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PLUG-AND-USE RENOVATION WITH ADAPTABLE LIGHTWEIGHT SYSTEMS



**D3.6**

# Validation of the SEM system through simulation case studies

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Prepared by	Jordi Macià, Angelos Mylonas, Thibault Pean, Jordi Pascual, Jaume Salom (IREC), Athanasios Grigoropoulos (INTRA)	30/06/2023
Reviewed by project partners:	Athanasios Grigoropoulos, Ioannis Christou (INTRA), Daniel Philippen, Jeremias Schmidt (SPF)	27/06/2023

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## Terms, definitions and abbreviated terms

AL	Active Layer
API	Application Programming Interface
ConExWall	PnU kit developed by SPF
COP	Coefficient of Performance
DHW	Domestic Hot Water
eWH	External Wall Heating (ConExWall)
FE	Final Energy
HP	Heat Pump
Ir	Solar radiation
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
MINLP	Mixed integer nonlinear programming
MIP	Mixed integer programming
PE	Primary Energy
PnU	Plug and Use
RC	Equivalent electric resistor-capacitor circuit
Sh	Space heating
SC	Space Conditioning
SC%	Self-Consumption
SEM	Smart Energy Management
WG	Winter Garden

## Executive summary

This deliverable aims to demonstrate the remote implementation of SEM in efficient building control, showcasing its effectiveness in monitoring and manipulating building parameters. It offers valuable insights into the potential of SEM for enhancing overall building performance.

The Smart Energy Management system (SEM) is designed as an adaptable control system that enables efficient energy management in buildings. Its core functionality lies in optimizing energy consumption and making informed control decisions based on real-time data and predictive algorithms. In the context of the PLURAL project, SEM's primary focus is on demonstrating its remote implementation capabilities. By enabling remote control of a building without the need for physical intervention in the existing hardware, SEM offers significant advantages in terms of flexibility and scalability. One of the key components of the SEM module is the Model Predictive Control (MPC) methodology. By employing MPC, SEM utilizes predictive algorithms to optimize energy consumption and adapt control strategies accordingly. These algorithms have been developed and tested in the previous stages of the PLURAL project, specifically in T3.4. Through this deliverable, we aim to validate SEM's remote implementation and evaluate the performance of the MPC-based control system. Simulation studies are conducted to assess SEM's effectiveness in optimizing energy consumption, enhancing overall building performance, and showcasing its potential for practical application. By actively controlling Heating, Ventilation and Air Conditioning (HVAC) systems, Domestic Hot Water (DHW) system, and energy storage components within a virtual demo building, we can observe the impact of SEM on energy efficiency and system dynamics. These studies encompass different scenarios, including various seasons and simulation periods to provide a comprehensive understanding of SEM's capabilities. The outcomes of these simulation studies will contribute to the broader objectives of the PLURAL project by demonstrating the feasibility and effectiveness of SEM in remotely controlling buildings and enhancing energy management. Furthermore, the findings will provide valuable insights for practical implementation and integration of SEM in real-world applications.

Chapter 2 describes the integration and connection of the SEM algorithms developed in the Task 3.4 (Adaptation of the smart Energy Management (SEM) analytics) of the PLURAL project to the LYSIS platform, using the big data solution-StreamHandler. This combination of technologies will be included in the control Toolbox of the PLURAL solutions. The platform provides the hooks for interconnecting, storing, transforming and processing data as well as validating and executing the developed algorithms. This will provide inputs to the system management current status and for the efficiency of the equipment, their optimal operation and their interactivity. Moreover, the correct implementation and the input/outputs communication protocol between the complete system test hardware and the management system was ensured.

To achieve this goal, an entire simulation framework was put into place. The simulated systems (heat pump, storage, PV etc.) were modelled in TRNSYS software using the PYTRNSYS package for Python. The optimization part of the controller was written in the software suite OR-Tools using C++ language and coupled

to the simulation environment through the Apache Kafka libraries. The controller calculates the optimal decisions at regular intervals, using feedbacks from the PYTRNSYS models, forecasts and simplified models. This environment enables the repeatability of the simulations and a thorough comparison of the SEM system performance against a more standard controller in the same exact boundary conditions as shown in Figure 1.

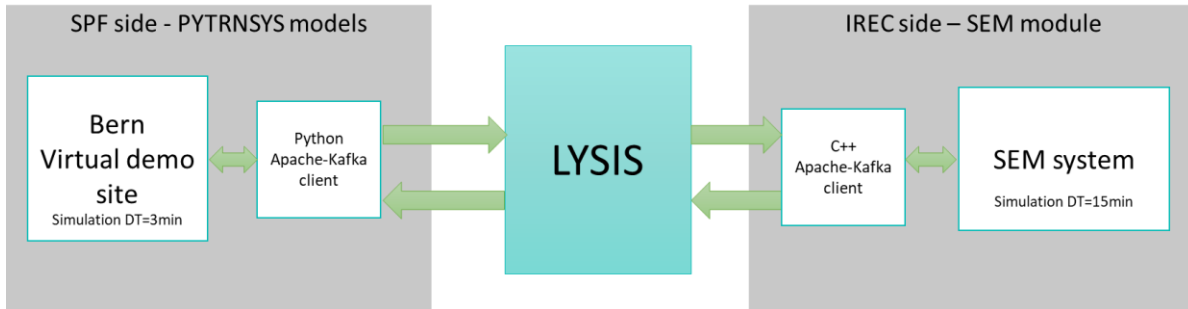


FIGURE 1. HIGH LEVEL WHOLE SYSTEM OPERATION AND DATA EXCHANGE

In chapter 3 is designed a simulation plan to demonstrate the connectivity and remote-control capabilities of the SEM system by simulating selected representative periods at the Bern virtual building demo site. These simulations included comparisons between the reference rule-based control and the SEM control. Analyzing the performance of both controllers across different weeks and seasons, the study focused on evaluating their effectiveness in achieving energy and economic savings, enhancing self-consumption, and reducing CO<sub>2</sub> emissions.

Chapter 4 presents the results, demonstrating the capability of SEM to optimize building operation. The control system exhibits high reliability in regulating the Heat Pump (HP). Successful optimization is observed across all scenarios based on the self-consumption (SC) and Final Energy (FE) criteria. While the Cost criterion sometimes falls slightly short of achieving the best possible results, the differences are minimal and comparable to other criteria. These findings confirm the effectiveness of the SEM system in achieving optimal control and highlight its potential for enhancing overall building performance. The results also emphasize the system's ability to regulate the HP with high precision and reliability, contributing to efficient energy management.

## 1. Introduction

The primary purpose of this deliverable is to provide a robust demonstration of the proof of concept, showcasing the capability to remotely implement SEM; a Model Predictive Control (MPC) based methodology for efficient building control. Through the utilization of SEM, our aim is to establish a comprehensive approach that enables remote monitoring and manipulation of diverse building parameters, thereby facilitating optimized control and management of building systems.

The use of flexibility provided by the HPs and thermal storage (including the buildings themselves) is nowadays a subject of study [1]. This combination allows to shift electrical loads of HP operation by storing heat when it is attractive. Thus, considering the inclusion of these devices in residential buildings, where there is an Energy Management System (EMS), offers improved management capabilities.

Typically, an EMS applied to a residential building with renewables integrates a HP, PV panels with an inverter, storage tanks and sometimes a battery, as an electric storage system. The energy management of this type of system is well known and in its simple version implements a control strategy based on an instantaneous self-consumption: the excess PV generation is either exported to the grid or utilized by the HP to produce hot water that is then stored in the storage tanks. A more profitable management can be considered if we integrate the buy and sell price signals from the energy markets and forecasting methods to optimally operate considering a future horizon. To achieve this, one possibility is to apply a MPC algorithm to predict the future for a defined time-horizon, thus obtaining control signals that minimize an objective function. An example of this procedure is to find the optimal strategy in terms of electricity cost savings and system performance. Depending on the underlying model, predictive EMSs integrate different forecasting methods for weather variables, demand loads as well as PV generation.

Due to the intricate nature and multifaceted components of these systems, the implementation of suitable control strategies is essential to ensure their optimal efficiency. Within the PLURAL project, a key objective was the development of a SEM system capable of effectively managing the complexity and maximizing system performance. The SEM component is developed based on the MPC methodology built on simplified models of the distinct items of the building components, involving the iterative solution of an optimization problem and ensuring at the same time results robustness and operativity of the whole system. Thus, this optimization problem necessitates simplified models of the systems to predict their behaviour under various scenarios, real-time measurements of system dynamics, and forecasts of external factors such as weather conditions, occupancy and domestic appliances patterns and schedules, DHW demand, and electricity prices. By leveraging this information, the SEM system determines the optimal trajectory for the systems over a predefined prediction horizon (e.g., 24/72 hours ahead). The initial control actions derived from this optimal trajectory are implemented in the systems until the SEM system controller is invoked in subsequent iterations every 15 minutes. Figure 2 demonstrates the high-level scheme of the sequence of operations and data



exchange between the two involved sides as foreseen for the Bern virtual demo site, as the one used as a proof of concept of the present T3.5.

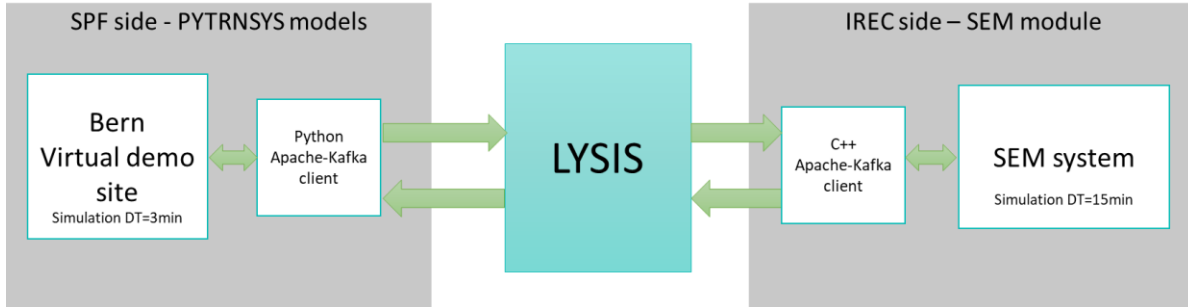


FIGURE 2. HIGH LEVEL WHOLE SYSTEM OPERATION AND DATA EXCHANGE

The models and algorithms of the SEM system have been previously developed and assessed through individual instances of the optimization problem in the D3.4 [2]. Subsequently, the emphasis was placed on practically implementing the outputs of the SEM controller within the simulated systems. This facilitated the observation of system responses and the analysis of how the controller interpreted and responded to feedback over an extended period. The present report presents the findings of this co-simulation, which involved integrating the dynamic system simulation framework with the optimization model.

This deliverable provides a comprehensive description of the integration and interconnection process of the algorithms developed for the SEM system as part of T3.4 within the PLURAL project, to the controller of the Bern virtual demo site via the LYSIS platform. The integration involves incorporating these algorithms into the LYSIS platform, leveraging the big data solution-StreamHandler for seamless connectivity and data management. The functionality and performance of the SEM system will be evaluated through its integration with a simulation environment. This evaluation process aims to highlight the advantages of remotely applying the SEM system, specifically in terms of building control without the need to physically modify the existing hardware infrastructure. The focus is on leveraging the building's existing Building Management System (BMS) for efficient control and optimization.

The complete systems under investigation were simulated using the PYTRNSYS software for the Bern virtual building demo site located in Switzerland. The SEM system was configured separately and integrated with the corresponding PYTRNSYS models (description can be found in D3.3 [3]) to enable the application of the SEM control outputs within the simulation environment. This approach facilitated the repetition of simulations under identical boundary conditions while employing different control strategies. To compare the performance of different controllers, simulations were conducted in two iterations: first with a reference "state-of-the-art" rule-based control, and secondly with the SEM control. To simplify the analysis, specific weeks during the winter and spring seasons were selected as simulation periods.

The tool is founded on the principle of real-time optimization of the target system under control, encompassing the scheduling of consumption, storage, and power generation activities. This optimization is achieved by the implementation of the subsequent functionalities:

- It possesses the capability to effectively handle real-time measurements obtained from the electrical network-connected equipment.
- It is capable of making real-time decisions regarding the behaviour of the equipment in order to optimize user objectives, such as minimizing economic costs.
- Utilizes weather forecasts, energy prices, and projected consumption data to conduct an optimization process.

These new functionalities will provide advanced management flexibility and optimize the operation of the building energy system while pursuing an occupant-specific target such as cost reduction, thermal comfort, or maximization of onsite renewable energy use.

The remote implementation of SEM control serves as a demonstration to showcase the feasibility and effectiveness of incorporating SEM as a valuable component. This demonstration provides valuable insights into the practical application of SEM in improving overall building performance.

## 2. Simulation environment

The main elements comprising the simulation environment are the PYTRNSYS building model, the SEM system module and the LYSIS module. The Bern building virtual demo site was developed in PYTRNSYS to emulate the thermal and electric elements of the air-source HPs, the DHW and Space Conditioning (SC) tanks, the radiant wall heating systems ConExWall, and its constituent elements, as well as the PV panel installations. This environment accommodates the presence of either the SEM control system or a reference control procedure (rule-based). The simulation software handles both the reference control and the system simulation, while the simulated SEM is formulated and executed using OR-Tools and the C++ programming language, which is invoked from PYTRNSYS. The LYSIS module accommodates the communication and data exchange and management between the SEM system and the PYTRNSYS building module. In essence, it is the intermediate layer between the two aforementioned components. Figure 2 above shows a high-level overview of the simulation environment and the related components.

