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Calibrated Simulation of a NZEB

The Solar Decathlon China-2018 SCUT-PoliTo Prototype House

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Summary

The aim of this work was to test a fast way to calibrate a Building Energy Model able to perform a dynamic simulation of the behaviour of a single-family house. In particular, the case study was the SCUTxPoliTo prototype and the calibration was done with the scope of refining and enhancing the reliability of the model of the house during the contest conditions and for further energy planning, optimization and last days modification. The performed Calibration relies on the computer aided optimization. The first step was to set up a data collection campaign to monitor the behaviour of the prototype, considering the envelope, the energy systems and the outdoor weather [1]. All of these data will be used for comparison to assess the precision of the BEM [2]. To make the simulation match the real behaviour, a list of parameters has been selected and ranked using a sensitivity analysis procedure. After picking up only the most influential parameters, those have been variated among a pre-selected threshold following a hybrid optimization method (GPSPSOCCHJ) [3]. The main innovation lies in the use of a mathematical based optimization method to maximize the effectiveness of the Calibration, reducing the chance of human errors and allowing to search a wider hyperspace of solutions within a reasonable computational cost. Moreover, the sensitivity analysis, based on the Morris method, has been modified to match the Campolongo [4] optimized pattern search method to highly reduce the possibility of superposition in the variation of Calibration parameters, using the hyper cube generated by the parameters matching at its best [5]. The validity of the study has been proved by both the comparison with ASHRAE 14 guidelines (the BEM is considered fully calibrated) and the real operation [6]. To this last regard, during the SDC18 competition the reliability of the model helped the team to optimize properly the prototype and create a daily energy planning procedure to match energy production and consumption, giving a considerable help to the final score. Due to the superposition of Building phase and part of measurements campaign the calibration has been divided into two different steps: the first to be performed on the envelope, the second on the systems. The former focus on the air tightness, thermal transmittance and glazing characteristic, the latter on set points, real efficiency and schedule of the HVAC system. The results showed how the air infiltrations were underestimated, that the thermal transmittance of the main insulant was set to a higher value than the operational one and other minor change in the selected parameters. For what it may concern the systems, the main tuning regarded the set point of the HVAC (due to an error in the placing of the thermostats of the VRVs) and on the schedule of the ventilation system.

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1. Introduction

Building Energy Modelling (BEM) has been widely used in the last decades for design and retrofit purpose. One of the main problems of this procedure is to have an actual match between the real behaviour of the Building and the one simulated by the modeller. The United Nations' "World Urbanization Prospect" highlights how the expected increase in the construction of new urban dwellings has to meet the increasing requirements in reduction of the energy consumption and overall efficiency. This need requires a method capable of giving meaningful information on the building as well as a standardized procedure to achieve this info with computable data to ensure their effectiveness. In the last years, the calibration techniques have been increasingly used to fill the gap between real and simulated behaviour but many of them rely only on the capability and experience of the modeller to focus on the right parameters to be calibrated. The goal of this work is to assess a calibration methodology that relies only on the measured data, reducing the weight of the assumptions coming from the modeller.

The building selected for the calibration was the n-ZEB prototype "Long Plan" designed by Team SCUTxPOLITO, that took part in and won the competition Solar Decathlon China 2018 (SDC 2018). This choice was made for several reasons, such as the need for extended data for the competition, the availability to work intensively on the prototype, and the opportunity to test calibration both within full operational usage and in building site conditions. The building, that will be described deeper later, has a modular steel structure and it is mainly prefabricated; from the walls to the HVAC systems, all was preassembled in Guangzhou and then dispatched to Dezhou for the competition. The testing phase was divided between the two places and was comprehensive of weather data collection.

After the project data collection, the first step was the creation of a BEM with detailed modelling of all the systems. TRNSYS was chosen as the simulation software due to to the flexibility of the simulation and for the possibility to connect it with the many other software that have been used in this study. After the BEM was created a first validation was carried out to assess if the physics of the phenomena was verified.

Having a working BEM (Building Energy Model) made it possible to list all the parameters and select the one that could be meaningful for a calibration. Since the number of available parameters would have increased the computational cost of the simulation even if not necessary, a Morris's global sensitivity analysis was carried out. To magnify its effect and avoid superposition the sensitivity analysis was coupled with an optimized trajectory-finder following the Campolongo method. This procedure could highly reduce the cost of the calibration due to the selection of the most influent parameters.

The last step of the work was to collect the measurements and implement them in the calibration-modified BEM. The calibration itself was carried out through the coupling between TRNSYS and GenOpt (a Java-based optimization software) dividing it between building site calibration and operational calibration.

2. The Solar Decathlon Competition

Solar Decathlon is an international competition where the fields of architecture and engineering are mixed together to give life to a real house prototype. The first edition was held in Washington D.C. in 2002 after the proposal of Richard King, who is considered the father of the Solar Decathlon. Different teams made by students and teachers from the universities of the America for the first edition, and all the world after, participate in the competition, designing and then building their prototype. The name decathlon represents itself the competition's nature, because it is based on ten sub-contests, where the teams need to achieve the highest possible score to win the competition.

Since the extreme success of this event, many editions have been realized, not only in America, but in the rest of the world, like Europe, Latin America, Africa, Middle East and, nevertheless, China. For the latest edition, the contests were Architecture, Market Potential, Engineering, Communication, Innovation, Water, Health and Comfort, Appliances, Home Life, Energy Contest

2.2 Solar Decathlon China 2018

The second Chinese edition of SD, Solar Decathlon China 2018, was held in Dezhou, in the Shandong province, located in the north of China. It has a main division in the contest, half of the points are subjected to a jury review, while the other half is related to a measurement system. The juries should consider drawings, construction specification, narrative and on-site evaluation. In particular, for each section:

- **Architecture (Jury)**
    - Architectural concept and design approach
    - Clear concept, coherence among different disciplines.
    - Architectural implementation and innovation
    - Integrated design, natural and artificial lighting, design quality.

- **Market Appeal (Jury)**
  - Liveability
  - Safety, functionality, comfort, appropriate operation, target client.
  - Marketability
  - Interior and exterior appeal, materials, sustainability features.
  - Buildability
  - Construction drawings and specifications.
  - Affordability
  - House cost with respect to the market capability.
- **Engineering (Jury)**
  - Innovation
  - Unique approaches to solve engineering design challenges, innovations, market leading technologies, integration.
  - Functionality
  - Comfort, house performance, HVAC system, indoor air quality.
  - Efficiency
  - Energy efficiency, energy saving, control system, effectiveness of the engineering design.
  - Reliability
  - Maintenance, availability and durability of the systems.
- **Communication (Jury)**
  - Communication strategy
  - Communications deliverables, educational and outreach messages.
  - Electronic communications
  - Online audience, website, social media.
  - Public exhibit materials
  - On-site signage and handout, creative, original and informative materials.
  - Public exhibit presentation

- Team tour, large crowds and long lines fast tour.
- Audio-visual presentation
- Interesting presentation, philosophy design and construction presentation.

- **Innovation (Jury)**
  - Water Usage
  - Water conservation, water saving, market potential, creative strategies.
  - Air quality
  - Air purification, creative strategies, market potential.
  - Space Heating
  - Creative strategies, novel application to replace central heating system, market potential.
  - Others
  - Innovation, innovative approaches, market need, new and atypical approaches, active and passive solutions.
- **Comfort Zone**
  - Temperature

Temperature must be kept inside the range 22 ÷ 25 °C to earn the maximum points, reduced points are earned from 22 °C to 19 °C, and from 25 °C to 28 °C.

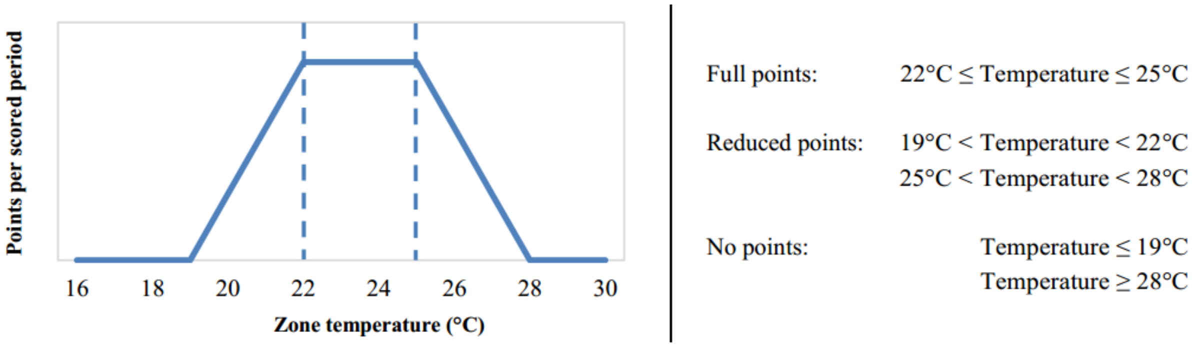
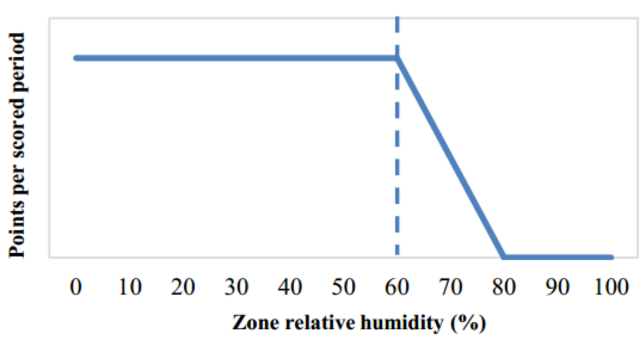


Figure 1: Temperature Score

- Humidity

The interior relative humidity should be below 60% to earn the maximum points, reduced points are earned from 60% to 70%.



Full points: Relative humidity ≤ 60%

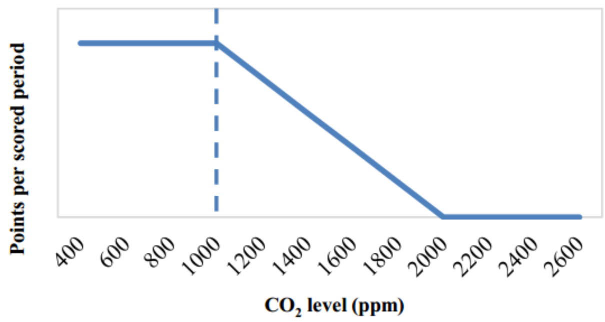
Reduced points: 60% < Relative humidity < 70%

No points: Relative humidity ≥ 70%

Figure 2: Humidity Score

- CO_2 Level

The CO_2 concentration should be below 1000 ppm to earn the maximum points, reduced points are earned from 1000 to 2000 ppm.



