperature T_{ext} for both stages of the heat pump.

$$C^*_{carnot}(t) = a \cdot T_{ext}(t)^2 + b \cdot T_{ext}(t) + c \tag{3.2}$$

The factors *a, b*, and *c* can be derived by minimizing the mean square error between $C^*_{carnot}(t)$ and $C_{carnot}(t)$:

$$\underset{a,b,c}{\text{minimize}} \sum_t \left(C^*_{carnot}(t) - C_{carnot}(t)\right)^2 \tag{3.3}$$

Make sure to identify the evaporator T_{evap} and the condenser T_{cond} temperatures accordingly. The T_{ext} values for each measurement period can be found in the csv file *Text.csv*. You will find some hints in the AMPL code provided.

Hint

The present section involves determining the **Carnot factor** $C^*_{carnot}(t)$ for the heat pump, which varies over time t as a function of the ambient temperature T_{ext}. In the process described herein you use the provided AMPL models to:

- **Calculate** $C_{carnot}(t)$ using the relationship between the actual $COP(t)$ and the theoretical Carnot COP $COP_{carnot}(t)$;
- **Develop a regression model** of $C^*_{carnot}(t)$ as a polynomial function of the ambient temperature $T_{ext}(t)$;
- **Minimize the error** between the actual and estimated Carnot factors by adjusting coefficients a, b, and c in the regression model.

This approach ensures that the theoretical maximum efficiency, operational data, and environmental conditions are all considered in your analysis.

3.5.2 Cost calculation

The main contributors to the investment cost of heat pumps are the heat exchangers and the compressors. Therefore you can neglect other units for the cost calculation of the two-stage heat pump. The **goal** is to calculate the unit cost for the two-stage heat pump using the cost functions provided in the AMPL model.

Hint

Make sure to:

- Assume the worst case conditions to evaluate the heat exchangers' area and to size the compressors;
- Consider the *reconciled results* and the T_{ext} values provided for the operating conditions that influence the cost functions (e.g. temperatures and pressures);
- Report the cost for the "worst" situation among the different operating conditions, that is, where the cost turns out to be the highest.

3.6 Summary

Given:

- The working, yet not calibrated, models of the two-stage heat pump for several working fluids;
- A csv file with 5 combinations of sets, only one of which is correct;
- A set of measurements for 7 working fluids, each with 2 temperature levels and from 6 to 11 periods;
- The AMPL files and a table with ambient temperatures for each measurement period.

Hint

For the two working fluids you have been working with, you should **present**:

- The polynomial function for the Carnot factor as a function of the ambient temperature T_{ext};
- The size of the heat exchangers and compressors;
- The total cost of the system including the investment cost of the heat exchangers and compressors;
- The unit cost of the system per kW of heat pump capacity installed.

You should be **able to**:

- Write a regression fitting model in AMPL;
- Use and interpret reconciled measurement data.

3.7 Additional information

3.7.1 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 flowrates 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.

3.7.2 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 (3.7.3).
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.

3.7.3 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 4

MILP Optimisation of Energy Systems and Scenario Analysis

4.1 General Overview

In the final part of the project, you model the whole EPFL campus. The aim is not only to model the current energy system of EPFL but also to determine the optimal energy system with new technological options (e.g. heat pumps, photovoltaic panels), taking into account their performance characteristics, capital and operating costs.
You are asked to develop this initial model. The next sections guide you through this development. First, the general mixed integer linear programming (MILP) model is explained. Then, you are asked to include your results from project parts 1, 2 and 3, by developing your own models of the energy conversion equipment for the campus.

4.2 MILP Formulation

A generic MILP model is given in the project files. Table 4.1 gives an overview about the sets, parameters and variables used in the model.