The simulation environment includes:

- the PYTRNSYS simulation module, which performs dynamic simulations of the systems (using one of the two control options, reference or SEM).
- SEM, as an optimization module, that generates optimal planning results.
- the LYSIS – StreamHandler modules that is responsible for the data exchange between the building model (PYTRNSYS module) and the optimization solver. The data exchange is based on the Apache Kafka stream processing platform and includes:
  - Weather data from the Bern demo site to the optimization module
  - Data regarding the initial states of the building and its components. In particular, the interior air temperature, the Active Layer (AL) temperature, the wall temperature and the DHW and SC tank temperatures at the initial instants of the optimization runs.
  - Optimization data from the SEM system to the PYTRNSYS Bern module. This data contains optimal temperature setpoints according to which the building will be controlled.
- The data folder comprises environmental time series, load profiles, internal gains, and electricity price profiles utilized in the simulation and forecasts of the SEM system. It is noteworthy that the data utilized in both the simulation and SEM forecasts are identical, as the studied cases assume perfect forecasts.

The entire simulation environment can be executed either manually or through the utilization of the PYTRNSYS package. The PYTRNSYS module sends the current simulation time and state to the optimization module (SEM at the beginning of the execution and each 15 minutes of simulation time, via LYSIS the current simulation time and state to the optimization module (SEM). The same module passes the simulation data (weather forecast and relevant time series) to generate the associated planning problem for the following

24/72 hours. Then, the optimizer operates and finally returns the optimal solution (temperature set-point values) to the PYTRNSYS building module via the LYSIS platform.

Figure 3 depicts the execution flow of the simulation environment in the reference scenario. In that case, the simulation environment loads the configuration, the implemented Types, the required data from the external files and executes the simulation. The reference control rules are implemented using the custom TRNSYS Type 888, included in the simulation module (further description in section 2.2).

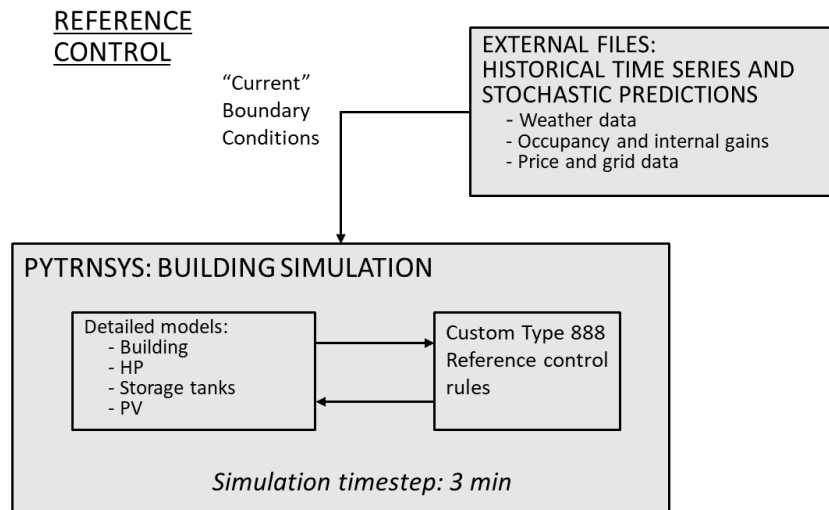


FIGURE 3. SIMULATION ENVIRONMENT MODULES IN THE REFERENCE CONTROL CASE.

If the control strategy is based on the SEM system, it incorporates an optimization module, as shown in Figure 4. The optimization module is invoked from the simulation at the start of the execution and every 15 minutes of simulation time. Upon invocation, the SEM system reads the current simulation time and state to an external file and subsequently performs the optimization procedure. The SEM module begins by reading the simulation data to formulate the corresponding planning problem for the next 24/72 hours. It then produces the optimal set-points, which subsequently via LYSIS to the PYTRNSYS module. Further details of this module can be found in section 2.1. As the optimization module is located outside the simulation module, the simulation execution is paused until the optimization procedure ends.



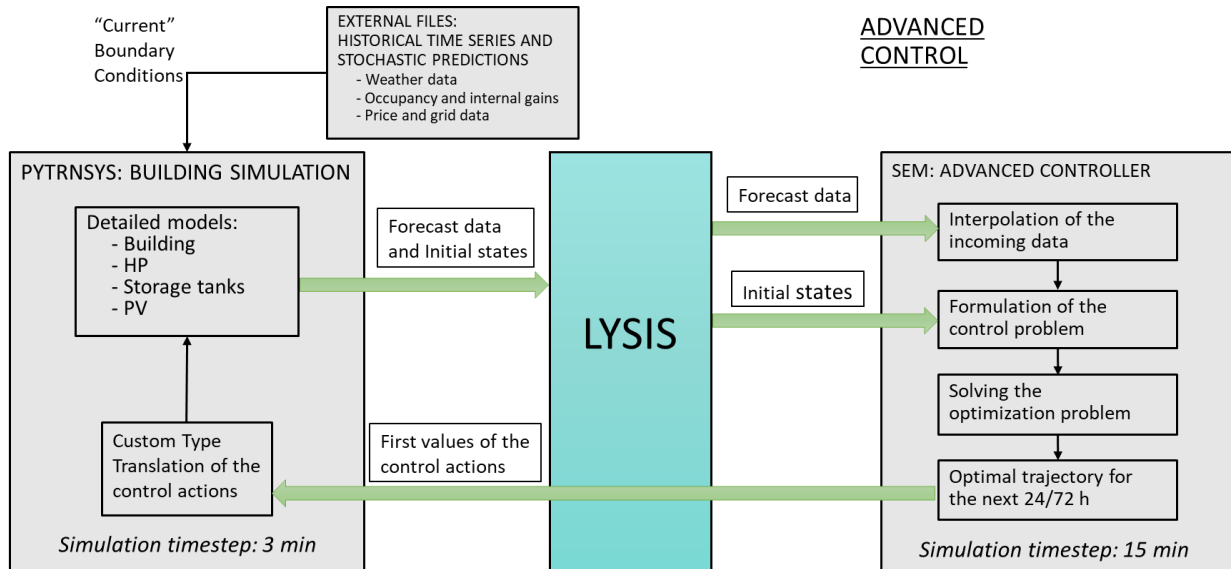


FIGURE 4. SIMULATION ENVIRONMENT MODULES IN THE SEM CONTROL CASE.

Finally, in both cases, the data of the weather and the relevant time series falls outside the modules' frame and it does not change along the simulation execution. The forecast data passed from the PYTRNSYS module to the optimization module is calculated according to the interpolation methodologies based on initial realistic data contained in the PYTRNSYS module. These data have been validated against existing data which reassures that the optimization module makes perfect use (ideal) forecasts and runs as if it had a perfect knowledge on the future disturbances. As a consequence, the impact of the SEM system in a real-life environment could decrease when using imperfect forecasts that are updated along the simulation. The quantification of the uncertainty of imperfect forecast is outside the scope of the present project.

## 2.1 SEM

The SEM system was designed based on three main steps: 1) modelling and validation of the components' behaviours of the Bern virtual demo site, 2) definition of the optimization criteria, and 3) testing under realistic and wide scenarios where it operates in a variety of possible situations that it can find [4], [5].

### 2.1.1 SEM optimization tool

The purpose of the SEM system is to provide optimal set-points to the controllable components within the installation, based on the outcomes of previously conducted individual optimization problems. At regular intervals of 15 minutes throughout the simulation period, the SEM system is invoked to assess the system's current state, update forecasts for the subsequent 24/72 hours, and solve the corresponding optimization problem [4]. Upon returning to the simulation, the installation retrieves the optimal power set-points for the



current simulation time and translates them into control actions for the relevant components. This process continues until the next invocation of the SEM system.

The existing building reference control system assumes the responsibility of providing a business-as-usual approach to determine the fundamental actions of the controllable components within the installations. This approach is structured as a decision tree that calculates its control actions based on factors such as the seasonal mode, system temperatures, and overall status. The main objective of the reference control is to utilize its outcomes for the purpose of comparing and validating against the SEM results, rather than showcasing the performance of the SEM.

### 2.1.2 SEM structure

The structure of SEM with its workflow and elements related is depicted in Figure 5. The core of the SEM system are the simplified models, formulated as Mixed Integer Linear Programming (MILP) equations which are solved by the optimization algorithm according to the computational requirements. As inputs, the system needs the forecasting of the occupancy and appliances profiles, weather conditions, as well as the initial statuses of the models with the measurements on-site. As an output, the SEM provides the optimized values, that in this case are the thermal energy flows from the HP to the DHW and SC systems. This output can be either sent to the real facilities, or to a visualization program to advise the facilities operator.

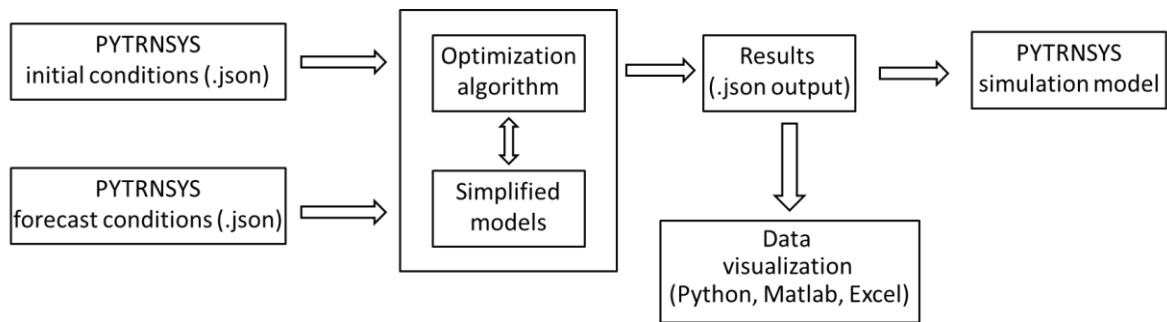


FIGURE 5. HIGH LEVEL SEM STRUCTURE.

In the first step, the model is expressed as a MILP optimization problem formulated in OR-Tools [6] in C++ language as modelling environment. OR-Tools is an open-source software suite for optimization, tuned for tackling the world's toughest problems in vehicle routing, flows, integer and linear programming, and constraint programming [6]. Besides, the model and the data work together, the data could be easily modified without changing the model which enables to test different scenarios quickly. There are many other modelling language providers such as AMPL, LINGO, AIMMS, OPL [7], etc. However, OR-Tools was chosen due to the complex structure of the energy management systems which allows to create a highly compact mathematical model that can be adjusted to this environment. In the context of conducting tests across

multiple scenarios, the utilization of OR-Tools proves to be suitable for facilitating the creation and management of data in a relatively straightforward manner. To solve the MILP problem, the SCIP solver (version 8.0.3) was chosen. SCIP is currently one of the fastest non-commercial solvers for Mixed Integer Programming (MIP) and Mixed Integer Nonlinear Programming (MINLP). It allows for total control of the solution process and the access of detailed information down to the core of the solver [8], [1].

The SEM system runs an iteration every 15 minutes of the PYTRNSYS simulation. The communication between the PYTRNSYS and the SEM system is done via the LYSIS StreamHandler solution that utilizes the Apache Kafka protocol. So, until the initial and forecast data is passed from the PYTRNSYS module to the SEM module for optimization, the optimization data produced during the previous time-step is sent back to the PYTRNSYS module again via the LYSIS StreamHandler solution. Once it is called, the optimization module reads the current simulation time and relevant inputs and performs the tasks depicted in Figure 6.

- First, it extracts the appropriate initial conditions - temperatures, forecasts regarding the weather and environmental conditions, load profiles (DHW load, building internal gains, electric load of appliances excluding HVAC) and electricity prices for the 24/72 hours following the current simulation time.
- Then, it reads the configurational data of the installation components. Those configurational parameters correspond to the values of the different parameters (building characteristics, heat pump performance etc.), as well as their restrictions (minimum indoor temperature, maximum HP power etc.).
- Following, it reads the initial conditions that were communicated by PYTRNSYS: ConExWall temperatures, building interior air temperature and tank temperatures.
- As a last step, using all these data, it builds the optimization formulation of each of the system components and assembles it altogether into a planning optimization problem.

The resulting optimization problem is a Mixed-Integer Linear Problem (MILP) model written in the optimization software suite OR – Tools in C++. Once the problem is generated, the optimization module calls the optimization solver SCIP.

Finally, once the solver has finished, the optimization module passes the optimal setpoints found during the optimization procedure in JSON file format via the LYSIS platform to the PYTRNSYS module. At the same time, all the optimization results are written in an output file for validation purposes. In this simulated environment there is no delay since the PYTRNSYS module waits until the optimization finishes. Therefore, the component set-points are always applied already from the first-time interval solution. In reality, the computation time takes several minutes, and the set-points can only be applied after finishing the optimization and with a certain delay, whereas the systems keep operating while the optimization is being processed.