Full points: CO_2 level ≤ 1000 ppm

Reduced points: 1000 ppm < CO_2 level < 2000 ppm

No points: CO_2 level ≥ 2000 ppm

Figure 3:: CO2 Score

- PM 2.5 Level

The PM 2.5 concentration should be below 35 μg/m^3 to earn the maximum points, reduced points are earned from 35 to 75 μg/m^3.

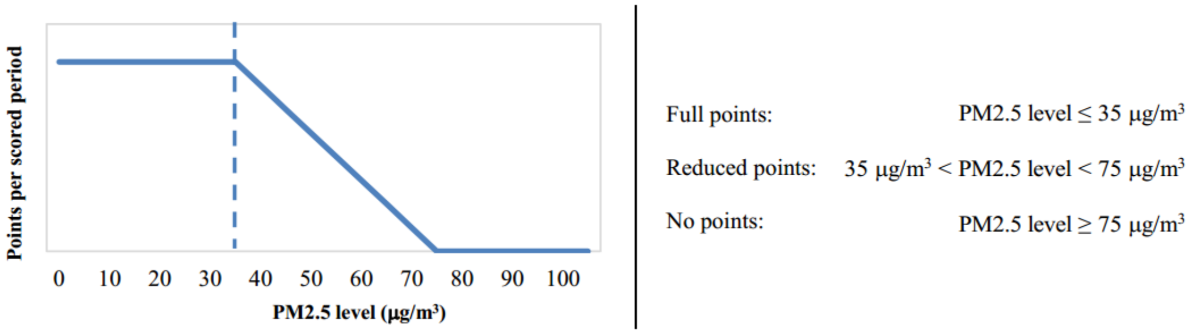


Figure 4: PM2.5 Score

- **Appliances**
  - Refrigerator

The internal temperature must be inside the range 1 ÷ 4 °C to earn the maximum points, reduced points are earned from 1 °C to 0 °C, and from 4 °C to 5 °C.

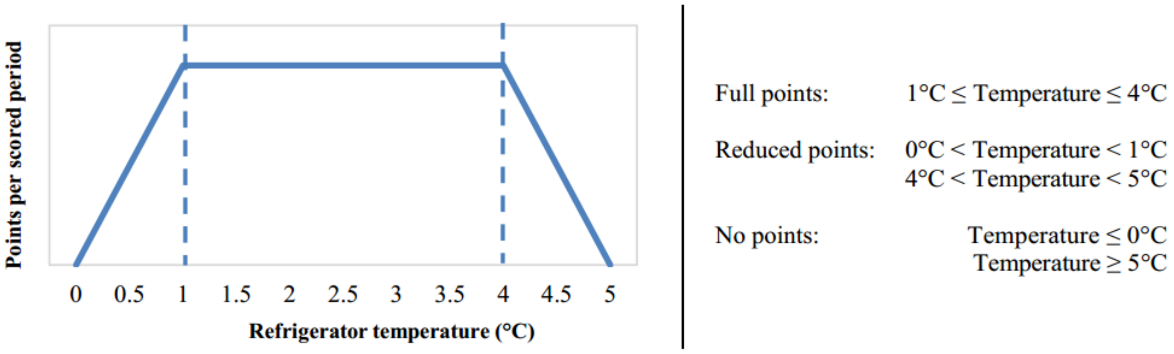
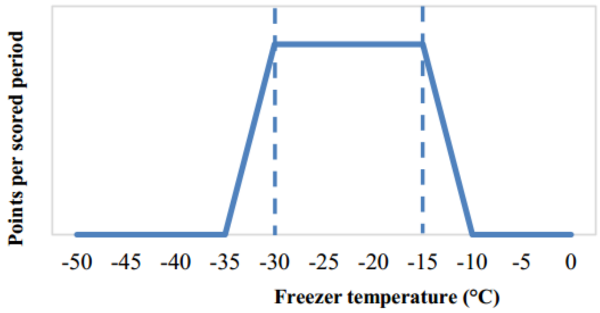


Figure 5: Refrigerator Score

- Freezer

The internal temperature must be inside the range -30 ÷ -15 °C to earn the maximum points, reduced points are earned from -30 °C to -35 °C, and from -15 °C to -10 °C.



Full points:	-30°C ≤ Temperature ≤ -15°C
Reduced points:	-35°C < Temperature < -30°C -15°C < Temperature < -10°C
No points:	Temperature ≤ -35°C Temperature ≥ -10°C

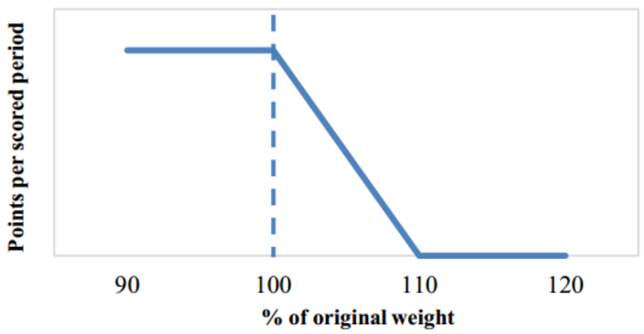
Figure 6: Freezer Score

- Clothes washer

A load of laundry should be washed in a complete, normal cycle, in a certain time.

- Clothes drying

The same load of laundry should be dried after the wash, with reduced points for a final weight between 100 % and 110 % of the original.



Full points:	% of original weight ≤ 100
Reduced points:	100 < % of original weight < 110
No points:	% of original weight ≥ 110

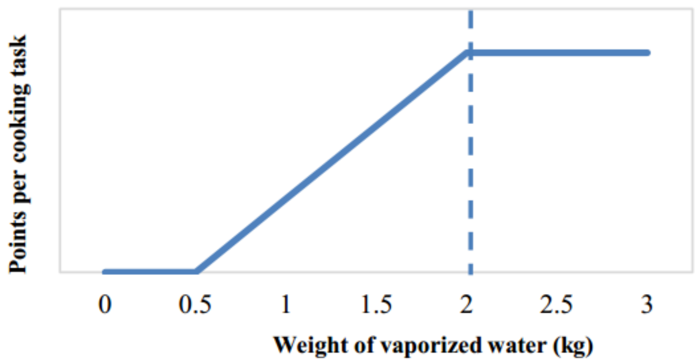
Figure 7: Drying Score

- Dishwasher

To get the full score, the temperature during a washing cycle must be, at least 49 °C

- Cooking

To earn the full point 2 kg of water out of 3 should be vaporized in 2 hours, reduced points are earned if the final quantity of water is between 0.5 and 2 kg.



Full points:	Weight ≥ 2 kg
Reduced points:	0.5 kg < Weight < 2 kg
No points:	Weight ≤ 0.5 kg

Figure 8: Cooking Score

- **Home Life**
  - Lighting

All the lights must be kept on at maximum power, during specific periods of time.

o Hot water

Sixty litres of domestic hot water must be delivered in no more than 10 minutes, at a temperature of, at least, 45 °C. Reduced points are earned in the range of temperature between 45 and 38 °C.

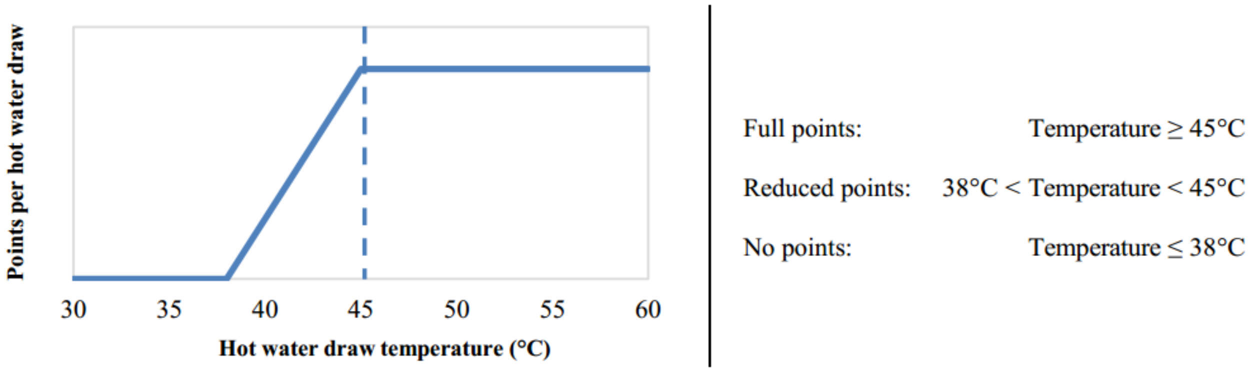


Figure 9: Hot Water Score

o Home electronics

Television and computer must operate at 75% of brightness for a certain period of time, to get the full scores.

o Dinner party

Two dinner parties shall be hosted by the team, inviting two decathletes from other three teams, serving a complete meal.

o Movie night

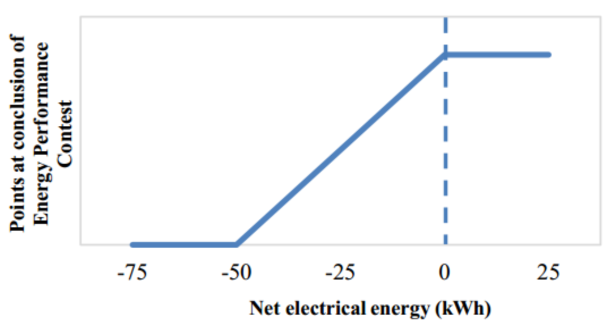
As for the dinner party, other decathletes must be invited from other teams to watch a movie.

- **Commuting**

The electric vehicle must be driven for about 20 km, 8 times during all the contest period. Reduced points are scaled linearly for a shorter distance covered.

- **Energy**
    - Energy balance

At the end of the contest, full points are given to a positive balance between production and consumption, reduced points are given to a negative balance, up to -50 kWh.