4.2.1 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 equipment 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 by 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 4.1: Description of sets, parameters and variables in MILP

Set	Description
T	Set of timesteps
B	Set of buildings
LB	Set of buildings heated by the low temperature loop
MB	Set of buildings heated by the medium temperature loop
TC	Set of technologies
L	Set of layers (resources)
G	Set of grid units
U	Set of utilities
UT	Set of utilities of a certain type (heating and/or electricity)
UL	Set of utilities using a certain resource layer
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 [-]

4.2.2 Main Equations

The objective function of the optimization is the total annual cost of the system *TOTEX* (Eq. 4.1), comprising the annual operating *OPEX* (Eq. 4.2) and annual investment *CAPEX* (Eq. 4.3) costs.

$$\min \mathrm{TOTEX} = \mathrm{OPEX} + \mathrm{CAPEX} \tag{4.1}$$

$$\mathrm{OPEX} = \sum_{u}^{\mathbf{U}} \sum_{t=1}^{\mathbf{T}} (\mathrm{C^{op1}_{u,i,t}} \cdot y_{u,t} + \mathrm{C^{op2}_{u,t}} \cdot f_{u,t}) \cdot \mathrm{t^{op}}(t)) \tag{4.2}$$

$$\mathrm{CAPEX} = \sum_{u}^{\mathbf{TC}} (\mathrm{C^{inv1}_{tc}} \cdot y_u + \mathrm{C^{inv2}_{tc}} \cdot f_u) \tag{4.3}$$

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 y_u and $y_{u,t}$ determine the existence of utilities and whether they are used or not at time segment t, respectively. Eqs. 4.4 and 4.5 link 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 Eq. 4.6.

$$\mathrm{f_u^{min}} \cdot y_u \leq f_u \leq \mathrm{f_u^{max}} \cdot y_u \quad \forall\, u \in \mathbf{U} \tag{4.4}$$

$$\mathrm{f_u^{min}} \cdot y_{u,t} \leq f_{u,t} \leq \mathrm{f_u^{max}} \cdot y_{u,t} \quad \forall\, u \in \mathbf{U}, t \in \mathbf{T} \tag{4.5}$$

$$f_{u,t} \leq f_u \quad \forall\, u \in \mathbf{U}, t \in \mathbf{T} \tag{4.6}$$

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: a low temperature and a medium temperature. Eqs. 4.7 and 4.8 express the heat balance equations for the medium temperature and low temperature loops, respectively.

$$\mathrm{\dot{Q}mt^{-}_{i,t}} = \sum_{u}^{\mathbf{UT}_{ty}} h_{u,t,tl} \cdot \mathrm{q_u^{hs}} \quad \forall\, t \in \mathbf{T} : T_{mt} \leq T_u,\ ty = \ 'Heating' \tag{4.7}$$

$$\mathrm{\dot{Q}lt^{-}_{i,t}} = \sum_{u}^{\mathbf{UT}_{ty}} h_{u,t,tl} \cdot \mathrm{q_u^{hs}} \quad \forall\, t \in \mathbf{T} : T_{lt} \leq T_u,\ ty = \ 'Heating' \tag{4.8}$$

The continuous variable h is defined to determine the heat flowing from the utilities to each temperature level of heating, and $\mathrm{q_u^{hs}}$ 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 $\in$ **TL**) by using Eq. 4.9. For example if a boiler supplies 300 kW to the medium temperature level and 200 kW to the low temperature level, the size of the boiler must be 500 kW.

$$\sum^{\mathbf{TL}} h_{u,t,tl} = f_{u,t} \quad \forall\, u \in \mathbf{U}, t \in \mathbf{T} \tag{4.9}$$

For electricity and other resources, the flow into and out of utilities is calculated by Eqs. 4.10 and 4.11.

$$\dot{M}^{\mathrm{in}}_{\mathrm{u,t}} = f_{u,t} \cdot \mathrm{m_u^{in}} \quad \forall\, t \in \mathbf{T} \tag{4.10}$$

$$\dot{M}^{\mathrm{out}}_{\mathrm{u,t}} = f_{u,t} \cdot \mathrm{m_u^{out}} \quad \forall\, t \in \mathbf{T} \tag{4.11}$$