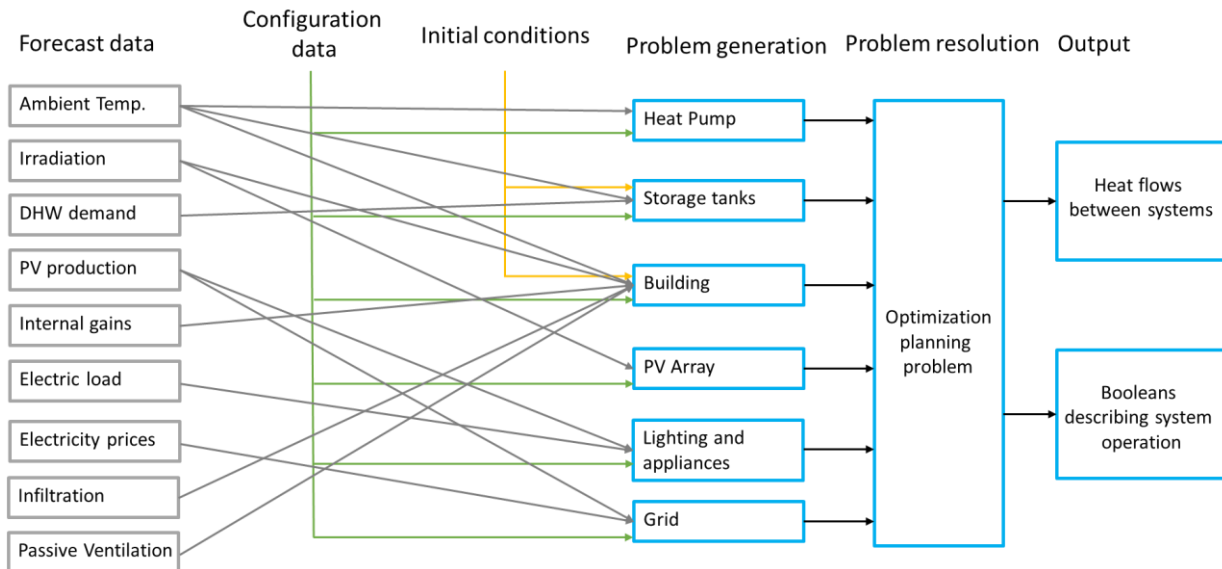


FIGURE 6. OPTIMIZATION MODULE PROCESSES

### 2.1.3 Objective function

As it was described in detail in D3.4 [2], the purpose of this optimization problem is to obtain an optimal planning of the electric and thermal actions of the system along certain time horizon. The optimization criteria that have integrated in the SEM are, the following:

- Self-consumption (**SC**): Maximize the use of the energy from the PV produced on-site. It is calculated based on the difference between exported and imported from the grid energy.
- CO<sub>2</sub> emissions (**CO<sub>2</sub>**): Minimize the emissions due to building's operation. They are computed according to the energy imported from the grid, applying a coefficient for the emissions per kWh.
- Cost (**Cost**). Minimize the electricity costs. It is calculated based on the energy imported from the grid, the energy exported to the grid and the buying and selling prices.
- Final energy (**FE**) Minimize the final energy used by the building. It is based on the sum for the energy used for SP and DHW needs.

## 2.2 Simulation models: PYTRNSYS and Simplified models

The PYTRNSYS module contains the Bern virtual demo site of the building model and its systems and services (HVAC, DHW, distribution systems, tanks, PVs etc.). Similarly, the active building components mentioned earlier were modelled using equations. These equations represent the behaviour and characteristics of the components in a simplified manner, allowing for computational modelling and analysis. By utilizing these mathematical models, the performance and interactions of the active building components can be simulated and studied in a more efficient and manageable way. Likewise, the building was represented using a



simplified Resistance-Capacitance (RC) model. This model captures the dynamic thermal behaviour of the building by dividing it into a series of thermal resistance and capacitance elements. All these dynamic elements of the Bern virtual demo site can be controlled either via the reference controller, which in this case is a rule-based controller, or via the SEM system controller.

The PYTRNSYS package, details of which can be found in D3.3 [3] offers a comprehensive framework for the execution, processing, visualization, and reporting of TRNSYS simulations. Its purpose is to provide researchers with a streamlined, automated, and replicable approach to conducting and disseminating TRNSYS simulations through the utilization of a concise configuration file. Moreover, the package offers a wide range of commands for efficient post-processing of simulation outcomes. The package was developed at the SPF - Institute for Solar Technology at the OST - Eastern Switzerland University of Applied Sciences.

The simulation module consists of the TRNSYS models of the overall systems. The models of the individual components are put together using the open source PYTRNSYS package in Python [9]. This tool enables to create a single input file (DCK file) that can be run with TRNSYS, using individual DDCK files describing the separated components. A Graphical User Interface (GUI) is used to facilitate the creation of the links between the different parts of the hydraulic and thermal systems and ensure that the mass flow balances are respected in every circuit. The DDCK files describing each individual component are then parameterized to reflect the actual behaviour of the systems, e.g., by changing the fitting coefficients of the performance curve of the heat pump and the size of its nominal capacity. The documentation of the PYTRNSYS simulation environment can be found online at <https://pytrnsys.readthedocs.io/en/latest/> and can be downloaded from the SPF-OST GIT web page at <https://github.com/SPF-OST>.

### 2.2.1 Bern demo site and systems

The Bern building is a typical four storey multi-family house located in Bern (Switzerland), divided in two blocks: number 43 and 43a. Unlike the other demo cases, the building has already been renovated with the selected PLURAL technology (i.e., ConExWall) in 2019 but on a low prefabrication level (hence, “existing state” means in this case before this renovation). There were two oil boilers (one boiler for each building) for space heating and electrical heaters for domestic hot water preparation. Only one of the two building parts (part 43a) is equipped with a centralized ventilation system with heat recovery. The ConExWall Plug-and-Use (PnU) kit is incorporated in prefabricated timber walls. Innovative windows (with ventilation unit integrated in the frame) and PV panels on the roof and on the walls of the building complete the renovation concept. Detailed description of the building, its systems and services can be found in D3.4 [2].

Figure 7 shows the image of the Bern building from the southwest and northwest facades.



FIGURE 7. BERN BUILDING EXTERIOR VIEWS AFTER PLURAL RENOVATION IN 2019.

The demo building of Bern has been already renovated with a preliminary version of the ConExWall. The implemented measures are:

#### Passive

- High external insulation ( $U_{wall} = 0.13 \text{ W/m}\cdot\text{K}$ )
- Airtightness. The building infiltration is reduced to  $0.15 \text{ m}^3/\text{m}^2\cdot\text{h}$ .
- A winter garden in the south façade, which acts as a sun collector.


#### Active

- ConExWall, an external wall distribution system
- Ventilation system
- The production of renewable electricity (PV)
- Two Heat Pumps that replaced the oil boilers, one per each block.
- Six storage tanks: two for space heating and four for the DHW.

The implementation of all the measurements mentioned above resulted in a highly efficient building with a space heating demand of  $11.03 \text{ kWh/m}^2\cdot\text{year}$ .

### 2.2.2 SEM - Simplified model overview

A computationally efficient SEM based on Model Predictive Control (MPC) relies on very fast numerical models for the components and the complete system. Thus, the models used in the simulation framework such as TRNSYS are not adequate. A simplification of each component model is necessary in order to be able

	<p>This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958218</p>	<p>18</p>
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to calculate many possibilities each time the optimization algorithms try to find the optimal solution for a specific target. The simplified models used were developed in T3.4 and are described in detail in D3.4 [2]. They are:

- a) RC model. It calculates the behaviour of the whole building as a single entity, using the weighted average temperatures of the zones air ( $T_{in}$ ), the solid mass ( $T_{wall}$ ) and the active layer. In Figure 8 is presented the diagram of the R3C3 model of the building, together with the rest of the systems. The state-space model can be expressed in a matrix equation such as Eq. (1). Where matrixes A and B are made of RC parameters in the form of Eq.(2) and Eq.(3).

$$\dot{x}(t) = A \cdot x(t) + B \cdot u(t) \quad (1)$$

$$A = \begin{bmatrix} -\frac{1}{R_{int} \cdot C_{int}} - \frac{1}{R_{ext} \cdot C_{int}} & -\frac{1}{R_{int} \cdot C_{int}} & 0 \\ \frac{1}{R_{int} \cdot C_W} & -\frac{1}{R_{int} \cdot C_W} - \frac{1}{R_W \cdot C_W} & \frac{1}{R_W \cdot C_W} \\ 0 & \frac{1}{R_W \cdot C_{AL}} & -\frac{1}{R_W \cdot C_{AL}} \end{bmatrix} \quad (2)$$

$$B = \begin{bmatrix} \frac{1}{C_{int}} & 0 & \frac{1}{R_{ext} \cdot C_{int}} & 0 \\ 0 & \frac{g \cdot A}{C_W} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{C_{AL}} \end{bmatrix} \quad (3)$$

Table 1 shows the identified parameters during the calibration, and. This model was developed in T3.4 and calibrated with the TRNSYS model, with an adjustment of 1.7% NRMSE.

TABLE 1. RC PARAMETERS IDENTIFIED FOR THE BUILDING MODEL.

$C_{int}$ [kW/K]	$R_{int}$ [m <sup>2</sup> K/kW]	$C_W$ [kW/K]	$R_W$ [m <sup>2</sup> K/kW]	$C_{AL}$ [kW/K]	$R_{ext}$ [m <sup>2</sup> K/kW]	$gA$ [m <sup>2</sup> ]
0.21102	0.03125	421.4972	0.74510	27.2333	1.34329	98.69

- b) An RC model for the heat storage tanks based on the physical properties in the datasheet of the manufacturer.
- c) HP model based on TRNSYS model equations, and it was adjusted with a linear regression to the performance chart supplied by the manufacturer.
- d) PV model based on TRNSYS using a simplification developed in PVGIS free calculation software which consists of 6 coefficients that depend on the type of PV panel technology used.



Figure 8 presents an overview of the simplified models comprised in the Bern virtual demo site.

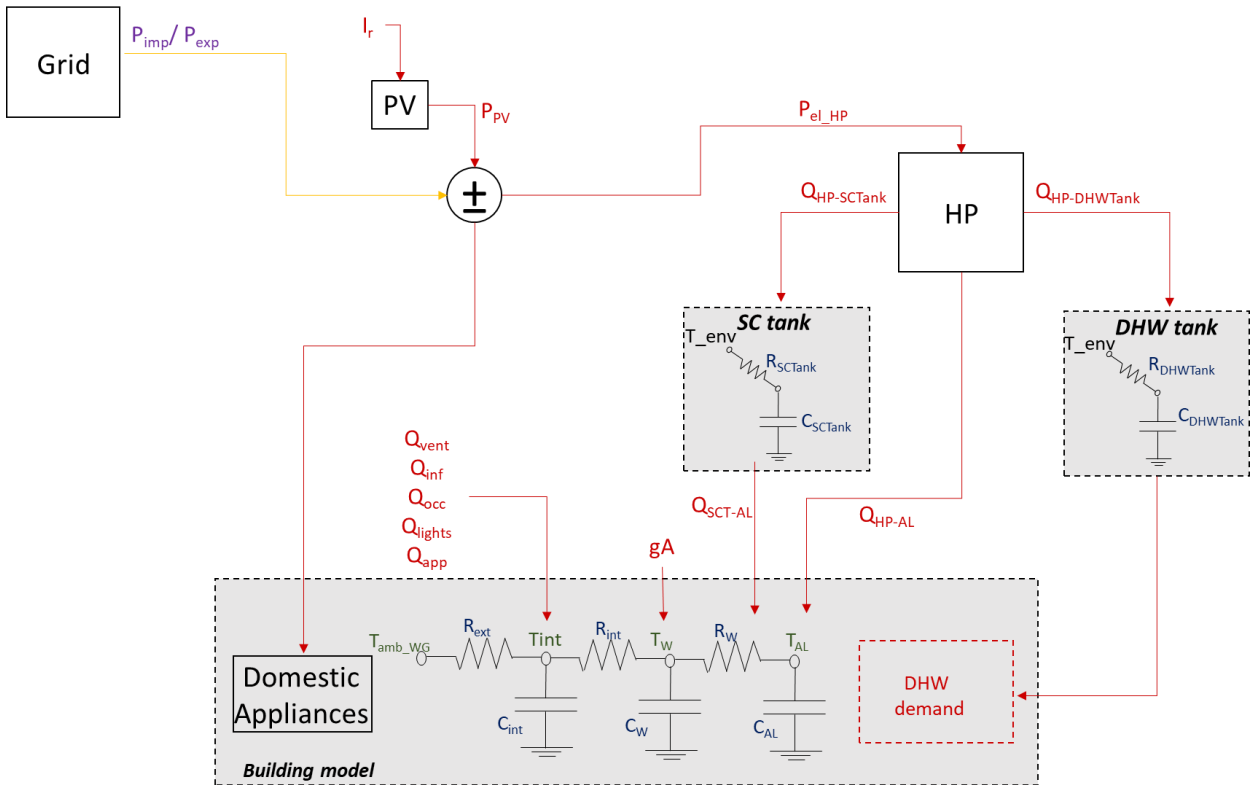


FIGURE 8. SIMPLIFIED MODELS SCHEME FOR THE BERN DEMO SITE.

### 2.2.3 PYTRNSYS model

The Bern virtual demo-site was simulated with a PYTRNSYS model based on TRNSYS. This model consists of these components:

- Type 56: Multi-zone building
- Type 977: Compression Heat Pump Model
- Type 194: PV module for the 8 PV fields
- Type 888: Heating control to manage the HP and the storage tanks
- Type 1925: Plug flow tank for the two tanks of space heating and DHW
- Type 1630: A modified version of type 163 that connects with Python script that link with the LYSIS and SEM.
- Type 9351: A hydraulics solver to calculate temperatures and mass flowrates of all the hydraulic elements in the system. This type comes exclusively from the PYTRNSYS module and counts with its own GUI in order to provide an easier design and analysis tool. Figure 9 shows the layout of the Bern-



demo site hydraulics installation consisting of the HP, two storage tanks (Sh and DHW) and the active layer loops for the walls of each zone.