Full points: Net electrical energy ≥ 0 kWh

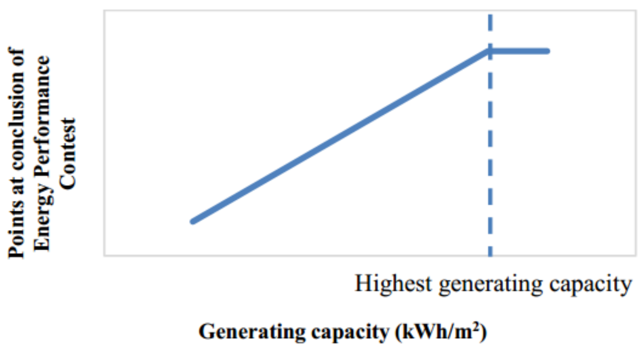
Reduced points: -50 kWh < Net electrical energy < 0 kWh

No points: Net electrical energy ≤ -50 kWh

Figure 10: Energy Balance Score

- Generating capacity

The generating capacity is calculated as the ratio between the energy produced during the contest, and the PV area installed. The full points are given to the team with the highest value, reducing proportionally the points for the other teams.



$$\frac{Reduced\ points}{Full\ points} = \frac{Team's\ generating\ capacity}{Highest\ generating\ capacity}$$

Figure 11: Generating Capacity Score

For this edition, the participating teams are:

1. **Team HKU:** *University of Hong Kong*
2. **Team PKU:** *Peking University*
3. **Team THU:** *Tsinghua University*
4. **Team XJTU-WNEU:** *Xi'an Jiaotong University / Western New England University*
5. **Team YI:** *Yantai University*
6. **Team WashU-BLD*:** *Washington University in St. Louis*
7. **Team Istanbul:** *Istanbul Technical University / Istanbul Kultur University / Yildiz Technical University*
8. **Team SUES-XD:** *Shanghai University of Engineering Science*
9. **Team Shunya:** *Indian Institute of Technology, Bombay*
10. **Team Montreal:** *McGill University / Concordia University*
11. **Team JIA+:** *Xiamen University / National School of Architecture of Brittany / High School Joliot Curie of Rennes / University of Rennes 1 / Technical School of Compagnons du Devoir of Rennes / National Institute of Applied Sciences of Rennes / Shandong University*
12. **Team NJFJ**: *New Jersey Institute of Technology / Fujian University of Technology*
13. **Team SEU-TUBS**: *Southeast University / Technical University of Braunschweig*
14. **Team XAUAT**: *Xi'an University of Architecture and Technology*
15. **Team SJTUIUC**: *Shanghai Jiaotong University / University of Illinois at Urbana Champaign*
16. **Team BJTU**: *Beijing Jiaotong University*
17. **Team SIE**: *Shenyang Institute of Engineering*
18. **Team TJU-TUDA**: *Tongji University / Technical University Darmstadt*
19. **Team Solar Offspring**: *Hunan University*
20. **Team SCUT-POLITO**: *South China University of Technology / Polytechnic of Turin*
21. **Team UNNC Alpha****: *University of Nottingham Ningbo China*

22. **Team Israel****: *College of Management Academic Studies / Afeka College of Engineering*

*Exhibition only

**Withdraw

2.3 Team SCUT-POLITO

The team **SCUT-POLITO** is a joint team between the two universities from China and Italy: South China University of Technology, which participated on the first edition of the SDC (2013), reaching the second position, and Politecnico di Torino. The team is composed by engineers and architects, both from Italian and Chinese universities, with a total number of more than 80 people. After the first months, with a preliminary admission, the Italian team fully entered the jointed design phase on September 2016, working hard with the Chinese partner. Changing and improving the design, the team produced the final design, which would be pre-built on Guangzhou, for testing, and then, shipped and assembled at the competition site, in Dezhou.

The prototype is based on the concept of the narrow house and bamboo house, since its main goal is to face the problems of land consumption, and high-density urbanization, highly present in China, but not less important in Europe. The main challenge was to realize a compact system, optimizing the space, keeping more space for the final users. To reduce the construction time, both for competition and market appeal, and to make the house more customizable, the team adopted a modular approach for the construction, using twelve modules.

Another important part is the control system. It allows the user to be informed about the operation of the majority of the systems, appliances and control them remotely through an app for smartphone, or tablet. But the most innovative idea is the management system supported by an artificial intelligence, that maximize the passive strategies utilization and the energy efficiency by analysing more than 600 correlations between personal comfort and inside parameters, like temperature, humidity, $PM_{2.5}$, CO_2, operating through the HVAC system. This way, people do not necessarily need to be experts to use the most technological solution adopted, because an expert can easily understand how to operate or set a system, but this way the system is user-friendly to everyone.

In the end, the team SCUT-POLITO won the competition with more than 959 points out of 1000, reaching the first place, scoring the highest value among all the teams for Engineering, Innovation, Comfort Zone, and Commuting. Moreover, it has been awarded the following prizes:

- Engineering – First Prize (96/100)
- Innovation – First Prize (95/100)
- Architecture – Second Prize (96/100)
- Market Appeal – Second Prize (97.70/100)
- Communication – Fourth place (92.60/100)

3. Team SCUT-POLITO prototype: LONG PLAN

As reported in the previous chapter, the outcome of the design phase has seen a huge variation in both the envelope and the systems of the prototype. This chapter will report only the final layout, without recalling all the design history of the project, from a purely engineering point of view. The main focus will be pointed at the envelope, the PV system and at the HVAC systems.

3.1 Envelope

The prototype design recalls the structure of the narrow house, a model of terraced house that has its main development in height penalizing the width. The building is a two-storey house divided in three main belts:

- **Implemented Wall:** The west-side external wall, the internal part of it contain all the distribution pipes for hot water, coolant, DHW and all the electrical and electronic connection

- **Service Belt:** The narrow section of the house, is composed by all the services and systems. Here lay the stairs, the 3 bathrooms, the mechanical room, the aquaponic system and the kitchen appliances.

- **Living Belt:** This section is composed by the 4 conditioned zones: living room, kitchen and the two bedrooms. There is one corridor for each floor too and a central patio, considered non-conditioned zone thanks to the capability to completelly close it.

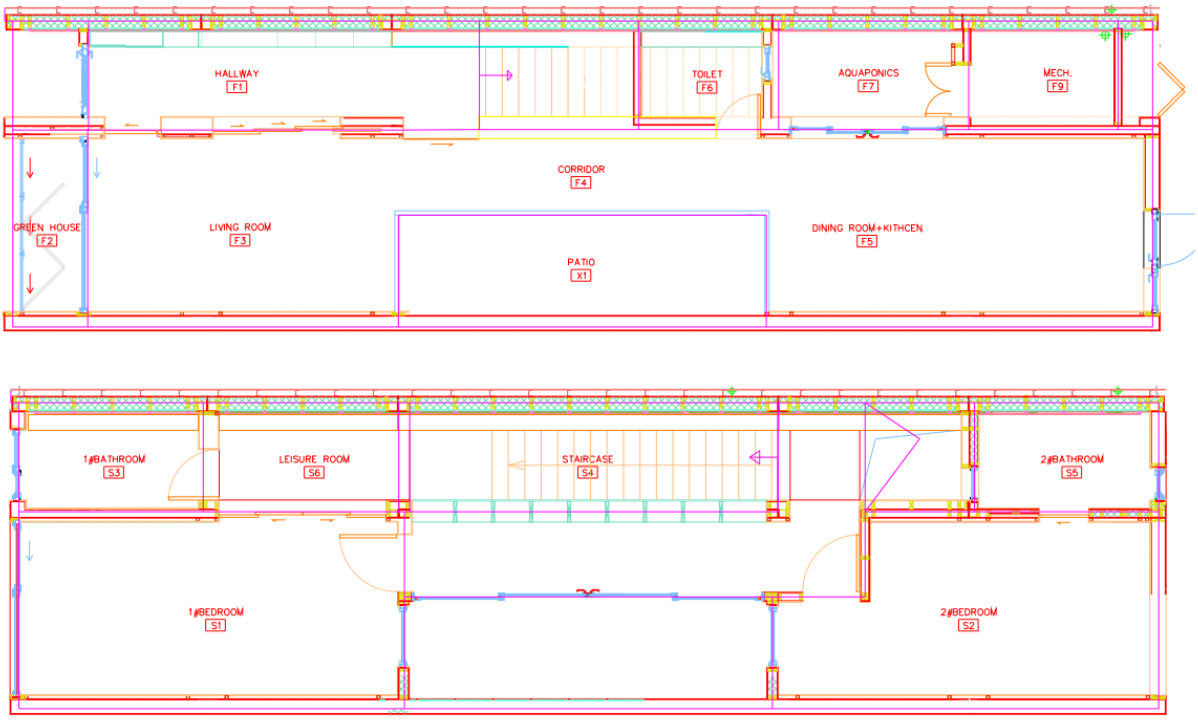


Figure 12: Prototype section plan

The main design challenge was to simulate the presence of the two adjacent buildings or at least to mitigate the dispersion. This has been achieved using a high-performance structure for the wall at west and east and removing any opening on them. Moreover, despite being the HVAC system designed for the whole volume, the building offers the possibility to reduce the size of the conditioned space cutting off the service belt; because of this the internal walls have been designed to have a good insulation too. The floor is not in direct contact with the ground but below has a buffer space, closed to the external environment. The roof of the building is not directly exposed to sunlight: a steel structure holds the PV and thermal panels at 1m height from the roof surfaces. This will reduce the amount of solar radiation absorbed by the rooftop and the gap will allow natural ventilation to cool down both PV panels and the roof surface itself. In the next tables the composition of the walls is reported:

Table 1: External Wall

External Wall	
Layer	Thickness [mm]
Façade siding	30
Façade cavity	100
Water barrier	1
Oriented Strand Board	12
Phenolic insulation	200
Vacuum Insulation Panel (VIP)	20
OSB	12
Vapor barrier	1
Internal cavity	50
Wood finishes	12

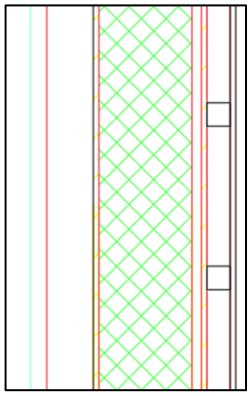


Table 2: Ground floor

Ground Floor	
Layer	Thickness [mm]
Laminate floor	15
Capillary Heating System + Concrete	50
Waterproof film	1
OSB	12
Phenolic insulation	220
OSB	12
Vapor barrier	1
Concrete fiber board	12

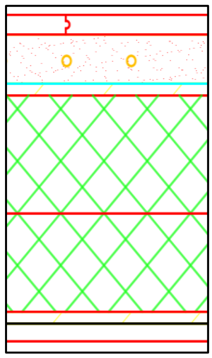


Table 3: Roof structure

Roof Structure	
Layer	Thickness [mm]
Self-adhesive waterproofing	15
OSB	50
Waterproof film	1
OSB	12
Phenolic insulation	220
OSB	12
Vapor barrier	1
Cavity	12
Wooden finishing	5

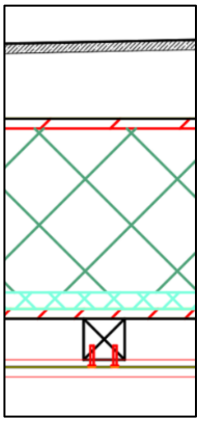
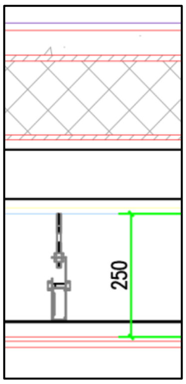