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 Eqs. 4.12 and 4.13, respectively.

$$\mathrm{\dot{E}^{-}_{t}} + \sum_{u}^{\mathbf{UL}_l} \dot{M}^{\mathrm{in}}_{\mathrm{u,t}} = \sum_{u}^{\mathbf{UL}_l} \dot{M}^{\mathrm{out}}_{\mathrm{u,t}} \quad \forall\, t \in \mathbf{T} : l = \ 'Electricity' \tag{4.12}$$

$$\sum_{u}^{\mathbf{UL}_l} \dot{M}^{\mathrm{in}}_{\mathrm{u,t}} = \sum_{u}^{\mathbf{UL}_l} \dot{M}^{\mathrm{out}}_{\mathrm{u,t}} \quad \forall\, t \in \mathbf{T} : l \neq \ 'Electricity' \tag{4.13}$$

4.3 MILP Model Adaptations from your group

The MILP model is the center of the whole project, meaning that the results from parts 1, 2 and 3 must be integrated in it. The following sections guide you through the development of the MILP model.

At this stage

- You should be able to run the generic model you have received.

4.3.1 Initialization of MILP model

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. This section explains how you can use your project results of part 1 in the MILP model. The weather data and the operating time of the typical timesteps have to be added in file *moes.dat*. Like in part 2, the buildings data have default values. Build and debug your code with these default values and then use Quarto to send your data from the csv file to AMPL.

Hint

- All data connected to the unit "Watt" has to be converted to "**Kilo**watt". This applies even to building parameters like k_{th}, which has to be converted to kW/m^2/K;
- Remember to change the set for defining the timesteps in the very beginning of file *moes.dat*;
- The same for the temperature levels, pay attention that each building has the right heating temperature.

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 $\bar{\dot{q}}_{people}$;
- All building models of EPFL campus are included in the model;
- The model is converging to an optimal solution.

4.3.2 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

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 be 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