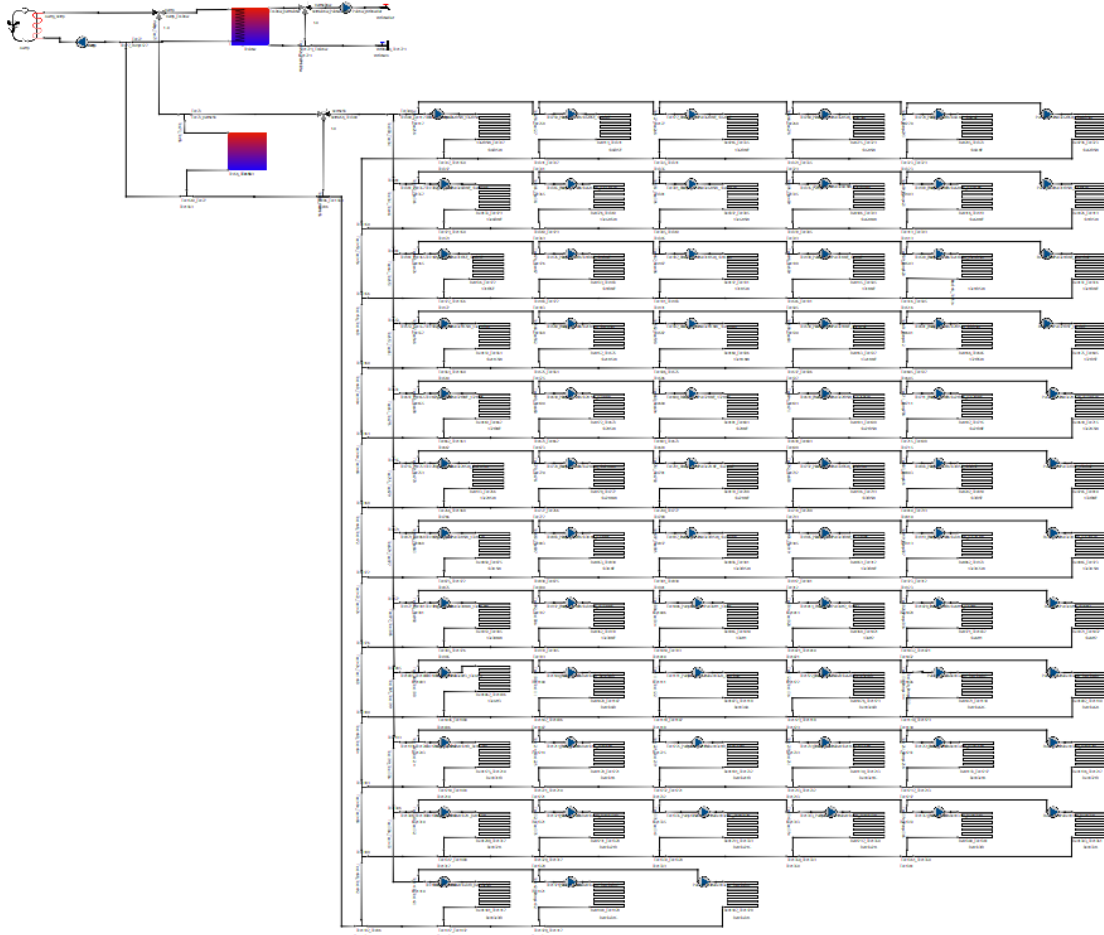


FIGURE 9. SCHEMATICS OF THE HYDRAULICS IN THE BERN DEMO-SITE (FROM PYTRNSYS GUI).

## 2.3 LYSIS integration

Lastly, the LYSIS platform forms the communication layer that facilitates the interactions between the SEM system and the PYTRNSYS model of the Bern virtual demo site. It is responsible for the data transmission between the SEM system and the PYTRNSYS building model.

### 2.3.1 LYSIS platform

As described in the D5.2 [10] PLURAL proposal, the data management needs of the PLURAL project will be served by the LYSIS platform. The basis of the LYSIS platform is the StreamHandler platform (sometimes abbreviated as SHP), developed by INTRA for similar project needs. The LYSIS platform servers as a data



management layer that will satisfy the data exchange needs of the SEM system. LYSIS itself is built around Apache Kafka [11], which is an open-source, high-performance, distributed event-streaming platform following a topic-based publish/subscribe messaging pattern. It is used both for facilitating the asynchronous, loosely coupled interaction between the different components by defining respective Apache Kafka topics and configuring them accordingly, and for offering the long-term storage of data for post-processing activities. Extensive information regarding the LYSIS platform and description of its functionalities can be found in D5.2 [10] and D3.2 [12].

Figure 10 demonstrates a general overview of the data management layer (LYSIS).

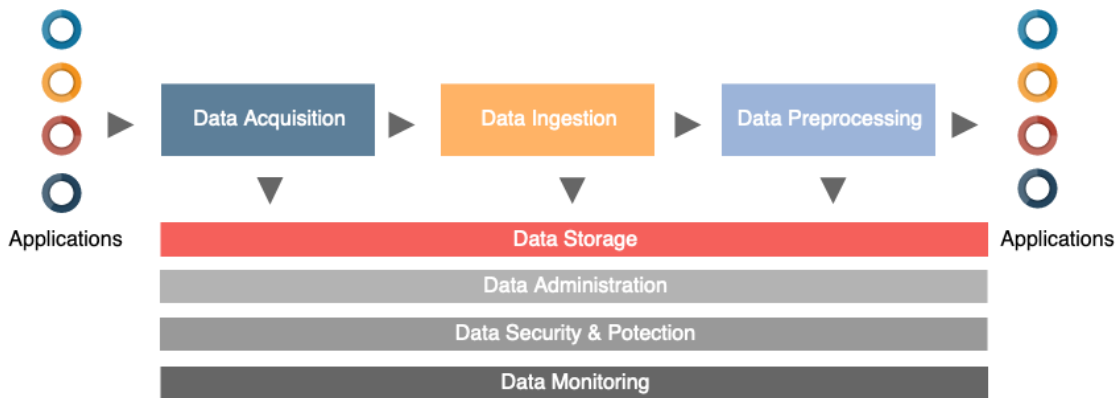


FIGURE 10. DATA MANAGEMENT LAYER

Figure 11 shows the SEM-TRNSYS architecture communication.

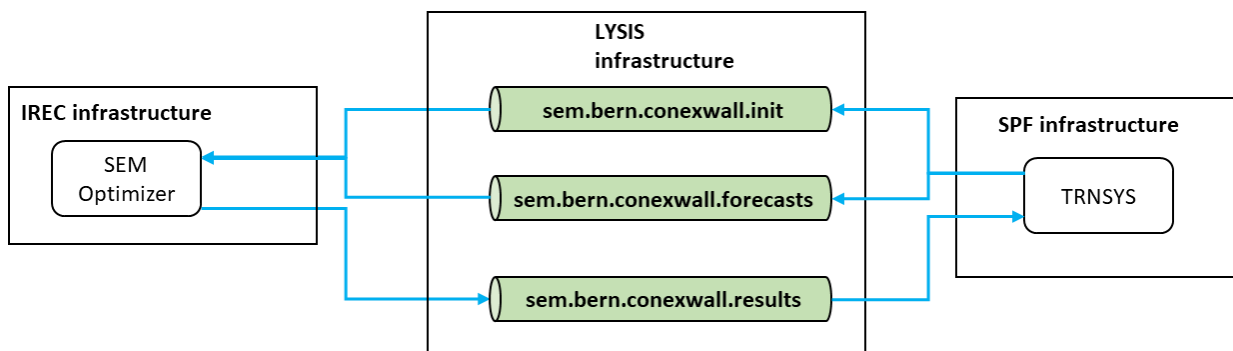


FIGURE 11. LYSIS ARCHITECTURE OVERVIEW

## 2.3.2 LYSIS integration in SEM

### 2.3.2.1 Apache Kafka

The Apache Kafka cluster comprises of multiple Kafka brokers, which collaborate to establish load balancing, reliability, redundancy, and failover mechanisms. These brokers undertake the responsibility of storing incoming data and facilitating the essential functionalities for data producers and consumers. In Kafka, information is stored as streams of messages or records organized under specific categories known as Topics. A Kafka record comprises of a key, representing the data producer-provided value, and a timestamp, appended by Kafka. While the key may be optionally provided, the timestamp is automatically added by Kafka. For the purposes of the project, the implementation of consumers and producers was specifically carried out using the C++ programming language. Figure 12 presents the sequence of operation in the form of a flowchart for the entire SEM operation, including the optimization module, the Boundary Conditions (BC) function and the Kafka Producer and Consumer modules that are responsible for the data communication. All the depicted functionalities were implemented in C++.

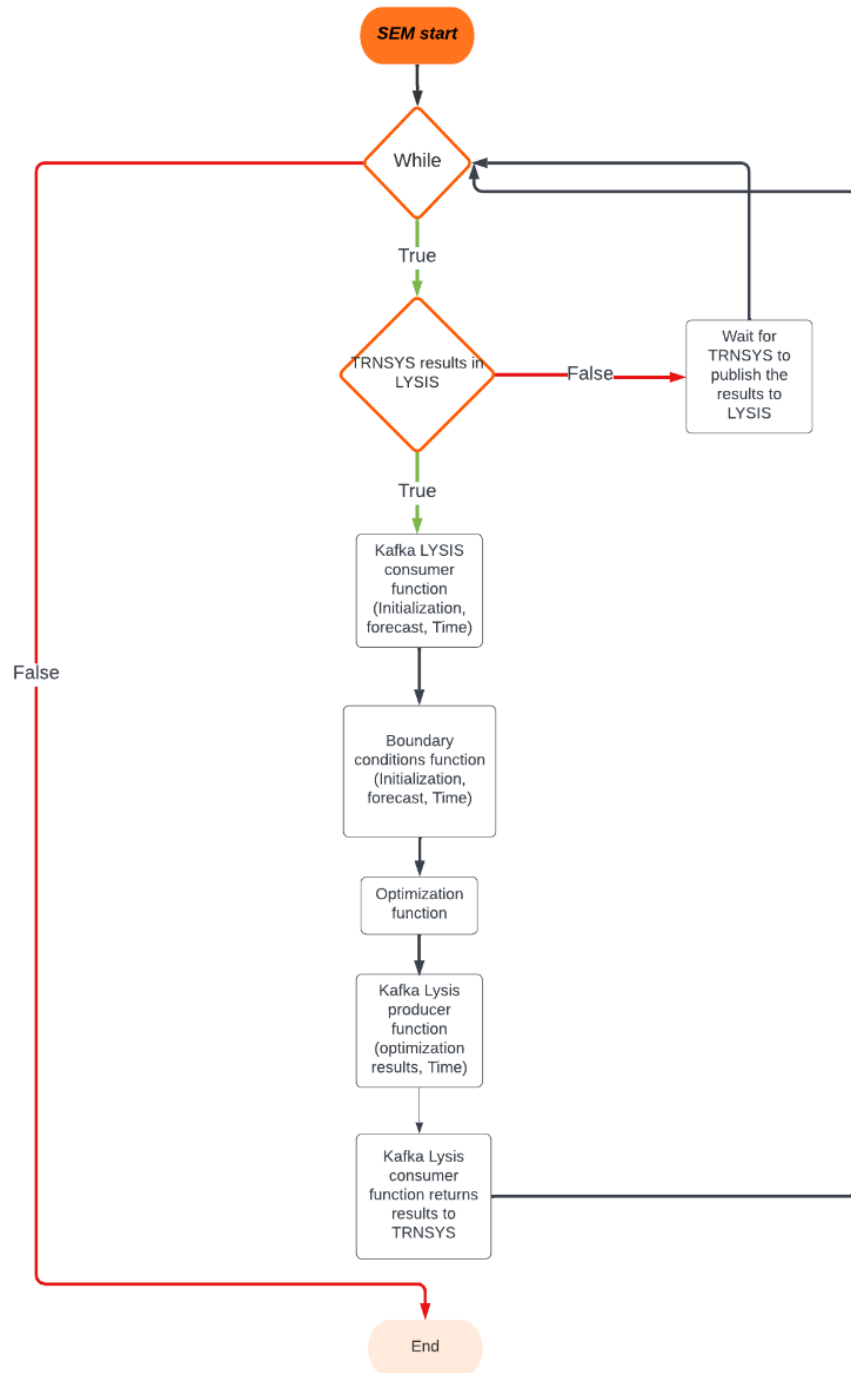


FIGURE 12. FLOWCHART OF THE ENTIRE SEM OPERATION.





### 2.3.2.2 Kafka Producer

The Kafka Producer API is a component of the Kafka client library that enables developers to create applications that publish messages to Kafka topics. It provides a set of functions and methods that allow Producers to send data records to Kafka brokers for storage and subsequent consumption by consumers. The Kafka Producer API allows users to configure various aspects of message production, including specifying the Kafka cluster's broker addresses, serialization and deserialization of message payloads, and handling of acknowledgments and message retries. To use the Kafka Producer API, users typically initialize a producer object, configure it with the necessary settings, and then use the provided functions or methods to send messages to specific topics. The API supports both synchronous and asynchronous message sending modes, providing flexibility based on the application's requirements.


In our case, the Kafka Producer plays a crucial role in the communication flow between the TRNSYS-based virtual building (SPF) and the SEM module (IREC) via the LYSIS interface. The Producer is tasked with selecting and transmitting the initialization and forecast conditions generated by TRNSYS from the SPF side to the SEM module. It is responsible for converting the chosen message into an appropriate format to ensure successful transmission, reception, and interpretation by the Kafka Consumer.

Once the SEM module receives the message through the Kafka Consumer and the optimizer completes the optimization process, which is determining the optimal building setpoints, the Producer is again responsible for transmitting the resulting message back to the virtual building module. This allows the optimal setpoints to be applied within the virtual building. The Producer accomplishes this by sending the message via the LYSIS interface.

Overall, the Kafka Producer plays a crucial role in facilitating the exchange of data and instructions between the virtual building and the SEM module, enabling effective coordination and optimization of the building's performance.

### 2.3.2.3 Kafka Consumer

The Apache Kafka Consumer API is a component of the Kafka client library that allows developers to create applications that consume messages from Kafka topics. It provides a set of functions and methods that enable consumers to retrieve and process data records that have been published by producers to Kafka. The Kafka Consumer API allows users to configure various aspects of message consumption, including specifying the Kafka cluster's broker addresses, the topics to subscribe to, and the desired offset management strategy (e.g., earliest, latest, specific offsets). To use the Kafka Consumer API, users typically initialize a consumer object, configure it with the necessary settings, and then use the provided functions or methods to subscribe to specific topics and retrieve messages from Kafka. The Kafka Consumer API supports both manual and automatic message consumption modes, providing flexibility based on the application's requirements. Consumers can retrieve messages individually or in batches, and they have the ability to commit their current position (offset) in the Kafka topic to ensure reliable processing and prevent message duplication. The

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Consumer API also supports parallel processing and allows for the distribution of workload across multiple consumer instances within a consumer group.