Table 4: Ceiling 1st floor

Ceiling - Floor	
Layer	Thickness [mm]
Laminate floor	15
Capillary Heating System + Concrete	50
Waterproof film	1
OSB	12
Phenolic insulation	150
OSB	12
Ceiling Cavity	250
OSB	9
Light wood ceiling	12



3.2 HVAC system

The HVAC system of the prototype was developed focusing on the modularity and feasibility of the project. All the technologies applied for the systems are market-available. The design of the system was composed by two phases: a first one, in which the components were sized through standards and technical booklet [7], and a second one, in which further modifications were carried out after the first dynamic simulations had been performed on the model [8]. The riser diagram and the technical scheme of the system are shown in the following table:

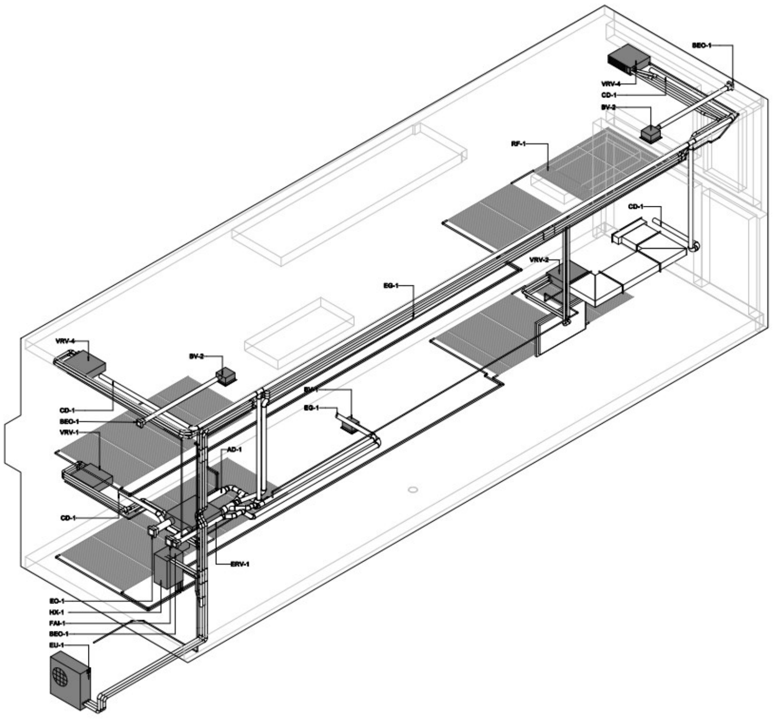


Figure 13:HVAC Equipment & Distribution Isometric

The thermal loads have been evaluated as 16 kW for cooling and 9 kW for heating with respect to the city of Dezhou, Shandong, China. Regarding the ventilation the average request for ventilation has been evaluated in 350 m^3/h of fresh air, an averaged value of 1 ach in order to clean the amount of CO_2 and $PM_{2.5}$ that maybe would be accumulated during the contest's tasks period.

3.2.2 Cooling system

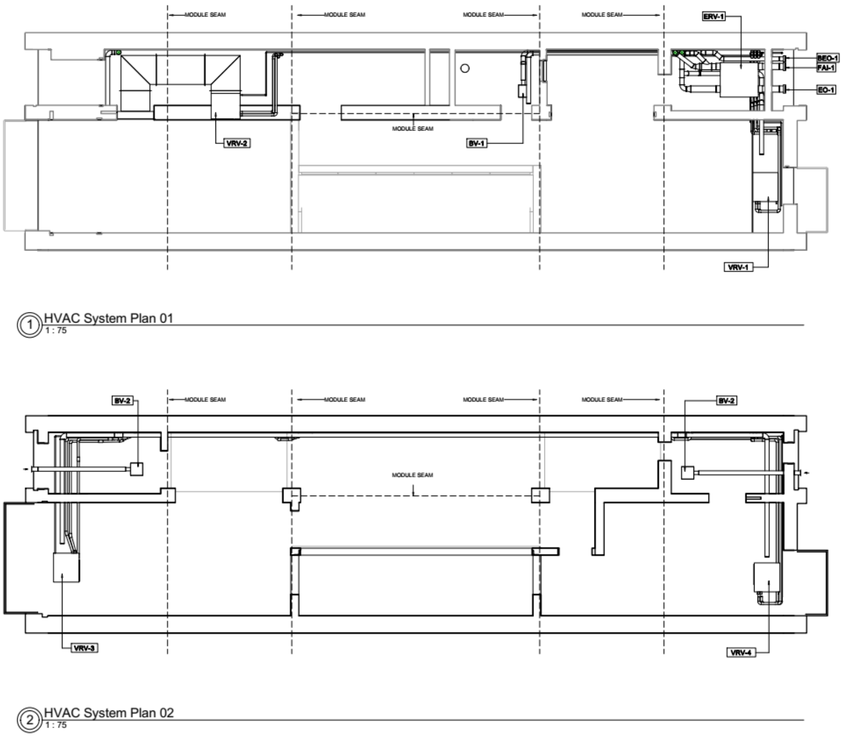


Figure 14: VRV distribution

To cover the cooling load the selected system was a Variable Refrigerant Volume (VRV-Daikin®) Heat Pump connected with four internal units with enhanced dehumidification capability. The model selected was the RBZQ6AAv, the data of which are shown in the table below:

Table 5: HP specifications

Daikin RBZQ6AAv			
Rated Freq. & Voltage			50 Hz 220V
Cooling Capacity		kW	15.5
Heating Capacity		kW	18
Heating Capacity		kW	16
IPLV©		-	7.1
Running Sound		dB(A)	55
Rated power	AC cooling	kW	4.19
	AC heating	kW	4.45
	Heating	kW	3.86
Machine size		mm	990x940x320
Weight		kg	80

Where the IPLV (Integrated Part Load Value) is defined as:

$$IPLV = 0.01A + 0.42B + 0.45C + 0.12D$$

Where:

- A = COP @ 100% Load
- B = COP @ 75% Load
- C = COP @ 50% Load
- D = COP @ 25% Load

While the internal machines data are:

Table 6: VRV specifications

		FQRSP 32AAPN	FQRSP 28AAPN	FQRP 56AAPN	FQDP 63EPVC
Room	-	Bedroom 1	Bedroom 2	Livingroom	Kitchen
Power supply	-	50 Hz 220V			
Cooling power	kW	3.6	2.8	5.6	6.3
El. Power	W	36/32	33/29	55/51	52/48
Cooling mode	m3/min	8,3/5,8	7,2/5,4	39/33	13.5/9
	dB(A)	34/27	32/26	13,5/10,0	40-32

The system has a connection factor (calculated as the installed internal power on the nominal power of the system) of 115% with a maximum deliverable cooling power of 14 kW on all the 4 conditioned zones.

3.2.2 Heating System

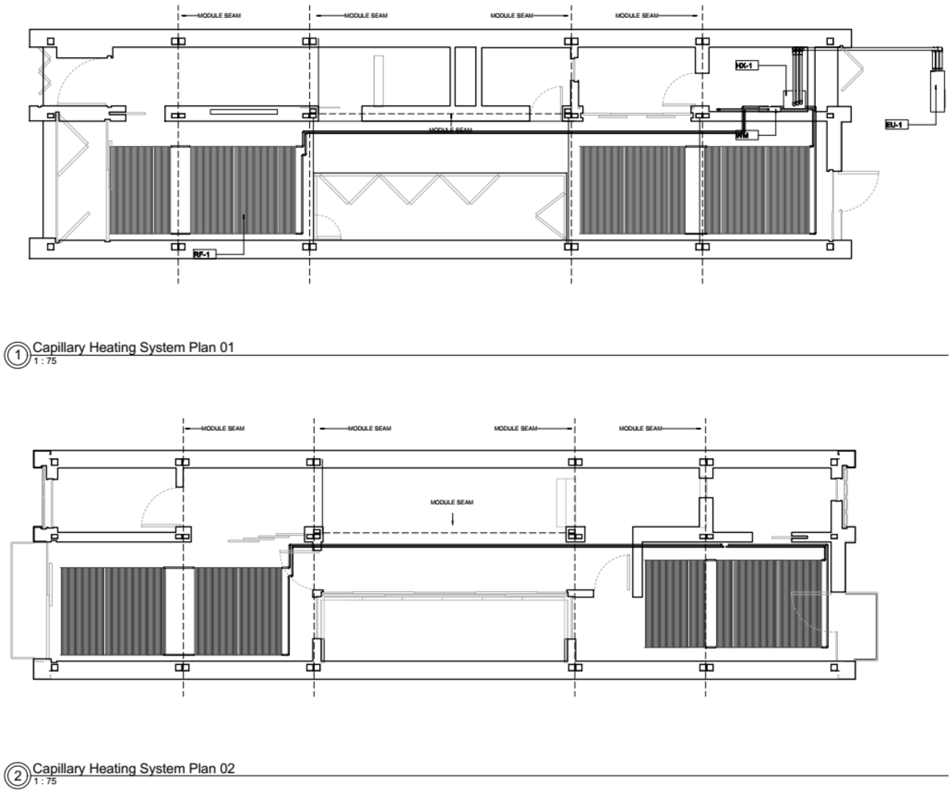


Figure 15: Heating system

The heating system is composed by a 4-loop capillary heating system that is fed by the same external heat pump through a high efficiency heat exchanger. The four loops are independent, the mats are pre-casted inside the concrete of the floor in the main conditioned rooms. In the table below the main data about the system are shown:

Data	Unit	Value
Module size	m	2.5 x 1
# of modules	-	18
Diameter	mm	4.3
Total surface	m^2	45
Water temperature	°C	35
Water capacity	l/m^2	0.29
Water tank	l	40
Heat dissipation	W/m^2	~100

Thanks to the independent pumps system the 4 zones can be heated just when needed using the enhanced part load efficiency of the heat pump.