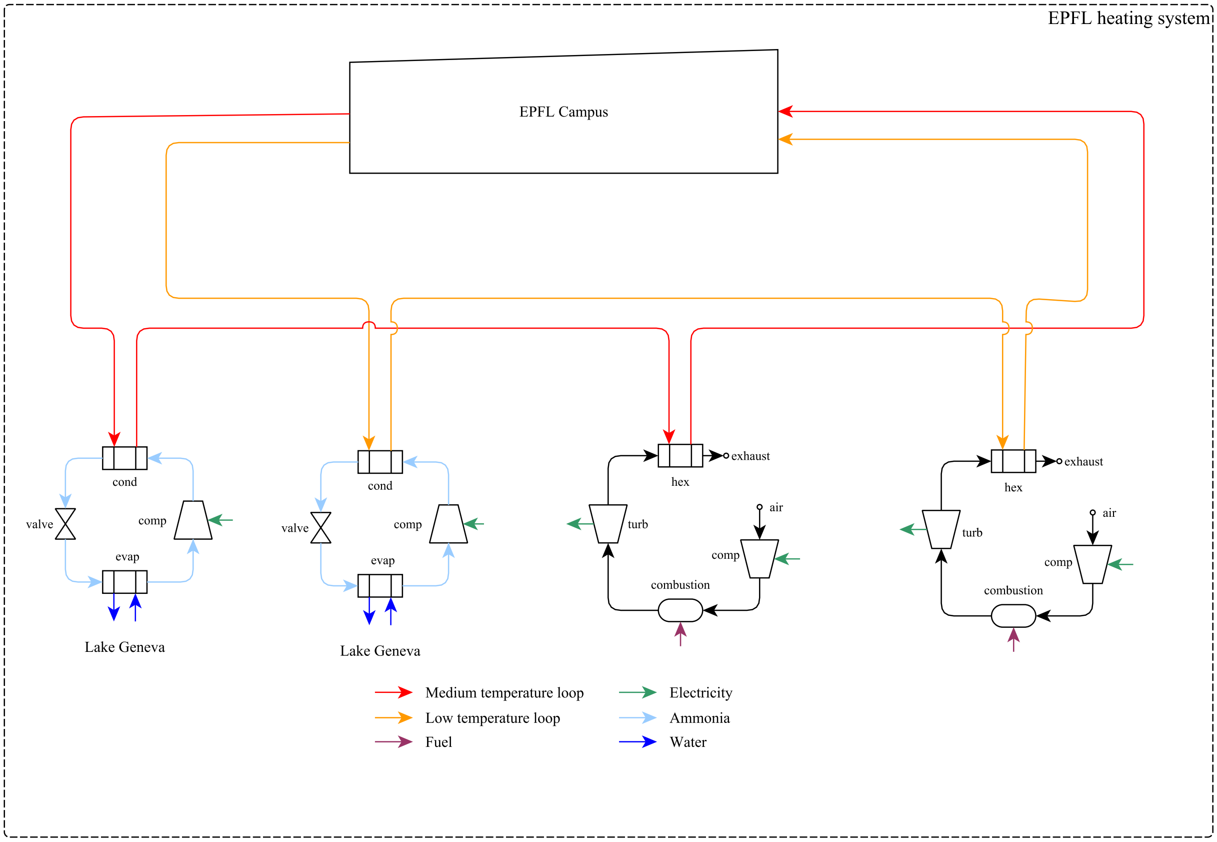


Figure 4.1: Current heating system of EPFL.

- Two single-stage heat pumps - one for low and one for medium temperature loop
- Two-stage heat pump
- Geothermal cogeneration system
- Cogeneration engine
- Solid oxide fuel cell (SOFC)
- Photovoltaic panels
- Your ideas

The initial model already contains basic models of the photovoltaic panels and the boiler. You can also further improve the models and change performance parameter (this is optional). Each group should integrate additional technologies to the optimization, either from the list or from your own ideas. Extra points will be given to the groups reporting their own review for the costs of the technologies. Otherwise, here are some literature that might be helpful:

- Model-based sizing of building energy systems with renewable sources, Stadler Paul Michael, 2019
- Fifth generation district energy systems for low carbon cities, Suciu Raluca-Ancuta, 2019

- Analysis, synthesis and design of chemical processes, Turton Richard, 2018

Overview

The present part of the project builds upon the results obtained along the semester, from the calculation of the building energy demands (**Part 1**) to the heat recovery/pumping (**Part 2**), as well as data reconciliation of the heat pump (**Part 3**). 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 4.3.3);
- Suggest at least three different new energy systems (combination of heat pumps, import of natural gas, etc.) for the EPFL campus (Section 4.3.4);
- 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 4.3.5);
- Assess the sensitivity of your solutions to variations in e.g. the natural gas and electricity prices (Section 4.4).

4.3.3 MILP Optimisation of the EPFL energy system

What you need to add/change in the MILP model:

- The heat recovery options (**Part 2**);
- The two-stage heat pump characteristics in the MILP (define the Carnot efficiency and temperature levels in the MILP model based on the Vali results (**Part 3**);
- Integrate emission factors for the imported electricity (c_{elec}) and natural gas (c_{ng}) in the MILP model;
- 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.