The Kafka Consumer component fulfils essential functions within the communication flow between the TRNSYS-based virtual building (SPF) and the SEM module (IREC) via the LYSIS interface. The consumer's primary task is to receive the initialization and forecast conditions selected and transmitted by the Kafka producer from the SPF side to the SEM module. By employing the Kafka consumer API, it interprets the received message, allowing for successful reception and further processing. Once the SEM module receives the message through the Kafka consumer, the optimizer performs the optimization process to determine the optimal building setpoints. The consumer then retrieves the resulting message containing the optimized setpoints and transmits it back to the virtual building module using the LYSIS interface. This facilitates the application of the optimal setpoints within the virtual building. Through its involvement in the communication flow, the Kafka consumer significantly contributes to the effective coordination and optimization of the building's performance by enabling seamless data exchange and instruction execution between the virtual building and the SEM module.

### 2.3.3 LYSIS integration in TRNSYS

The integration of LYSIS in the TRNSYS model is carried out using Type 1630, which is a modified version of Type 163. This Type executes a Python script when called, which is in charge of communicating with LYSIS. This Type was modified to only call the Python script at the first iteration every 15 minutes of simulation, instead of at every time iteration of every time step, which is resource consuming and useless in the present case. The communication between TRNSYS and Python is done through reading/writing/input/output text files, so until the next optimization is performed, the output values of the Type 1630 remain the last optimization set points written in those text files. Once it is called, the optimization module reads the current simulation time, and performs the tasks depicted in Figure 13 as described below:

- It extracts the appropriate forecasts of environmental factors (ambient and ground temperature, irradiation), load profiles (DHW load, building internal gains, electric load of appliances excluding HVAC) and electricity prices for the 24 hours following the current simulation time.
- Writes the current simulation values of temperature into a file which will be used as initial values for the SEM.
- Calls the Python script which sends the values to LYSIS with the Apache Kafka-producer module and waits until receives the answer back from SEM.
- Then writes the SEM results in a file so Type 1630 can read them and send them back to TRNSYS so the simulation can continue.



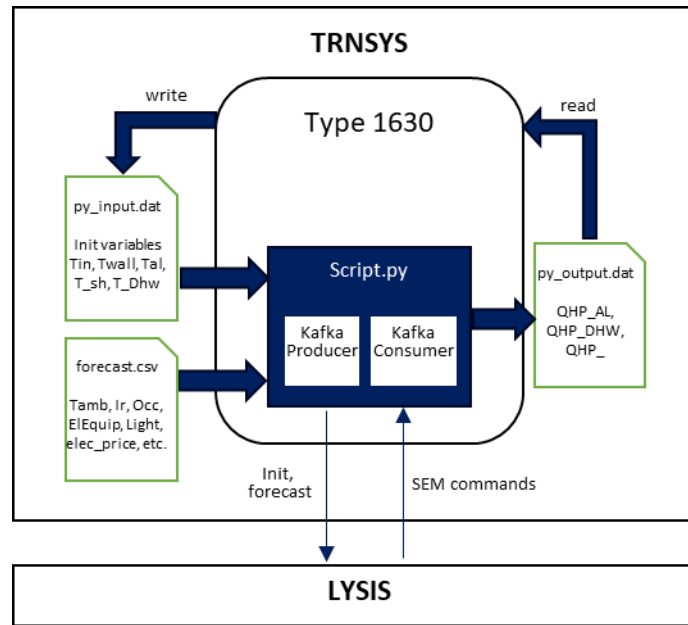


FIGURE 13. STRUCTURE OF CONNECTIVITY OF TRNSYS WITH LYSIS

### 2.3.4 Synchronization of the simulation

For a proper remote control, communication between the SEM and the building must be fluid and uninterrupted. As described in Figure 2, the operation runs sequentially in two different sides (SEM's and TRNSYS') and they have to work in coordination, thus, while one side is carrying out a task, the other side has to advance in parallel and meet at the same point when both have ended. There have been found several reasons that might interrupt that flow of information. As said before, in order for the producer to deliver the message, a Kafka Consumer has to be created previously, otherwise the message sent can be lost. Sometimes the optimization can be really fast (milliseconds), or it can be too long over the 100 seconds. Sometimes the TRNSYS simulation or the SEM optimization takes longer than expected, and this results in the creation of a producer which has not yet ready the consumer on the other side. To prevent this, the following measures have been taken:

- **Timeout**  
The Python Consumer shuts itself after a period of time (typically 60 seconds) after which it is considered that the simulation encounters some problem. The same mechanism is implemented in the SEM which stops the optimization function after the established time-out. After that the SEM applies the same control from the previous successful communication. If this occurs too often, then a warning is risen and the issues causing this have to be investigated.
- **Time-sleep**



Most of the times the simulation executes in a really short time (see Figure 284.4) and it can send the results with a producer even before TRNSYS can setup a Kafka Consumer. For that reason, the time-sleep makes the SEM wait (typically 1.5 seconds) before sending the results back to TRNSYS.

- Logfiles

Communications with LYSIS, information sent, and callback functions are time registered in a log file to trace the issues that may occur.

## 3. Test scenarios definition

### 3.1 Simulation plan design

The validity of the algorithms employed in the SEM system was demonstrated in D3.4 [4]. Building upon that, co-simulations were conducted with the SEM system for a series of selected representative periods. These simulation periods were carefully chosen to showcase the functionality and operation of the system. By incorporating these simulations, we aimed to evaluate the connectivity and effectiveness of the SEM system in practical scenarios. The results obtained from these co-simulations provide valuable insights into the system's performance and demonstrate its capability to operate seamlessly within a connected environment.

The key factors to design the testing scenarios will be used to demonstrate the capabilities of the developed algorithms for the SEM system. The factors considered for the scenarios are described in Table 2. A selection of the combination of these factors results in 12 scenarios, and for each of them the SEM was executed, and results were produced. In this document there are shown only the most representative ones.

TABLE 2. FACTORS USED TO DESIGN THE TEST SCENARIOS

Factor	Description	Number of levels	Levels
<b>Time horizon</b>	Operation period to be optimized	1	▪ 72h
<b>Duration</b>	Simulation period	2	▪ 72h ▪ 2 weeks
<b>Season</b>	Simulation season.	2	▪ Winter ▪ Shoulder (spring)
<b>Occupancy</b>	Energy consumption and internal gains derived from occupants' activity. Occupant activity can have a big influence in energy building demand, and thus, another profile with 1/3 <sup>rd</sup> of reference levels is also considered.	2	▪ Normal ▪ Low (1/3 <sup>rd</sup> )
<b>Infiltration</b>	Uncontrolled outdoor air leakage into the building. The estimated real value of the building is 0.15. However, since this building is very well sealed, 0.75 was taken as "normal" value for the simulation, in order to increase the demand of the building and observe a higher response for the different control strategies.	2	▪ Normal (0.75 m <sup>3</sup> /m <sup>2</sup> ·h) ▪ Low (0.15 m <sup>3</sup> /m <sup>2</sup> ·h)
<b>Optimization Criteria</b>	Criteria used to define the objective function according to the operation indicators to be optimized. The CO <sub>2</sub> criterion has not been considered to reduce the number of calculations due to its close similarity to FE in nature.	3	▪ (SC) Self-consumption; ▪ Cost; ▪ (FE) Final energy

From the combinations of the aforementioned parameters: control (reference or SEM criteria), and seasons (winter, spring/shoulder) 12 scenarios were simulated and analyzed, as seen in **Error! No s'ha trobat l'origen d e la referència..** For the winter period the simulations are between 15-17 February (1104h – 1140h), and a control reference scenario is included along with other SEM control criteria; for the shoulder period 19–21 April (2640h – 2712h). There have also been included two scenarios that run for two weeks, 15–28 February (1104h – 1440h). The results are presented separately in section 4.

TABLE 3. SIMULATION PLAN

Case #	Season	Criteria	Date start	Simulation period	Date End	Duration	Infiltration & Occupancy
1	Winter	FE	15/2, 0:00	1104-1140h	18/02, 23:59	72h	Normal
2	Winter	Cost	15/2, 0:00	1104-1140h	18/02, 23:59	72h	Normal
3	Winter	SC	15/2, 0:00	1104-1140h	18/02, 23:59	72h	Normal
4	Winter	Reference control	15/2, 0:00	1104-1140h	18/02, 23:59	72h	Normal
5	Winter	FE	15/2, 0:00	1104-1140h	18/02, 23:59	72h	Low
6	Winter	SC	15/2, 0:00	1104-1140h	18/02, 23:59	72h	Low
7	Winter	Cost	15/2, 0:00	1104-1140h	18/02, 23:59	72h	Low
8	Winter	FE	15/2, 0:00	1104-1440h	28/2, 23:59	2weeks	Normal
9	Winter	Cost	15/2, 0:00	1104-1440h	28/2, 23:59	2weeks	Normal
10	Spring	FE	19/4, 0:00	2640-2712h	21/4, 23:59	72h	Normal
11	Spring	Cost	19/4, 0:00	2640-2712h	21/4, 23:59	72h	Normal
12	Spring	SC	19/4, 0:00	2640-2712h	21/4, 23:59	72h	Normal

## 3.2 Simulation boundary conditions

### 3.2.1 User behaviour profiles

The user behavior comprises the occupancy, ventilation, lighting, equipment and DHW profiles. In figures below appear the profiles used for the simulation scenarios as they were introduced in D3.3 for V1-Bern demo-site. All the above-mentioned regimes are not periodic schedules. They are represented and introduced in the optimization module as static/realistic profiles generated from monitored data of reference buildings in Switzerland.

Figure 14 presents the number of occupants present in the whole building for a representative time frame of approximately four days during the winter period.

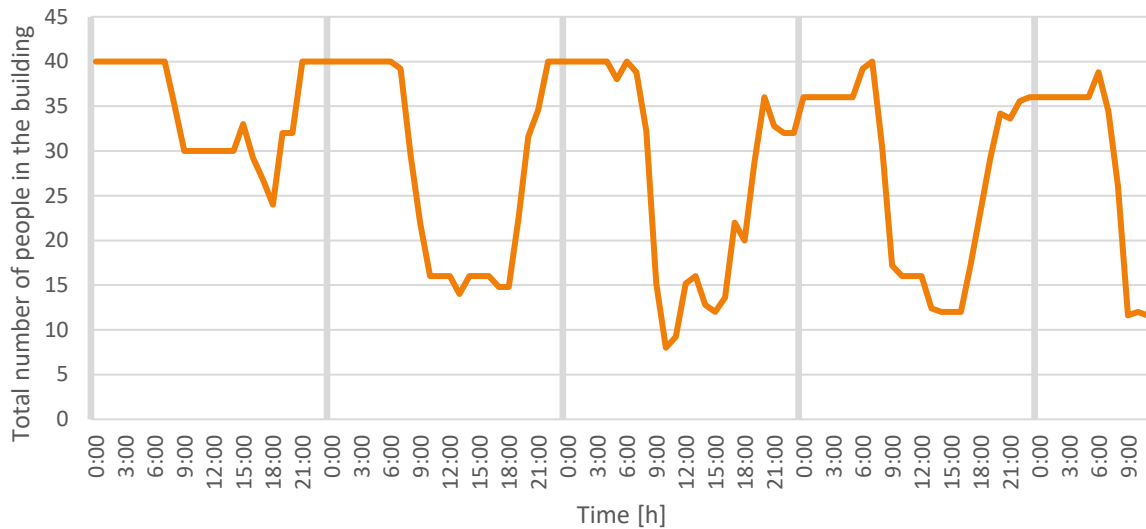


FIGURE 14. SAMPLE OF OCCUPANCY PROFILE FOR THE WINTER PERIOD.

Figure 15 presents the electric energy use attributed to illumination and domestic appliances for a representative time frame of approximately four days during the winter period.

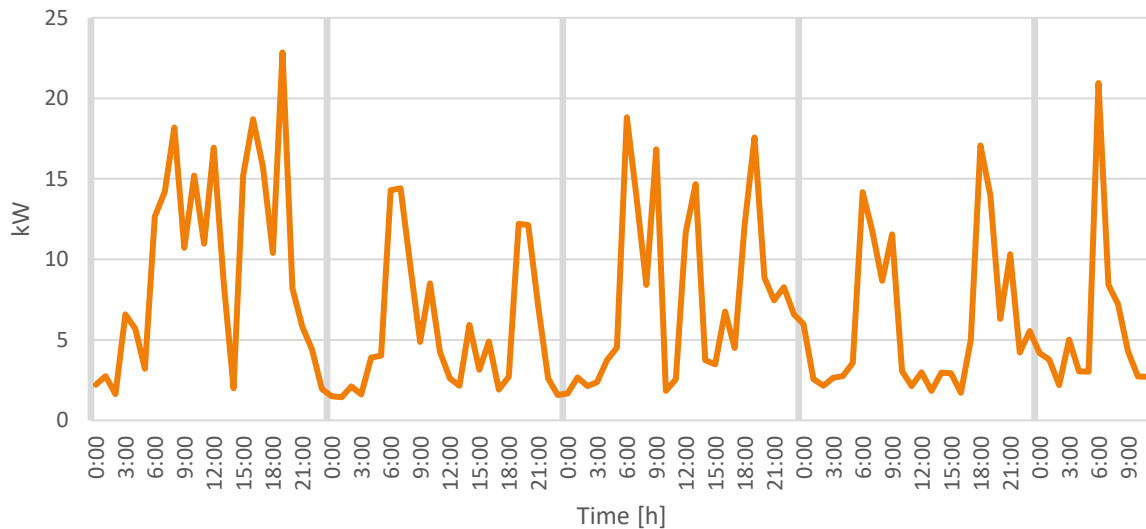


FIGURE 15. SAMPLE OF ILLUMINATION AND DOMESTIC APPLIANCES PROFILE FOR THE WINTER PERIOD

Figure 16 below shows an example of the DHW demand for a representative time frame of approximately four days during the winter period.