3.2.3 Ventilation system

The ventilation system has been designed in order to reduce the CO_2 and $PM_{2.5}$ concentration in the inside air. The selected method was the use of an Energy Recovery Ventilator with a fresh air flow of 350 m^3/h. The outdoor air is firstly filtered in a coarse filter and then in a finer one, obtaining a filtering efficiency to the PM2.5 >99%. The air then passes through a counter flow heat exchanger in which it exchanges sensible energy with the exhaust air to reduce the conditioning load on the inside. The air is sent directly inside the living belt, in the 4 conditioned rooms, while the extraction is located in the corridor of the first floor and next to the top of the aquaponic system on the second floor (this position was chosen to highly reduce the amount of humidity near the green-wall). The flow path is ensured by the normal air leakage of the internal doors without increasing the pressure drops considerably. The bathrooms ventilation is not connected with the centralized one and is an on-request ventilation with direct extraction on the first-floor bathroom and a by-pass heating coil mode for the bedrooms' bathrooms. The data about the system are shown in the following table:

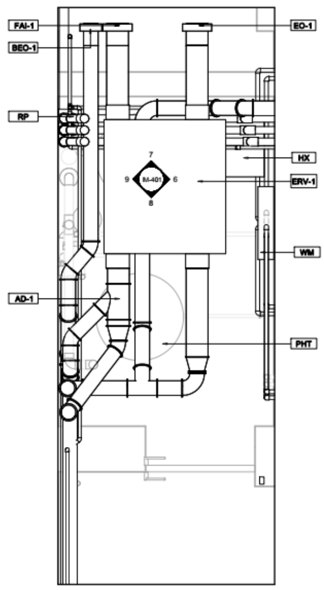


Figure 16: ERV top view

Table 7: ERV specifications

Panasonic FY-35ZDP1C					Exchange efficiency	
Power supply	Mode	Input Power[w]	Current[I]	Air flow[m^3/h]	Heating [%]	Cooling [%]
220V 50hz	Strong	257	1.17	350	61	76
	Interm.	210	0.96	290	62	77
	Weak	155	0.71	200	66	81

Table 8: Ventilation Bathrooms (2nd floor)

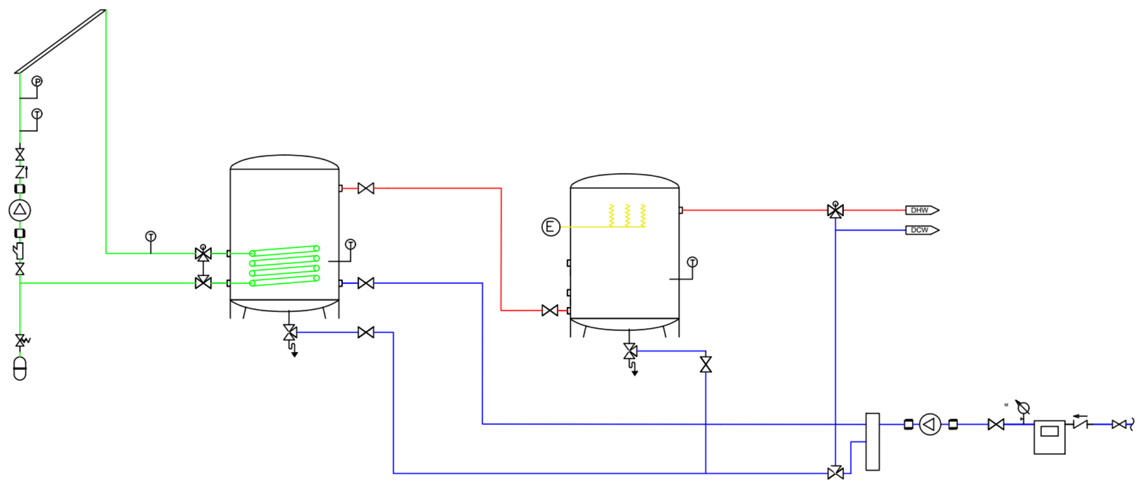
Manufacturer	Panasonic
Model	FV-30BUS3C
Power [W]	1650
Airflow [m^3/h]	170
Airflow [kg/h]	208,25
Heating Power [W]	1650
Ventilation Power [W]	26

Table 9: Ventilation Bathroom (1st Floor)

Manufacturer	Panasonic
Model	FV-24CU8C
Room	Bathroom 1
Power [W]	11
Airflow [m3/h]	140
Airflow [kg/h]	171.5

3.3 Domestic Hot Water

The DHW system is composed by a hot water storage of 300l divided in two 150l tanks. The first tank has the function of pre-heating water while the second one ensures the right amount of water at the design temperature. The pre-heating is obtained through 6m2 of solar thermal flat plate panels on rooftop while the second tank has a 1.5 kW electrical heater inside; the technical scheme is showed below:



3.4 PV System

The PV system of the prototype is composed by 34 bi-facial PV panels of two different models:

- TwinMAX 72 cell (1968x992 mm) – 0.33 kW/panel

- TwinMAX 60 cell (1658x992 mm) – 0.285 kW/panel

For a total installed peak power of 10.5 kWp. The average daily production during the contest period has been evaluated as 80 kWh with a maximum possible consumption ranging from 18 kWh to 65 kWh with respect to the different tasks to be performed. The system was designed in order to obtain all the requested energy without exceeding with the installed power. The simulations were carried out on PVsys to obtain the tilt angle that would have magnified the energy output using all of the available space on the rooftop avoiding possible shading. The data about the PV panels under normal conditions are shown below:

Table 10: PV panels data

		TwinMAX 60 cell	TwinMAX 60 cell
Max Power	W	285	330
Efficiency	%	17.3	16.9
$Voltage_{mpp}$	V	32	37.7
$Current_{mpp}$	A	8.91	8.76
$Voltage_{oc}$	V	39	46.6
$Current_{sc}$	A	9.30	9.25

The selected configuration instead used the optimized configuration with backside collection of solar radiation; this has been obtained increasing the space below the PV panels through a steel support structure and using a waterproofing membrane with higher albedo. The air gap has been proved to cool down the panel through natural ventilation. Even the use of sprinklers for cooling and cleaning the PV panels was used to improve the efficiency during the hottest hours of the competition periods.

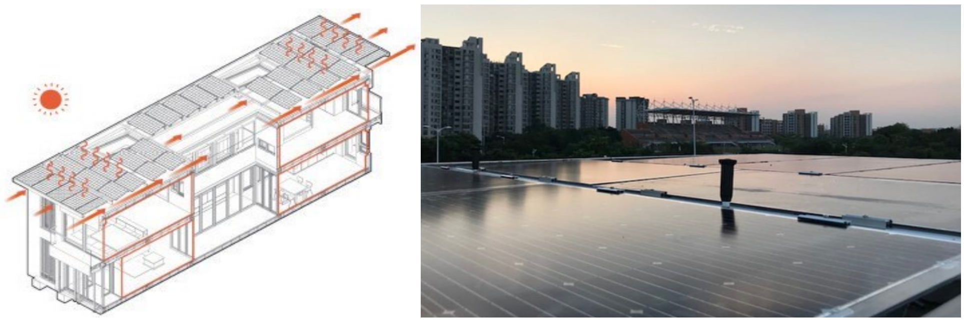


Figure 17: PV panels cooling modes

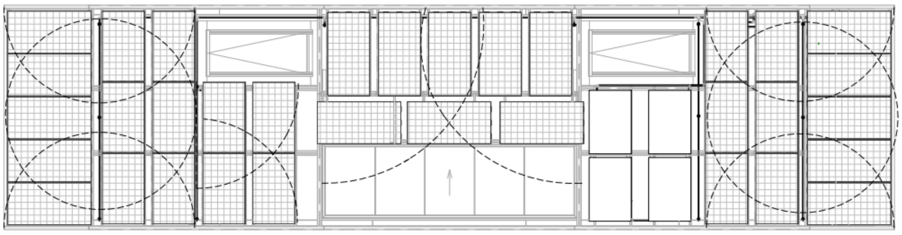


Figure 18: Sprinkler distribution

Table 11: Performance improving in PV panels

		TwinMAX 60 cell		TwinMAX 72 cell	
Max Power	W	356	+71	412	+82
Efficiency	%	21.6	+4.3	21.1	+4.2
Voltage$_{mpp}$	V	32	-	37.7	-
Current$_{mpp}$	A	11.1	+2.2	10.9	+2.2
Voltage$_{oc}$	V	39	-	46.6	-
Current$_{sc}$	A	11.6	+2.3	11.6	+2.4

The annual expected production is ~17000 kWh with an expected consumption in contest usage of ~4500 kWh divided as in [9]:

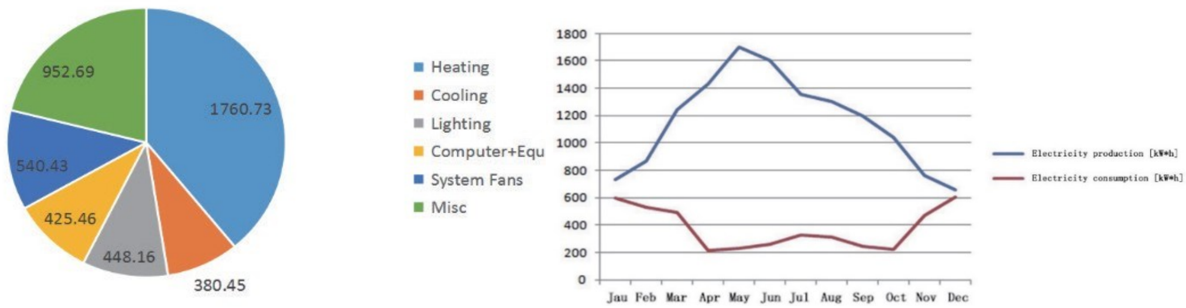


Figure 19: Energy Production-Consumption

4. Building Energy Modelling

Thanks to the information on the envelope and most of its systems it was possible to develop a detailed energy model of the envelope to be implemented with further data to allow its calibration.

The chosen software was TRNSYS 16, a transient system simulation software. One of the main advantages of this software is the flexibility offered to the simulator, in fact it is possible to insert self-written equations and detailed schedule with deep control on many aspects of the simulations. Since the BES has been carried out before the actual measurements no quantitative validation was available. This chapter will explain the modelling approach, will show the systems parameters and at the end will carry out a qualitative validation that relies on the logical behaviour that a well-designed model should maintain under the variation of different parameters.