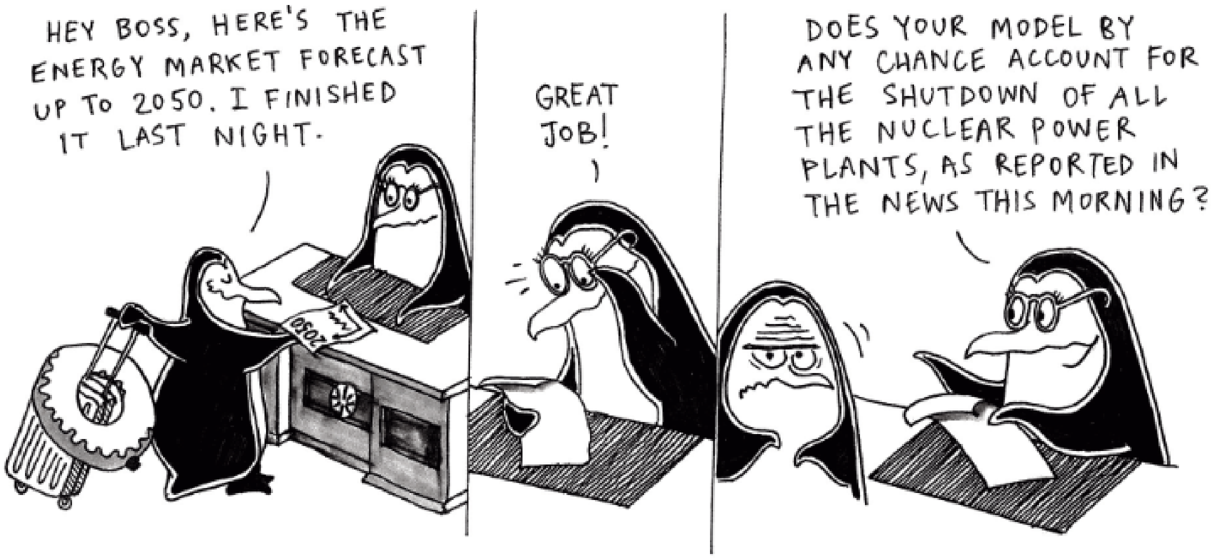
$$CO_2 = \sum(c_{ng} \cdot m_{ng} + c_{elec} \cdot E_{elec}) \tag{4.14}$$

4.3.4 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 objective functions 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.



by Outi Supponen

- 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 CO_2 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 CO_2 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.

4.3.5 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 4.2). 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.

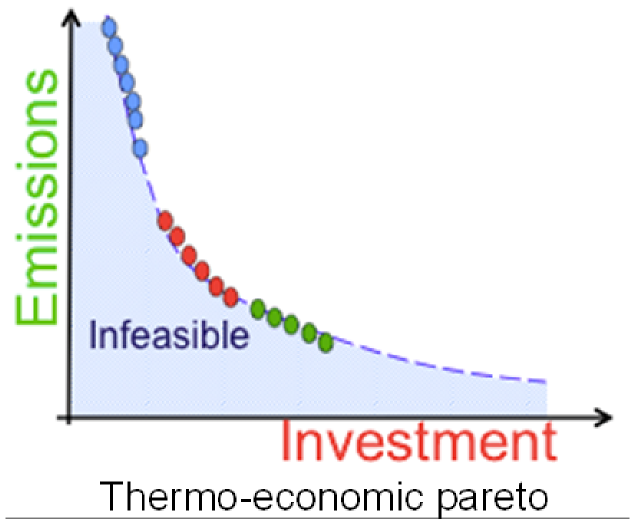


Figure 4.2: Example of Pareto front (trade-off environmental impact/investment costs) (`https://ipese.epfl.ch/ipese-research/ipese-process_design/`)

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 4.2. 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 4.2);
- 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 4.2);
- 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.).

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;
- **Answer**: Which are the configurations (Pareto optimal solutions) most representative of your Pareto set? Can you explain why? Select at least 3 solutions and discuss them in details (e.g. which technologies are implemented? What are their sizes?).

4.4 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 4.3).