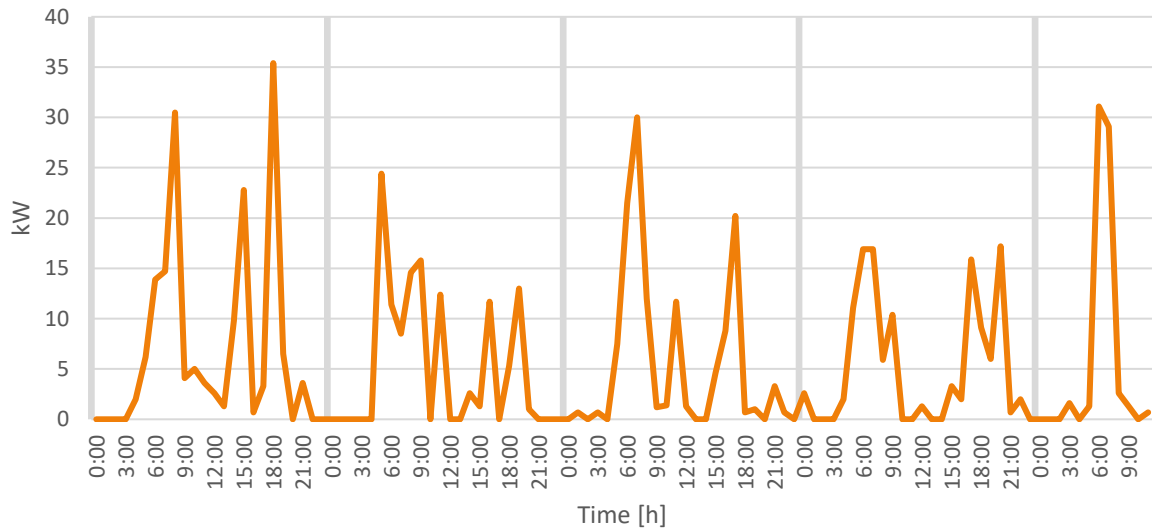


FIGURE 16. SAMPLE OF DHW DEMAND PROFILE FOR THE WINTER PERIOD.

### 3.2.2 Weather data

The weather data for the validation scenarios is from the Typical Meteorological Year (TMY) weather data from Bern, Switzerland. The goal was to obtain two data periods of the combinations of two temperature levels (high and low) and two solar irradiation levels (high and low) of the weather factors abovementioned.

To select the simulation periods, the weather data was first filtered to only include the hours where the temperature was either above or below a certain threshold (determined by degree-hours, calculated as the number of degrees above or below a base temperature) and the solar irradiation was above or below another threshold (determined by the accumulated daily radiation).

From this filtered data, two representative periods were selected. These periods were then used to create the validation dataset and are presented in Figure 17 and Figure 18.





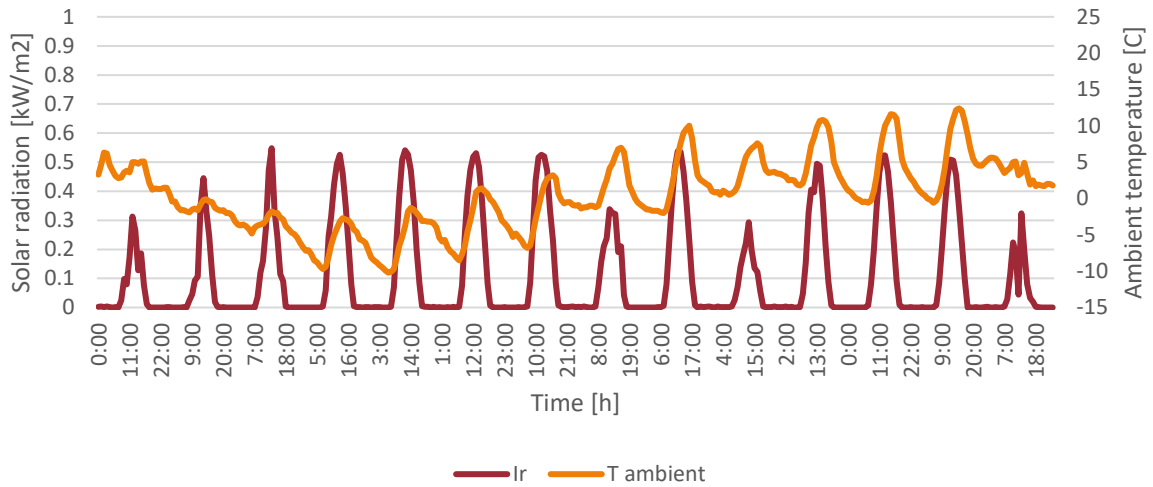


FIGURE 17. WINTER PERIOD WEATHER CONDITIONS

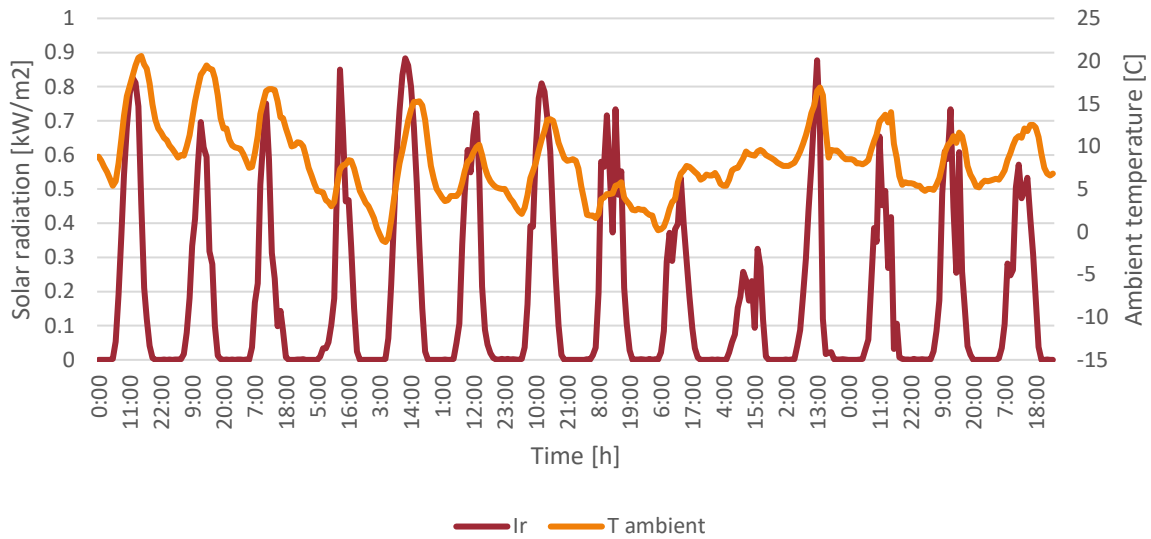


FIGURE 18. SHOULDER PERIOD WEATHER CONDITIONS

### 3.2.3 Electricity price and CO<sub>2</sub> emissions signal

Despite the SEM has the capacity to work with time-varying forecast of the prices of the electric market and of the CO<sub>2</sub> emissions, they have all been considered constant. The electric prices are 0.297€/kWh for buying and 0.187€/kWh for selling. Likewise, the factor of CO<sub>2</sub> emissions of the final energy imported from the grid has been considered constant as 0.331 kg-CO<sub>2</sub>/kWh.



### 3.3 Reference controls

The reference control for the heating system of the Bern virtual demo site was implemented using the TRNSYS type 888 [13]. Type 888 in TRNSYS simulates an electronic controller specifically designed for a heating system and heat source operation. It is used to control the operation of the heating system based on various inputs and setpoints.

The HP serves as a dual supplier for both the DHW system and the SC system in an interchangeable manner.

The DHW system incorporates a 4 m<sup>3</sup> tank that ensures a continuous supply of warm water to the building occupants upon demand. A mixing valve is responsible for regulating the temperature of the DHW before it reaches the users, with temperature limit set to a maximum of 70 °C.

As for the SC system, the HP provides warm water to both the SC tank and the AL (ConExWall) simultaneously or individually based on predefined setpoints. The SC system, including both the tank and AL, maintains temperature limits according to a heating curve which is a function of the outdoor temperature average and the indoor air setpoint. To keep the heating curve, the SC incorporates a mixing valve who is responsible for regulating the temperature of the warm water supplied by the HP and the SC tank to the AL (ConExWall). This ensures that the temperature of the water distributed for space heating purposes remains within the desired range, maintaining comfort and efficiency.

Finally, the distribution of heat for each individual loop of the ConExWall for each building dwelling is carried out with dead band controllers that activate individually the circuits of a zone when the air temperature drops below the comfort temperature setpoint in that specific zone. The sum of the activated circuits is the demand that the HP with the SC tank system has to supply.

### 3.4 Key Performance Indicators (KPIs) definition

To evaluate and compare the performance of the two control strategies, several KPIs are computed for each simulation. The technical performance of the solutions will be assessed through specific indicators, such as the Coefficient of Performance (COP) of the HP under certain conditions. The economic performance of the solutions will be calculated considering the cost of energy (kWh). Full list of the KPIs can be found in D1.4 [14]. However, the KPIs are intended as a standardized evaluator within the PLURAL project, but are calculated for the simulation period, and not for the time periods as they are defined (not annual).

Table 4 presents the full list of the KPIs, their units and calculation formulas.

**TABLE 4. MAIN KPIs FOR THE REFERENCE CONTROL AND THE SEM CONTROL AND CALCULATION FORMULAS**

Indicator	Definition	Formula	Unit
$E_{final}$	Total energy use	$E_{final} = \sum P_{HP} \cdot dt$	kWh
$E_{imp}$	Total imported energy	$E_{imp} = \sum P_{imp} \cdot dt$	kWh
$E_{exp}$	Total exported energy	$E_{exp} = \sum P_{exp} \cdot dt$	kWh
$E_{PV}$	Total PV production	$E_{PV} = \sum PV \cdot dt$	kWh
$PE_{nren}$	Non-renewable primary energy	$PE_{nren} = E_{imp} \cdot f_{p\_grid\_nren} \mid$ $(f_{p\_grid\_nren} = 2.3)$	kWh
$PE_{ren}$	Renewable primary energy	$PE_{ren} = E_{PV,del} \cdot f_{p\_site_e} + (Q_{HP} -$ $P_{HP}) \cdot dt \cdot f_{p\_site_t} + E_{imp} \cdot f_{p\_grid\_ren} \mid$ $(f_{p\_site_e} = f_{p\_site_t} = 1, f_{p\_grid\_ren} = 0.2)$	kWh
$PE$	Total Primary energy	$PE = PE_{nren} + PE_{ren}$	kWh
$RER$	Renewable Energy Ratio	$RER = PE_{ren}/PE$	%
$Cost$	Cost of electricity	$Cost = \sum -P_{imp} \cdot elecbuyprice \cdot dt$ $+ P_{exp}$ $\cdot elecsellprice \cdot dt$	€
$SC$	Self-consumption. Energy produced on-site and used	$SC = 1 - \frac{E_{exp}}{E_{PV} + 0.001}$	%



In the following scheme, Figure 19, the boundaries considered for technical, economic and environmental KPIs calculation are shown. Inputs and outputs of energy from the system are represented.

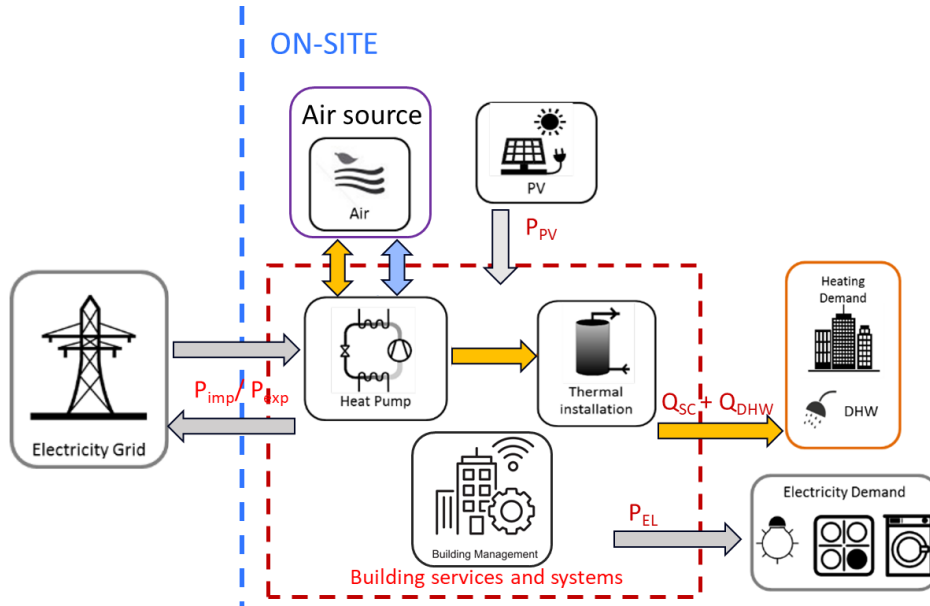


FIGURE 19. AIR-SOURCE HEAT PUMP SYSTEM AND ITS BOUNDARY FOR TECHNICAL, ECONOMIC AND ENVIRONMENTAL KPI DEFINITION.

## 4. Results

This section shows the results of two selected significant scenarios, #1 winter-FE and #11 spring-Cost, as well as the KPI for all the cases. It also contains the computational burden the optimization of the test scenarios.

### 4.1 Scenario #1 – Winter and Final Energy (FE) criteria

This section presents the detailed results of scenario #1 and its most representative KPI. Scenario #1 belongs to winter season, comprises 72h – 3 days – and is optimized according to the FE criteria.

This scenario consumes 1061.15 kWh of Final Energy, supposes 278.65 kg·CO<sub>2</sub> emitted, costs 221.06 € and a self-consumption ratio 58.61%. The simulation took 37.55 minutes to be completed.

Figure 20 shows the comparison between SEM control of the HP and the resulting thermal power in TRNSYS of the HP simulation. As it can be seen, the HP delivered power tries to follow the SEM command as tight as possible. However, due do model differences between SEM’s simplified model and TRNSYS detailed model, there is still a small gap difference.