4.1 Trnsys Modelling Approach

TRNSYS 16 is a transient systems simulator that runs on Fortran; its user interface is represented by different software that allow to manipulate the script. Simulation Studio is the platform in which the simulation is created, several plug in or compatible software can be called from this platform to perform the simulation (Es. Matlab, Contam, etc.), while there are some components, internal to simulation studios, that can be used to model some complex components (Es. Type 56 could be used to model the complete envelope). The simulation procedure is composed by the iteration, in a certain order, of blocks of equations that simulate the behaviour of a component or a physical phenomenon. These blocks are called Type, the equation that describe the behaviour could be already implemented or could be inserted by the users using some blank type. The interaction between them are structured using connections of input and output; the order of calling for all the Types is fundamental for the good behaviour of the simulation. The solution is an iterative one with an adjustable time step. The type structure is shown in the example below:

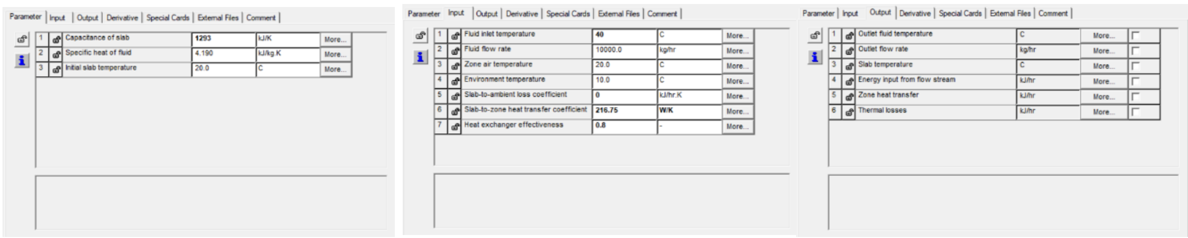


Figure 20: Trnsys Type Interface

The pre-written Fortran code will consider the inserted values: the parameters are time independent and will be used at every iteration without possibility to change them (with the exception of *ad hoc* Types); the input and outputs are updated at every timestep from another type, external file or direct calculation.

The simulation procedure for this study has been carried out starting from the definition of the envelope inside the Type56 plugin. Then the other HVAC systems have been added in separate macros connected with the envelope simulation, the weather file and the output procedure. All of this requires a preliminary work on the data, to ensure to insert them in the right format.

4.2 Type 56: Building model

The simulation is set up using the software SimulationStudio. As already said the core Type of the simulation is the Type-56; it allows a detailed description of the envelope and the different zones. It will solve the requested output using a nodal configuration for every zone. This Type work on another plug-in software called TRNBuild that provides a user interface to create the different zones, define the different walls and windows as well as schedule, gain, heating, cooling and ventilation system. In the next few paragraphs there will be reported the main step used to model the building in Type-56.

4.2.1 Surfaces editing

Before dividing the environment in different zones is necessary to identify all the surfaces, glazing and opaque, to create the walls and windows needed to define the thermal zones. The format for creating a new wall starts with the definition of all the materials used in the walls, identified as layers with the shown procedure:

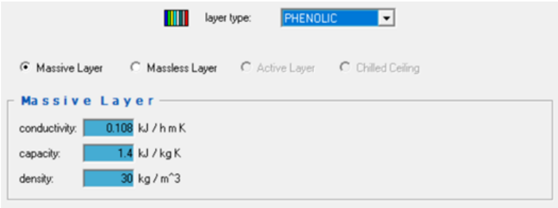


Figure 21: Layer form

The resulting layers used in the project are shown below:

Table 12: Layers

MATERIAL	Conductivity [W/m·K]	Conductivity [kJ/h·m·K]	Capacity [kJ/kg·K]	Density [kg/m^3]	Thermal Resistance [hm^{2}k/kJ]
OSB board	0.17	0.612	1	200	-
VIP	-	-	-	-	1
Phenolic insulation	0.03	0.108	1.47	30	-
Common concrete	0.93	3.348	1	2400	-
Wooden layer	0.17	0.612	2	600	-

These have been used to characterize the different walls used in the envelope:

Table 13: External Wall Trnsys

External Wall	Thickness [mm]	U-Value [W/m^2 K]
OSB board	12	-
Vacuum Layer	20	-
Phenolic insulation board 200mm	200	-
OSB board	12	-
Total	244	0.095

Table 14: Internal Wall Trnsys

Internal Wall	Thickness [mm]	U-Value [W/m² K]
OSB board	12	-
Phenolic insulation board 120mm	120	-
OSB board	12	-
Total	144	0.232

Table 15: Floor (Ground) Trnsys

Floor - Ground	Thickness [mm]	U-Value [W/m² K]
OSB board	12	-
Phenolic insulation board 200mm	200	-
OSB board	12	-
Common concrete	0.05	-
Wood layer	0.008	-
Total	332	0.129

Table 16: Floor (Ceiling) Trnsys

Floor - Ceiling	Thickness [mm]	U-Value [W/m² K]
OSB board	12	-
Phenolic insulation board 150mm	200	-
OSB board	12	-
Total	174	0.188

Table 17: Roof Trnsys

Roof	Thickness [mm]	U-Value [W/m² K]
OSB board	12	-
Vacuum Layer	20	-
Phenolic insulation board 200mm	200	-
OSB board	12	-
Total	244	0.095

For what it may concern the glazing area the software does not allow the use of a self-defined glazing surfaces; to overcome the problem the different windows were picked up among the libraries provided by the developers maintaining the closest value with the one used in the project. Due to the high amount of windows in the project and their huge variation to best match the properties seven different windows have been used, in the next table their properties are shown:

Table 18: Windows Trnsys

Windows Code	U-value [kJ/hm²K]	G-Value [%]	U-value$_{frame}$ [kJ/hm²k]
Window_0.19	0.73	0.567	2.15
Window_0.8	0.81	0.632	2.6
Window_1.2	1.23	0.436	4.32
Window_1.6	1.6	0.706	5.76
Window_2.5	2.51	0.366	9.04
Window_Patio	5.68	0.855	8.17
Window_Stairs	1.43	0.605	5.15

Their shadings have been designed as a schedule in simulation studio as the fraction of solar radiation let inside. These models have been used to characterize the following openings:

Table 19: Glazing list

Glazing opening	Height [m]	Width [m]	Area [m²]	U-value [W/m²K]
Livingroom: south door	2.6	2.7	7.02	0.8
Kitchen: North Window	2.6	1.6	4.16	0.8
Bedroom 1: south door	1.95	2.7	5.27	0.8
Bedroom 2: north door	2.25	1.6	3.60	0.8
Bathroom 2: north window	1.2	0.4	0.48	1.2
Bathroom 1: south window	2.4	1.1	2.64	0.8
Bedroom 1: north window	1.2	1.05	1.26	1.2
Bedroom2: south window	1.2	1.05	1.26	1.2
Bathroom2: south window	2.25	0.4	0.90	1.2
Bathroom 1: north window	2.4	0.4	0.96	0.8
Patio West Window	1.2	5.64	6.77	1.6
Kitchen West sliding door	2.25	2.66	5.99	1.6
Sun room folding door	2.598	2.738	7.11	2.5
Patio folding door - long	2.598	5.7	14.81	1.8
Patio folding door - short	2.598	1.6	4.16	1.8

4.2.2 *Zoning*

The prototype has been divided in 16 different zones, to each of them was assigned a code as seen in the table below where the conditioned ones are highlighted:

Table 20: Zones division

Code	Room/Zone	Vol [m^3]
F1	Hallway	20.7
F2	Greenhouse	9.6
F3	Living Room	39.7
F4	Corridor	20.3
F5	D.R.+Kitchen	49.4
F6	Bathroom 1	6.9
F7	Aquaponics	13.4
F8	Mechanical Room	10.6
S1	Bedroom 1	49.3
S2	Bedroom 2	44.3
S3	Bathroom 2	12.0
S4	Staircase	81.1
S5	Bathroom 3	12.0
S6	Leisure Room	14.6
X1	Patio	61.6
X2	Cabinet	3.0

This subdivision has been selected to allow direct control over the conditioned spaces even if they are part of a bigger open space [10]; having smaller thermal zones implies a higher control on the ventilation flow path and an higher precision on the temperature and humidity values in that particular part of the prototype: this characteristics are fundamental to reduce the averaging effect of the temperature in other zones and reach a lesser mismatch between the simulated and measured values. The format for the creation of a thermal zone is shown below:

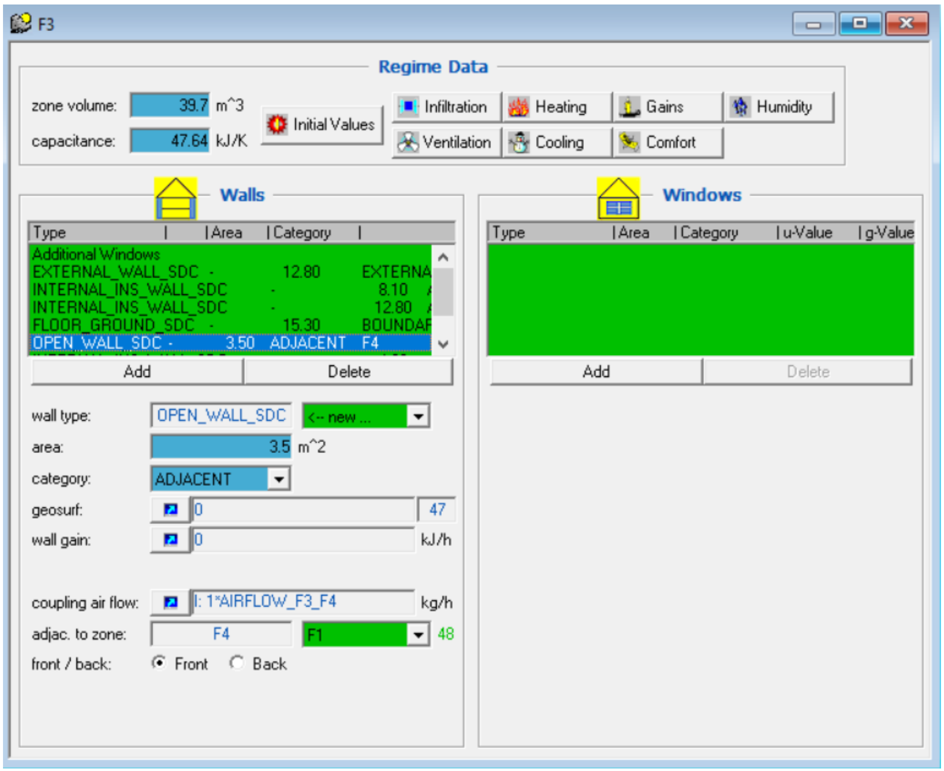


Figure 22: Trnsys Zone Format

Further data have to be inserted to complete the zone schematic:

- **Capacitance:** Since the calibration will be carried out without internal furniture the considered capacitance is calculated considering the volume filled just by air
- **Walls:** The thermal specs of the walls will be explained in the next paragraph, in this format are selected the size of the surface, the exposition (External, Adjacent to zone, Boundary), the fraction of direct solar radiation hitting it (*geosurf*), the wall gains, the presence of windows and the air flow balance.
- **Initial values:** Used only at the first timestep are used to start the simulation and have to be inserted manually in Type-56.
- **Ventilation, Heating, Cooling, etc.:** allow to turn on and off the systems, reading the values from an internal schedule, a fixed value or taking an input from the Simulation Studio's Types.