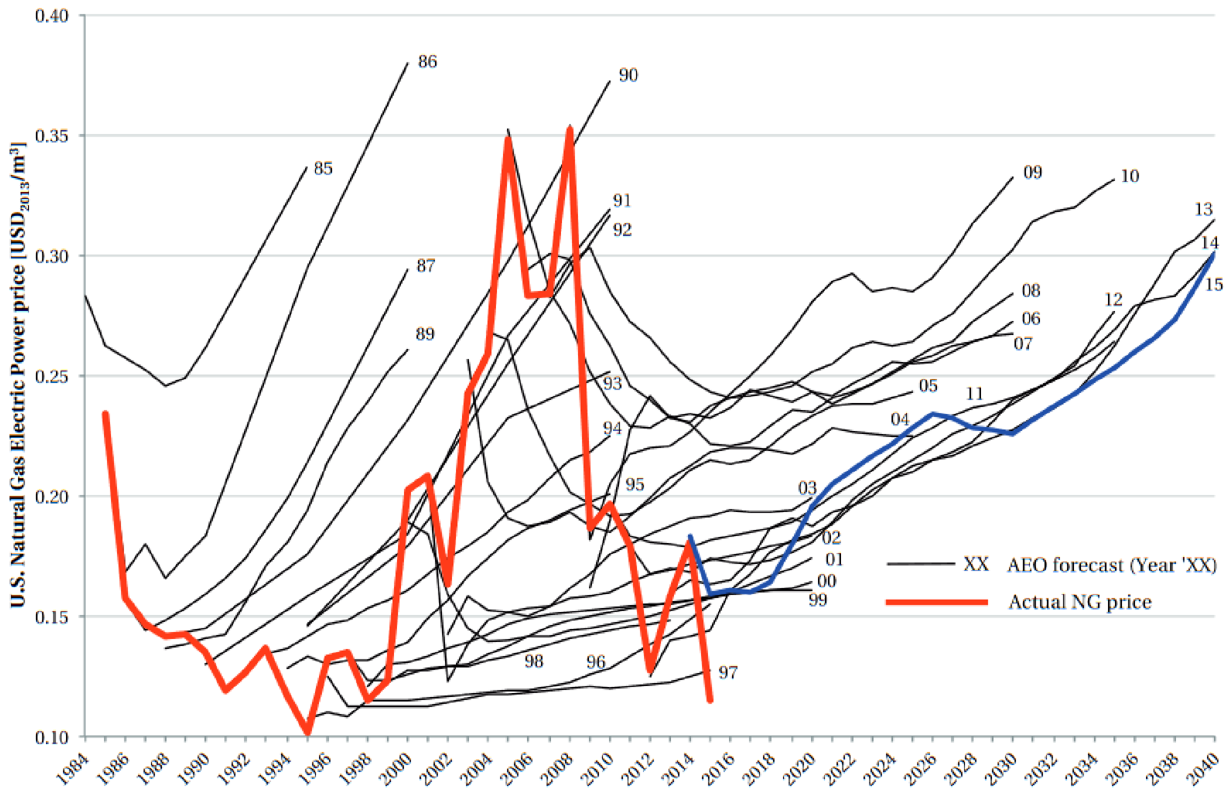


Figure 4.3: Example of differences between predictions and actual variations (natural gas price) [1]

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.

4.5 Summary

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.

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

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 4.3.3));
- 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 CO_2 taxes, and analyze the differences of the installation/operational strategies.

Appendix A

Appendix

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

Building	$\dot{E}_t^-$ **type A** [kW]	$\dot{E}_t^-$ **type B** [kW]	k_{th} [$\mathbf{W}/\mathrm{m}^2\mathrm{K}$]	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

Tables A.2 and A.4 characterize all process units and streams used the process model. The specification equations can be given as TAGS. When this is not possible, the specification is given using FLEX code.