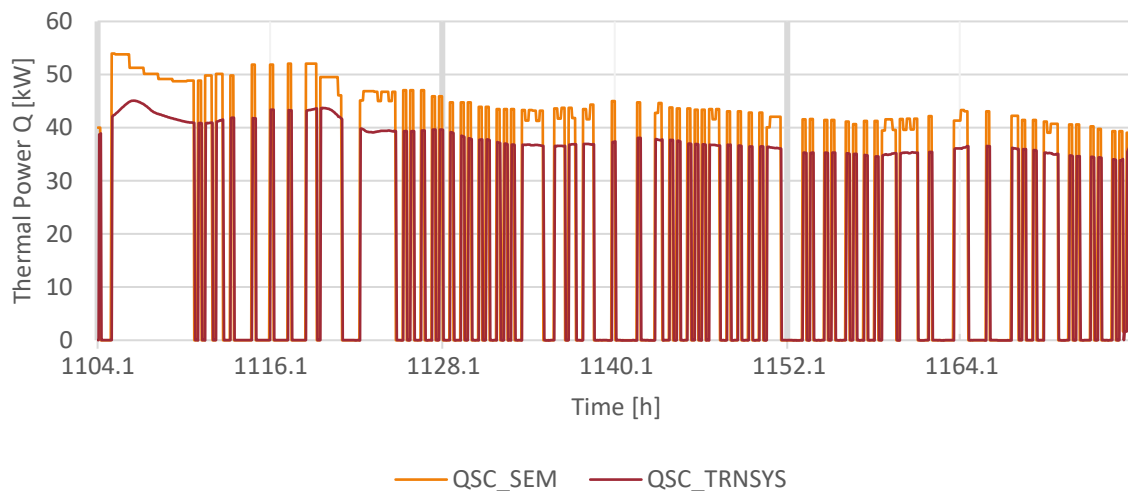


FIGURE 20. COMPARISON OF CONTROL SIGNAL FROM SEM WITH THE TRNSYS HP SIMULATION FOR SPACE CONDITIONING (SC) FOR SCENARIO #1.

Figure 21 shows the average building temperatures for the indoor air (“Tin”), the walls and structural mass (“Twall”) and the Active Layer (“Tal”) which distributes the heat of the ConExWall system. It can be observed that the comfort is maintained during the operation by keeping the Tin at the setpoint of 21°C.

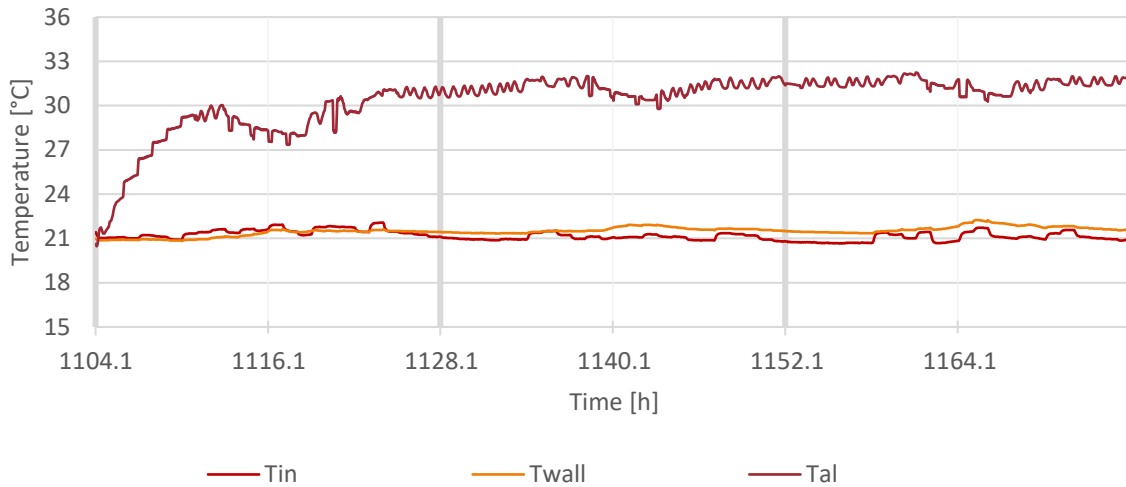


FIGURE 21. BUILDING AVERAGE TEMPERATURES FOR SCENARIO #1 CONTROLLED BY SEM.

The SEM manages the building at the general level and does not make individualized operation for each heating element. However, the general command results in a particular operation for each zone. Figure 22 shows an example of individual operation in dwelling 43a2fR. The plot shows the inlet and outlet temperature of the active layer (“Tin\_AL”, “Tout\_AL”), the node temperature also considering the solid mass of the active layer (“Tmass\_AL”), the air temperature of the zone (“Tair”) and also the heat delivered by the ConExWall (“QAL”).

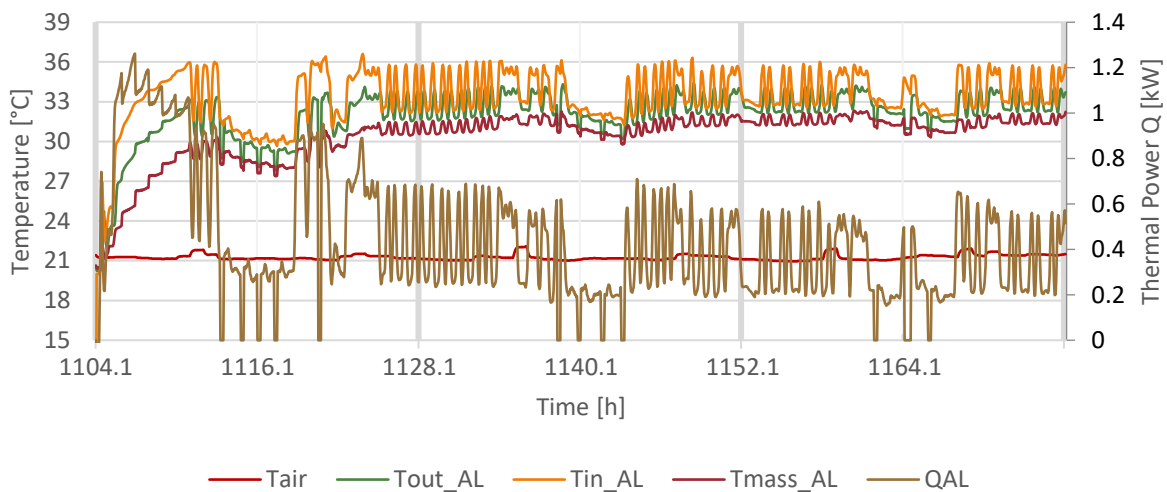


FIGURE 22. EXAMPLE OF INDIVIDUAL OPERATION FOR ZONE 43A2FR FOR SCENARIO #1.



Finally, Figure 23 shows the operation of the DHW system. TRNSYS operates the HP heat to the DHW tank according to the SEM commands. Here can be observed a gap between SEM command and TRNSYS operation with an average difference of 5 kW. The plot also shows that this operation satisfies the set point temperature of the tank.

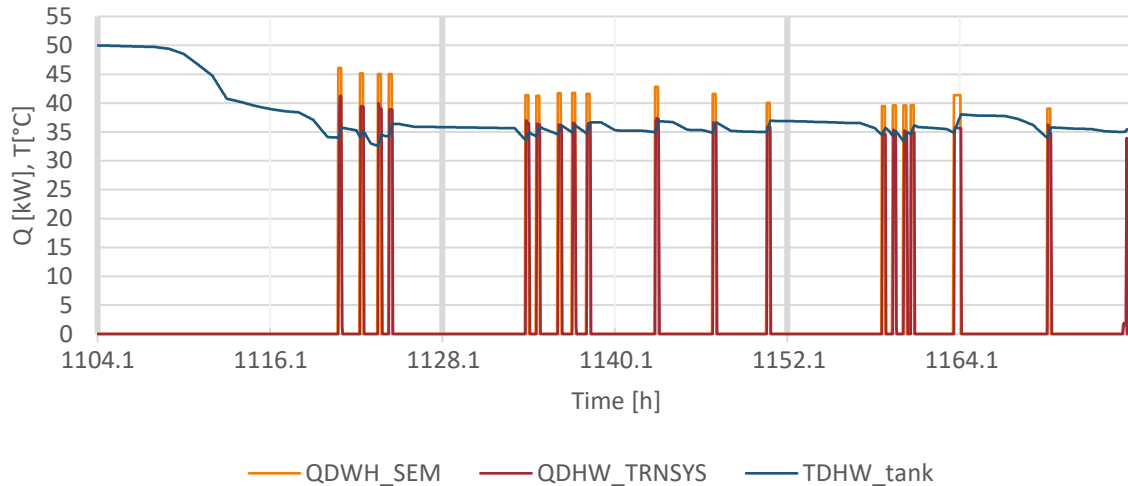


FIGURE 23. COMPARISON OF CONTROL SIGNAL FROM SEM WITH THE TRNSYS HP SIMULATION FOR DHW FOR SCENARIO #1.

## 4.2 Scenario #11 – Spring and Cost criteria

Scenario #11 belongs to spring season, comprises 72h – 3 days – and is optimized according to the Cost criteria. Similar to scenario #1 this section introduces the same results. Since this period is in spring, the energy demand diminishes and it can be observed in the KPI of the scenario, and also in the operation of the systems.

This scenario consumes 611.58 kWh of Final Energy, supposes 112.25 kg·CO<sub>2</sub> emitted, costs 23.52 € and a self-consumption ratio 39.76%. The simulation took 28.49 minutes to be completed.

Figure 28 and Figure 27 show the operation of the HP to supply heat demand for SC and DHW, respectively. Again, the HP TRNSYS operation follows the SEM command with a small gap difference. On the other hand, when the HP is active, the power supplied is higher (it can reach > 80kW) but the time active is shorter, resulting in a smaller demand than scenario #1. Figure 27 also shows that DHW tank is kept over the set point of 35°C.

Figure 25 shows the average temperatures of the building, where the AL temperature barely reaches the 30°C and still the system manages to keep the building comfortable over the 21°C set point temperature, and Figure 26 shows an example of temperatures of one zone (43a2fR).

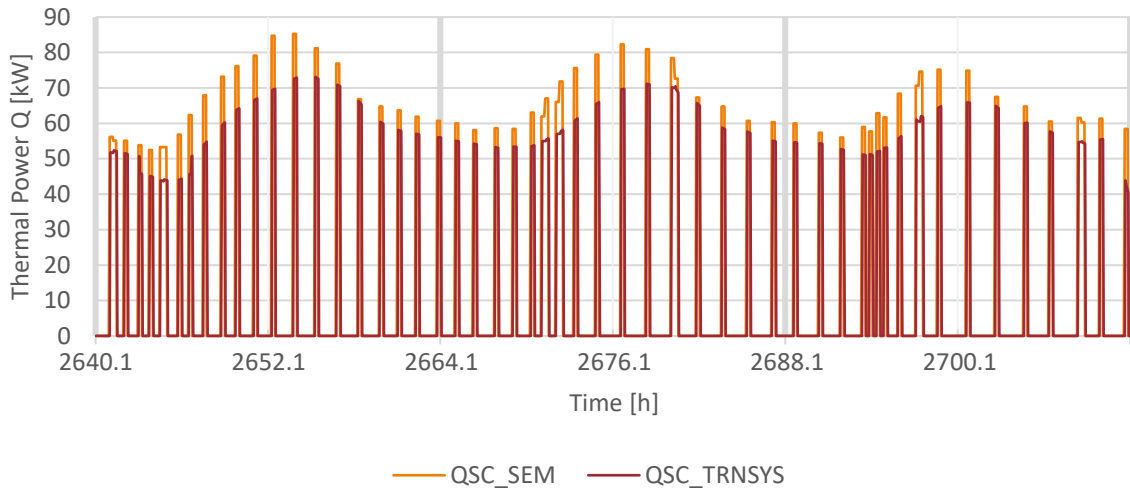


FIGURE 24. COMPARISON OF CONTROL SIGNAL FROM SEM WITH THE TRNSYS HP SIMULATION FOR SPACE CONDITIONING (SC) FOR SCENARIO #11.

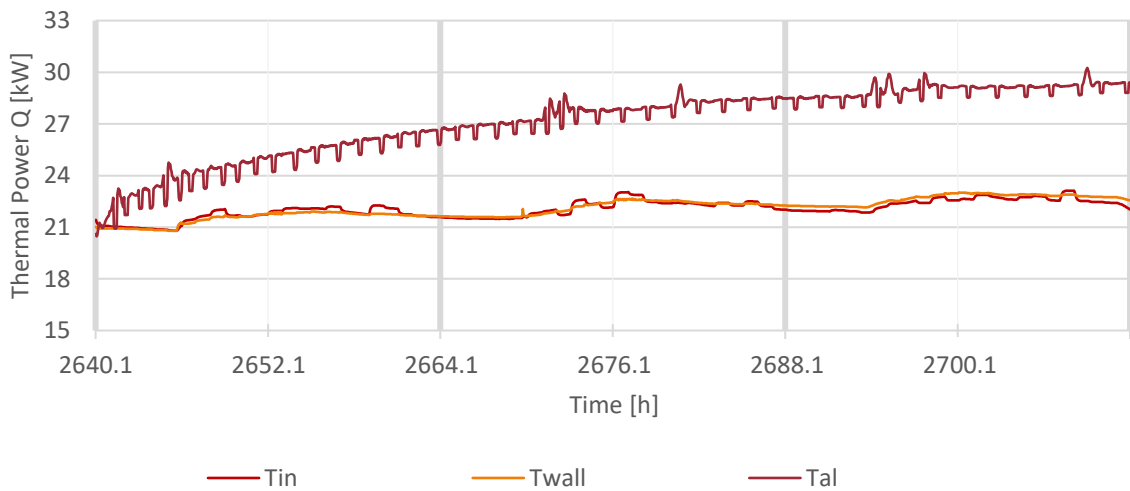


FIGURE 25. BUILDING AVERAGE TEMPERATURES FOR SCENARIO #11 CONTROLLED BY SEM.