In the carried-on simulation the Cooling and Heating load have been considered as Gains reading the valued provided by the systems in Simulation Studio:

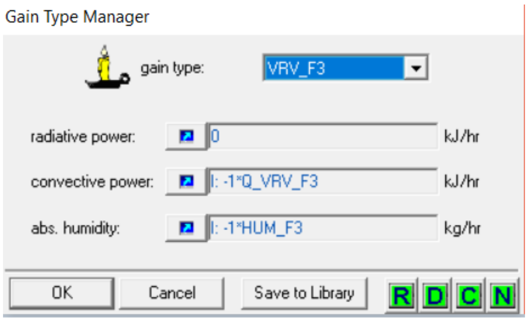


Figure 23: Gain Trnsys format

The Infiltration and the Ventilation also use data from the SS environment but connected with some pre-load schedule.

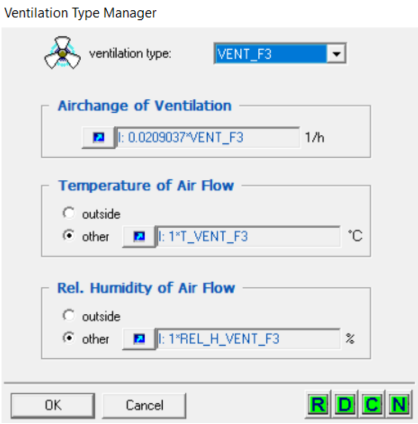


Figure 24: Ventilation Trnsys format

When all the zones are complete and connected the envelope is ready to be simulated as a nodal scheme that have to be interconnected with the HVAC scheme in the simulation studio platform.

4.3 SimulationStudio: HVAC system model

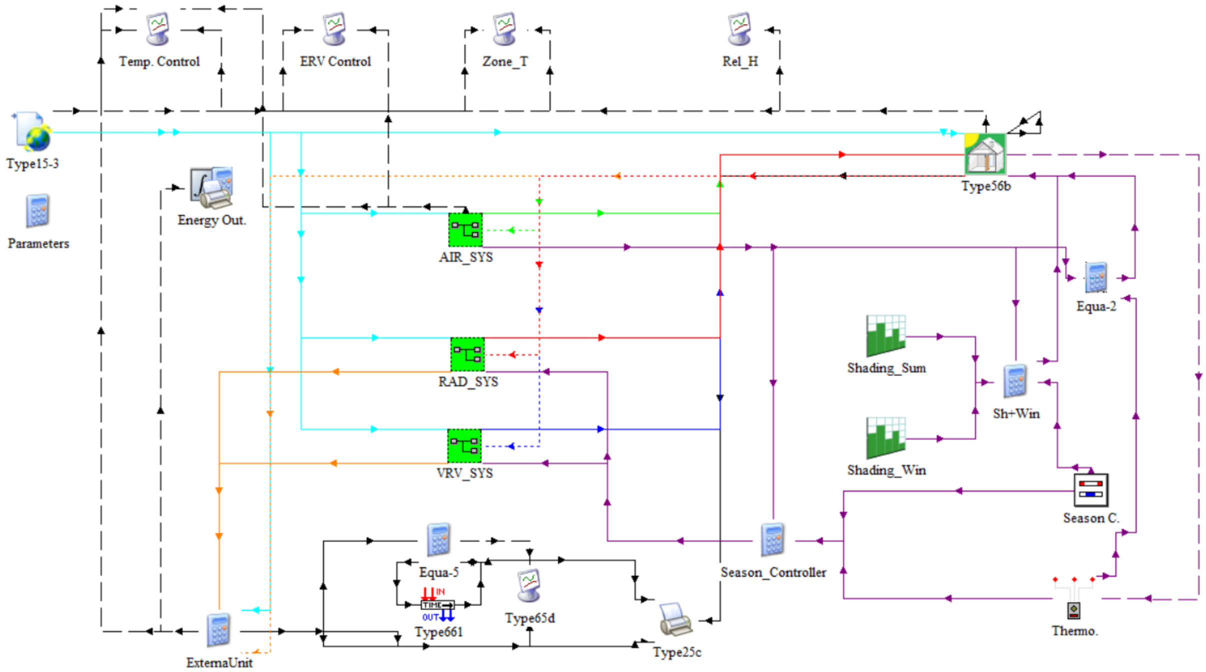


Figure 25: HVAC system overall scheme

The system has been divided in three different sections, incorporated as three macros directly connected with the Type56 both as input and output: the ventilation system, the heating system and the cooling system. In addition to this the simulation includes the management system, and graphical and numerical output. In this paragraph all the systems will be described in terms of operations, type and management.

4.3.1 Ventilation system

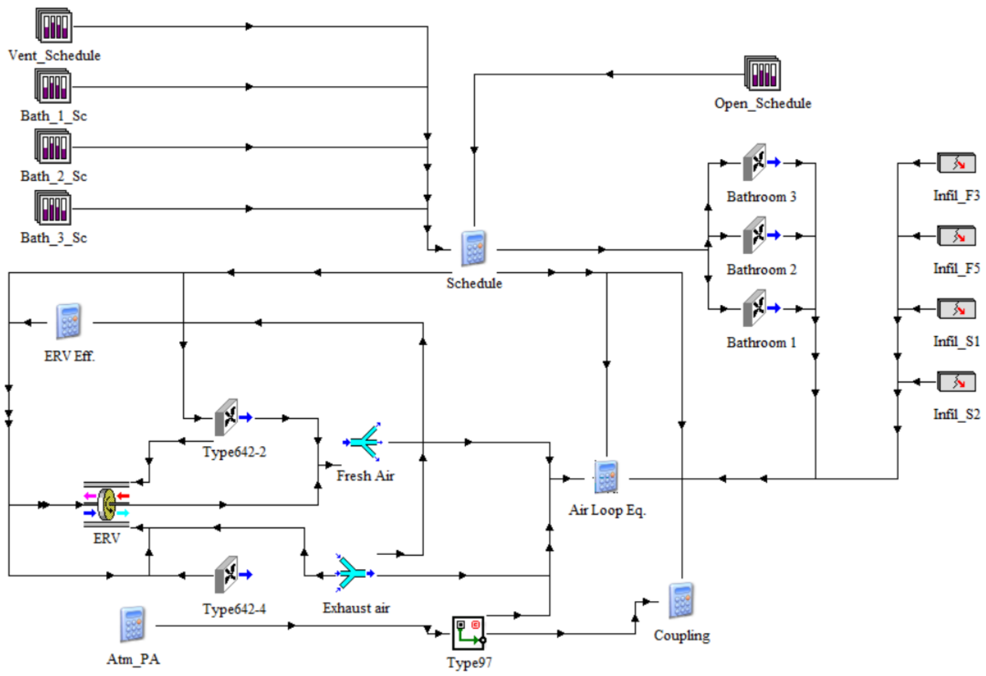


Figure 26: Ventilation System Overall Scheme

The mechanical ventilation system is mainly composed by an Energy Recovery Ventilator (ERV) whose main function is to provide the prescribed fresh air flow rate ensuring that the level of $PM_{2.5}$ and CO_2 will remain below the thresholds fixed during the contest. The efficiency work differently for heating and cooling mode, a logic switch ensures the use of the right one reading the external condition:

Table 21: ERV efficiency

Exchange efficiency [%]	
Heating	Cooling
61	76

The fresh air flow, 350m^3/h, exchange heat with the exhaust one, collected from the rooms F4(Corridor) and S4(Staircase), and then the flow is split in 4 equal flows directed to the conditioned zones: living room, kitchen and the two bedrooms. The ERV provides only sensible energy recovery, the control of humidity is done by the VRVs. The other mechanical equipment are the bathrooms ventilators, composed of 3 suction fans. The two used in the bathrooms on the upper floor also provide a fast heating capability: they recirculate a fraction of the flow heating it with an electrical resistance, this capability was simulated using a gain inside the zones. The infiltration was considered only inside the heating zones, being them the only one with façade's glazing opening on the outside. Due to the modular nature of the building and the fast assembling the air tightness could not be considered as good as for new buildings, the infiltration was calculated according to to ASHRAE standards for a medium thigh building using the following formula:

$$ACH = K_1 + K_2(T_{zone} - T_{ambient}) + K_3 * V_{wind}$$

$$K_1: Constant\ coefficient$$

$$K_2: Temperature\ dependent\ infiltration\ coefficient\ [\frac{ACH}{°C}]$$

$$K_3: Windspeed\ dependent\ infiltration\ coefficient\ \left[ACH.\frac{s}{m}\right]$$

A series of schedules control the turning on of the different systems and the switch between natural and mechanical ventilation-, the format allows to differentiate on hourly level and to select the number of different days:

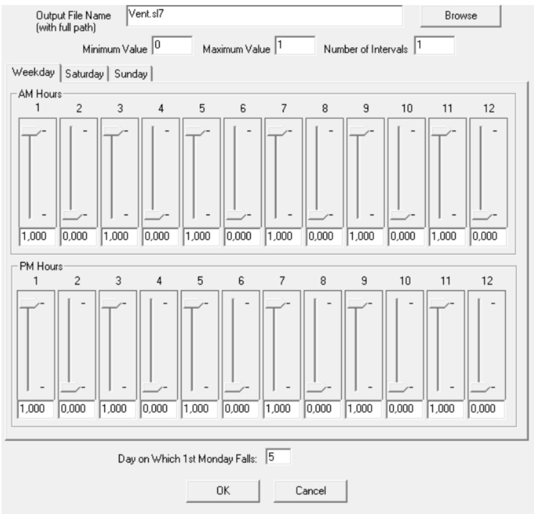


Figure 27: Ventilation Schedule

These signals are used to manually ensure the air balance between the different zones. To establish the airflow through the zones an external software was used to identify the air flows between the different zones with respect to the difference in temperature and pressure and on the size of the openings. The selected software was CONTAM; this software allows the user to create a model of the zones to be evaluated based on the air volume and geometrical size and then connect all the different zones through their openings [11]. The used openings for the simulation where:

Table 22: CONTAM opening

Name	Type	Formula
Open Door	Two-Way flow	Two-opening
Closed Door	Two-Way flow	One-opening
Open Window	Two-Way flow	Two-opening
Closed Window	Two-Way flow	One-opening
Open space	Two-Way flow	No-opening

Where:

- Two-opening: create a balance if there are more than one opening between two or more zones
- One-opening: used only if the connections are bi-univocal and mix the flows to balance both pressure and temperature through the single orifice
- No-opening: created to consider a perfect mixing between two zones that are not separated by any physical obstruction but are considered two different thermal zones