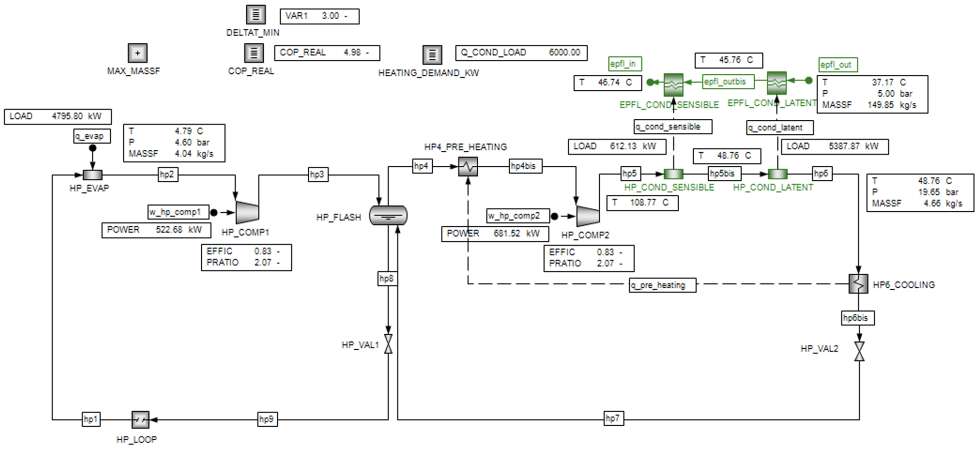


Figure A.1: Flowsheet of 2 stage heat pump developed in Belsim Vali

Table A.2: Streams of the model with their specification equations as TAGS.

Name	Type	Compound	TAGS
HP1	Material	Refrigerant	
HP2	Material	Refrigerant	Temperature = 5°C
HP3	Material	Refrigerant	
HP4	Material	Refrigerant	
HP5	Material	Refrigerant	
HP5bis	Material	Refrigerant	
HP6	Material	Refrigerant	
HP7	Material	Refrigerant	
HP8	Material	Refrigerant	
HP9	Material	Refrigerant	
EPFL_IN	Material	Water	Temperature Pressure = 5 bar
EPFL_OUT	Material	Water	Temperature Pressure = 5 bar
EPFL_OUTbis	Material	Water	Pressure = 5 bar
Q_EVAP	Thermal	-	
Q_COND_SENSIBLE	Thermal	-	
Q_COND_LATENT	Thermal	-	
W_HP_COMP_1	Mechanical	-	
W_HP_COMP_2	Mechanical	-	

Table A.3: Column name of working fluid reconciled data for project part 4

Column #	Column name
1	TAG NAME
2	MEASURED VALUE
3	MEASURED ACCURACY
4	RECONCILED VALUE
5	RECONCILED ACCURACY
6	UNIT

Table A.4: Process units of the model with their parameters and specification equations defined as TAGS and FLEX CODE. The FLEX CODE is written in pseudo-code.

Name	Function	Type	Parameters	TAGS	FLEX CODE
HP_EVAP	Evaporator	SATVAL	Vapour fraction = 1 Superheating = 3 K	Pressure drop = 0	
HP_COMP1	Compressor 1	COMVAL			isentropic efficiency
HP_FLASH	Flash	LVEVAL		Pressure drop = 0	
HP_COMP2	Compressor 2	COMVAL			isentropic efficiency comp ratio 1 = comp ratio 2
HP_COND_SENSIBLE	HEX (cooling)	SATVAL	Vapour fraction = 1 Superheating = 0 K	Pressure drop = 0	
HP_COND_LATENT	Condensor (phase change)	SATVAL	Vapour fraction = 0 Superheating = 0 K	Pressure drop = 0	
HP_VAL2	Expansion valve 2	DPVAL			pressure HP4 = pressure HP7
HP_VAL1	Expansion valve 1	DPVAL			
HP_LOOP	Close loop	CUTVAL	Thermal balance Pressure equality		
DELTAT_MIN	Pinch point temperature	FLXVAL			Temp HP5bis = Temp EPFL_OUTbis + 3°C
HEATING_DEMAND	Heat demand	FLXVAL			Load = Q_COND_SENS + Q_COND_LAT

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).