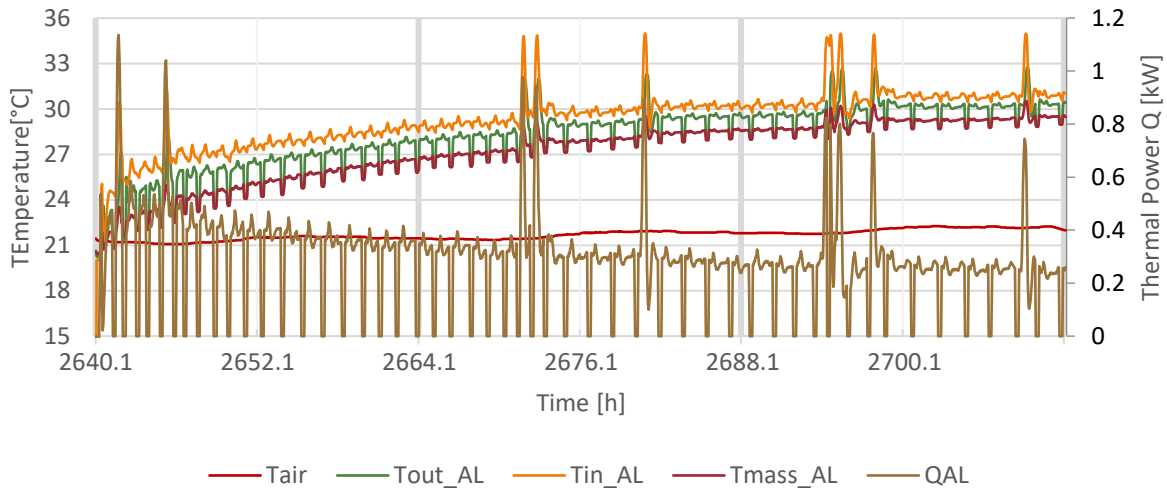


FIGURE 26. EXAMPLE OF INDIVIDUAL OPERATION FOR ZONE 43A2FR FOR SCENARIO #11.

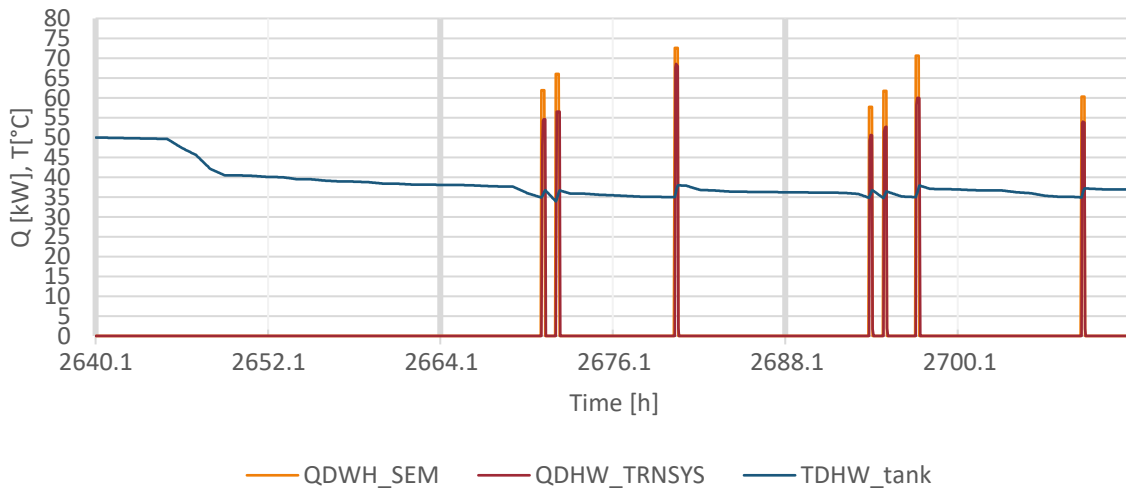


FIGURE 27. COMPARISON OF CONTROL SIGNAL FROM SEM WITH THE TRNSYS HP SIMULATION FOR DHW FOR SCENARIO #11.

### 4.3 All scenarios results

Table 5 shows the KPIs calculated for all the scenarios. They are presented in four blocks: the winter scenarios (1-4); the winter with Low Occupancy (LO) high infiltration (5-7); the winter two weeks duration (8-9); and the spring scenarios (10-12).



TABLE 5. KPIS VALUES OF THE SCENARIOS

#	Criteria/ Name	Final Energy [kWh]	Pimp [kWh]	Pexp [kWh]	PV [kWh]	Thermal Power [kWh]	PE_nren [kWh]	PE_ren [kWh]	PE_TOT [kWh]	RER %	CO2_em issions	Cost [€]	SC [%]
1	FE	1061.15	841.83	154.87	374.20	845.77	1644.94	1413.61	3058.55	33.76	278.65	-221.06	58.61%
2	Cost	1061.59	847.51	160.12	374.20	837.28	1656.04	1402.23	3058.27	33.83	280.53	-221.77	57.21%
3	SC	1064.86	834.87	144.20	374.20	855.09	1631.33	1430.72	3062.06	33.60	276.34	-220.99	61.46%
4	Reference	1016.61	789.06	146.65	374.20	787.48	1541.83	1341.69	2883.52	35.46	261.18	-206.93	60.81%
5	FE-LO	672.90	519.58	220.87	374.20	753.68	1015.25	1122.11	2137.37	35.45	171.98	-113.01	40.97%
6	SC-LO	699.00	500.00	176.00	374.00	809.00	978.00	1210.00	2190.00	35.50	166.00	-116.00	52.94%
7	Cost-LO	676.74	520.01	217.46	374.20	759.64	1016.10	1131.66	2147.75	35.75	172.12	-113.78	41.89%
8	2w-FE	4407.41	3272.23	1366.38	2501.56	2962.71	6393.94	5452.60	11846.54	161.60	1083.11	-716.34	45.38%
9	2w-Cost	4405.03	3278.30	1374.84	2501.56	2963.38	6405.80	5447.33	11853.12	161.80	1085.12	-716.56	45.04%
10	Spring-FE	608.00	341.00	419.00	685.00	662.00	667.00	1070.00	1740.00	41.70	113.00	-23.10	38.83%
11	Spring-Cost	611.58	339.12	412.81	685.28	666.48	662.64	1079.34	1741.98	42.05	112.25	-23.52	39.76%
12	Spring-SC	693.00	292.00	284.00	685.00	903.00	571.00	1430.00	2000.00	41.30	96.70	-33.60	58.54%

The findings from the analysis can be summarized as follows:

The first block (1-4) demonstrates that the SEM effectively achieves the desired outcomes for the various optimization criteria. The FE (Final Energy) criterion attains the lowest energy consumption of 1061.15 kWh, while the Self-Consumption (SC) criterion achieves the highest value of 61.46%. Although the Cost criterion does not yield the lowest cost value, the result is still highly accurate, potentially attributable to numerical imprecisions in the model.

In the case of the reference control scenario for winter cases, it is observed that it outperforms the SEM slightly. This can be attributed to the reference control's ability to perform individualized control for each zone, whereas the SEM is designed for overall building operation, with a specific focus on energy storage and PV self-consumption.

The second block (5-7) was introduced to obtain more realistic demand results by reducing the occupancy gains by one-third while restoring the original low infiltration rate. The results reveal lower energy consumption compared to the first block, with minimal differences between the optimization criteria. Once again, the SEM optimizes the FE (672.90 kWh) and SC (52.94%) criteria, while the difference in the Cost criterion remains insignificant.

In the third block (8-9), a long-term simulation covering a two-weeks period was conducted. Although the obtained results exhibit proportional magnitudes, they do not align with the optimization criterion. Nevertheless, the differences between them are minimal, indicating a narrow margin for optimization, particularly considering the cumulative operation over the two-week duration.

Lastly, the fourth block (10-12) encompasses the spring period, characterized by lower demand due to high temperatures and increased availability of solar resources. This implies a reduced margin for optimization. In this case, the FE and SC criteria once again successfully achieve their optimization objectives. However, the Cost criterion takes second place by a very small difference.

In summary, the results demonstrate that the SEM effectively controls the energy consumption of the building and is capable of optimizing it according to the desired criteria, except in the case of the cost criterion, where all the results are very similar, and the difference obtained is minimal. On the other hand, it should be noted that the building is highly energy-efficient (see 2.2.1), which limits the margin for optimization.

## 4.4 Computational burden

To carry out the simulation plan, the SEM was called and executed a total of 5613 times. Figure 28 displays the duration of all the calls to SEM. The average execution time for is 0.9253 seconds with a standard deviation of 8.2417 seconds.

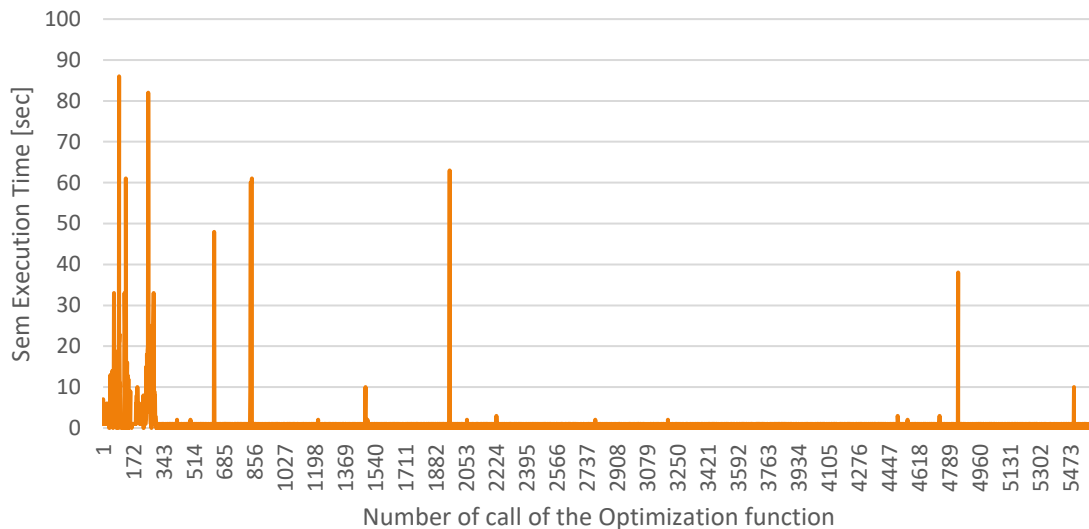


FIGURE 28. DURATION IN SECONDS OF EACH CALL OF THE SEM DURING THE SIMULATION PLAN.

On the other hand, Figure 29 shows it seems that there is no relationship between the objective function and the execution time. The objective function has no physical meaning since is a sum of different magnitudes to be optimized, but its value might be related to the complexity of the mathematical problem that has been put to SEM.

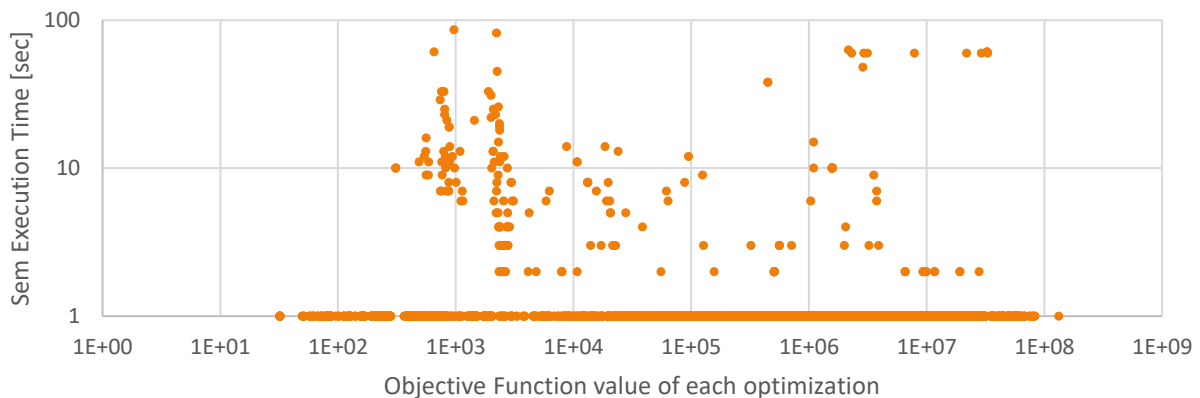


FIGURE 29. EXECUTION TIME OF THE OPTIMIZATION AS A FUNCTION OF THE OBJECTIVE FUNCTION VALUE.

## 5. Conclusions

In summary, the main objective of this deliverable is to present a robust demonstration of the proof of concept, highlighting our capacity to remotely implement SEM for efficient building control. By leveraging SEM effectively, we established a comprehensive framework that enables remote monitoring and manipulation of diverse building parameters, leading to optimized control and management of building systems. This demonstration serves as compelling evidence of the feasibility and effectiveness of SEM as a valuable component, providing valuable insights into its practical application for enhancing overall building performance.

The present work also demonstrates the possibility to remotely control a building and keep the thermal comfort. The experimental plan shows that the complexity of the setup related to the Apache Kafka communication, computational burden or synchronization of processes can be overcome and work successfully. The average optimization time is lower than one second and this allows a fluent communication between the two parts, optimizer and optimized. However, some measures have been applied to address synchronization problems such as the sleep timers or time-out commands.

In this project, the controlled building exists in a virtual and simulated environment. However, the accomplishments of this study suggest that the transition to a real-world implementation in an actual building would introduce heightened complexity and novel challenges. Nevertheless, it is reasonable to anticipate that the optimization and connectivity aspects with LYSIS would not necessarily become more difficult.

For future work, it is essential to explore the implementation of reference control in the Bern virtual demo site. The reference control uses separate control loops for each zone, which involves strict regulation due to the presence of one to three ConExWall circuits distributing hot water per zone. However, when utilizing SEM, the control should be extended to encompass the entire building. It is crucial to investigate and identify the underlying reasons for this variation and consider potential adjustments to optimize the performance of the SEM module accordingly.

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