The wind speed, direction and outer temperature are taken into account to modify the pressure on the envelope through the placing of mock up opening on the exposed facades. The difference in height was acquired using a multi-layer simulation with 3 zones working with double-height configuration (Patio, Aquaponic and Staircase); these zones have, other than the normal flow path, an internal calculation to maintain the air with different temperature with a right stratification using a model for natural ventilation on a closed space. The graphical representation of the simulation is, on a single layer show-off, reported below:

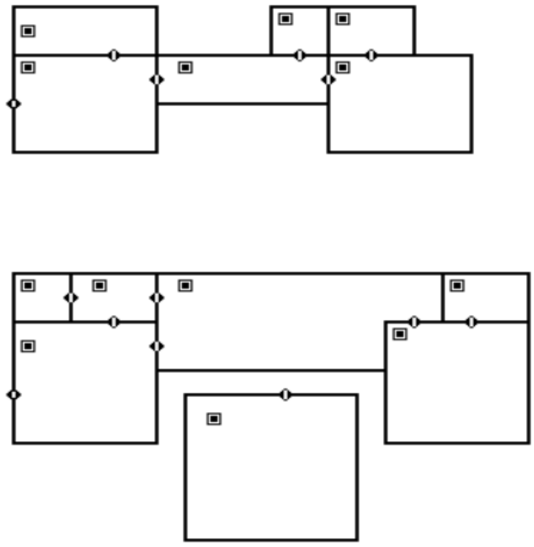


Figure 28: CONTAM Zone Distribution

The outcome of the simulation is the air flow between the adjacent zones with the relative temperature and pressure. These values were used to complete the air balance in the system. - this was obtained through a group of equation evaluating the flow between the zones, the mixing factor in natural ventilation and the infiltration expressed as air flows at outdoor conditions; In the following an example of balance equations for the zone F3-F4:

eql(Open,0)*F34+ gt(VV,0) * F_OUT_FLOOR/2 + gt(B1,0) * F_B1/2 +gt(Open,0)*Mix_al

Some considerations are needed:

- When the house is in natural ventilation mode the air flow due to the wind is remarkably higher than the one due to the pressure and temperature difference, therefore their value are mutually exclusive
- The mechanical ventilation air flows, the ERV and bathroom, due to their position are considered balanced between the adjacent room, so they are divided equally by the number of rooms.

Type:

- **Schedule – Type 516**

  The Multiple Schedules utility programs is used in conjunction with one another to input schedules with a Weekday, Saturday, and Sunday basis. It should be noted that while temperature notation is used throughout this documentation, there is no inherent reason why Type516 cannot be used to schedule any type of data desired by the user. Type516 allows for different schedules to be set for weekdays, Saturdays and Sundays.

- **Bathroom ventilator – Type 642**

  Type642 models a fan that is able to spin at a single speed and thereby maintain a constant mass flow rate of air. Type642 takes mass flow rate as an input but ignores the value except in order to perform mass balance checks. Type642 sets the downstream flow rate based on its rated flow rate parameter and the current value of its control signal input.

- **ERV – Type 760**

  Type760 uses an effectiveness – minimum capacitance approach to model an air to air heat exchanger that transfers only sensible energy. Type760 includes five different control modes. In the first of these control modes, the outlet temperatures of the two air streams are completely uncontrolled. In the other four operation modes, the temperature of either the fresh or exhaust air streams is maintained either above or below a user defined set point.

- **Infiltration – Type 571**

  ASHRAE long recommended the use of a semi empirical model for the calculation of infiltration to a conditioned zone. The so called K1, K2, K3 method is considered to be less rigorous than the calculation of infiltration based upon dynamic wind pressure, buoyancy forces and envelope characteristics. However, the more rigorous model requires extensive knowledge of parameters whose values are difficult to measure without a blower door test and the K1, K2, K3 model remains an accurate method for obtaining quick computation of infiltration.

- **Flow paths – Type 97**

This model allows to use the CONTAM Multizone Air Flow Model with TRNSYS. Type97 reads a CONTAM multizone building description file, computes the air flow model using CONTAM, and provides CONTAM outputs. CONTAM building description files (*.air files) can be created using the CONTAMW graphical user interface (use Simulation/Create TRNSYS input file in CONTAMW) [12].

4.3.2 Heating System

The heating system is composed by 4 different radiant floors in the main conditioned zones (F3, F5, S1, S2). Since the provided data gave only the specific power with a test floor a detailed simulation was carried out on a parallel simulation to calibrate the calculation of capacitance and heat transfer coefficient of the slab to be used in a simplified configuration. This process was carried out to speed up the simulation since the system will not be used for both calibration and the contest. The values were checked again through calculation.

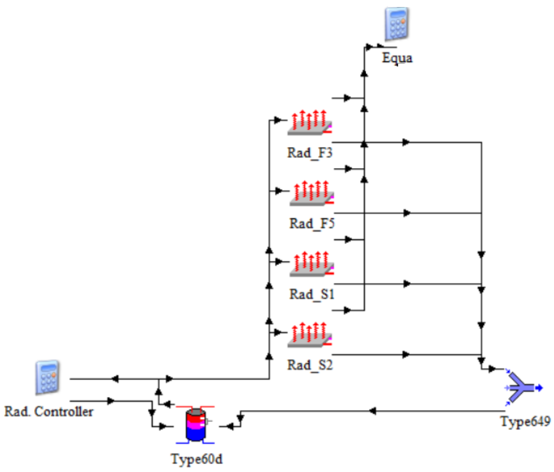


Figure 29: Heating system Overall Scheme

- Capacitance of the slab:

$$C_{slab} = \Sigma_i \rho^i c_p^i \lambda^i$$

- Heat transfer coefficient:

$$UA = \frac{A_{floor}}{\mathrm{R_{slab}}} = \frac{A_{floor}}{\frac{1}{h_{out}} + \Sigma\left(\frac{s}{\lambda}\right) + \frac{1}{h_{in}}}$$

The heat transfer coefficient was then split up to front and back to complete the configuration of the type. The tank is a 40l tank with an internal heat exchanger connected to a “black box” heat exchanger working as condenser of the HP. To simulate the process the internal heat exchanger was switched with a resistance and the energy input checked using equations. The control system relies on the rooms' thermostats input. A signal switch on and off the pump flow activating the heat exchange in the Radiant floor type. The energy is then sent to Type56 to be considered as a pure radiative gain in the zone.

Type:

- **Water tank – Type 60e**

  Type 60e models a stratified liquid storage tank. It includes numerous features such as thatallowing for multiple heat exchangers within the tank and allowing for unmatched numbers of inlet and outlet flows. This instance of Type60 models a vertically cylindrical tank with one inlet and one outlet flow. Users may define between 0 and 3 (inclusive) internal heat exchangers. It further includes calculation of losses from the tank to the flue if desired and assumes that all stratification nodes of the tank are uniform in size and that the UAs between each node and the ambient are equal.

- **Radiant Floor – Type 653**

  This component models a simple radiant slab (floor heating or cooling) system that operates under the assumption that the slab can be treated as a single lump of isothermal mass and that the fluid to slab energy transfer can be modelled using a heat exchanger effectiveness approach.

4.3.3 Cooling System

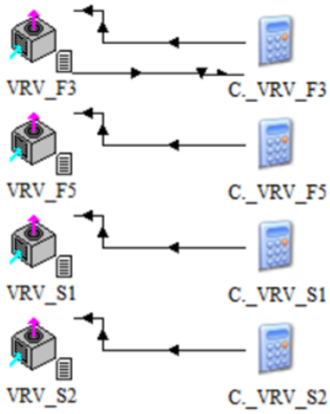


Figure 30: Cooling system Overall Scheme

The Cooling system is composed of 4 VRV connected with an external unit. Because of the peculiarity of the system the adopted solution to simulate it was to use 4 different standard split system, setting the rated maximum cooling power as from datasheet [13]. The part load power was evaluated by an equation type: reading the temperature in the room the type evaluate the energy needed to reach the setpoint in the evaluate timestep; if the energy is more than the one that the split can provide the temperature at the next timestep will be higher than the set point and the machine will work in full load, if the required energy is less than the one available the equation apply just part of that energy and the machine is considered on part load feature [14]. This procedure is applied to the 4 VRVs at every timestep. Knowing the part load, the temperature inside the room and the outdoor temperature it was possible to evaluate the COP of the machine using the capacity table provided by the sponsor, an example is provided below where TC indicate the cooling capacity and P the electrical power absorbed:

Combination (%)	Power (kW)	T out DB (°C)	T in WB (°C)													
			14.00		16		18		19		20		22		24	
			TC (kW)	PI(kW)	TC (kW)	PI(kW)	TC (kW)	PI(kW)	TC (kW)	PI(kW)	TC (kW)	PI(kW)	TC (kW)	PI(kW)	TC (kW)	PI(kW)
50%	7.75	10	5.2	0.45	6.2	0.52	7.2	0.59	7.8	0.63	8.3	0.67	9.3	0.76	10.3	0.84
		12	5.2	0.46	6.2	0.53	7.2	0.6	7.8	0.64	8.3	0.68	9.3	0.77	10.3	0.86
		14	5.2	0.46	6.2	0.53	7.2	0.61	7.8	0.65	8.3	0.7	9.3	0.78	10.3	0.87
		16	5.2	0.47	6.2	0.54	7.2	0.62	7.8	0.67	8.3	0.71	9.3	0.8	10.3	0.89
		18	5.2	0.47	6.2	0.55	7.2	0.63	7.8	0.68	8.3	0.72	9.3	0.81	10.3	0.91
		20	5.2	0.48	6.2	0.56	7.2	0.64	7.8	0.69	8.3	0.73	9.3	0.83	10.3	0.92
		21	5.2	0.48	6.2	0.56	7.2	0.65	7.8	0.69	8.3	0.74	9.3	0.83	10.3	0.93
		23	5.2	0.49	6.2	0.57	7.2	0.66	7.8	0.71	8.3	0.75	9.3	0.85	10.3	0.95
		25	5.2	0.5	6.2	0.58	7.2	0.67	7.8	0.72	8.3	0.78	9.3	0.89	10.3	1.02
		27	5.2	0.51	6.2	0.6	7.2	0.71	7.8	0.77	8.3	0.83	9.3	0.95	10.3	1.08
		29	5.2	0.54	6.2	0.64	7.2	0.75	7.8	0.81	8.3	0.88	9.3	1.01	10.3	1.15
		31	5.2	0.57	6.2	0.68	7.2	0.8	7.8	0.86	8.3	0.93	9.3	1.07	10.3	1.23
		33	5.2	0.6	6.2	0.72	7.2	0.85	7.8	0.92	8.3	0.99	9.3	1.14	10.3	1.3
		35	5.2	0.63	6.2	0.76	7.2	0.9	7.8	0.97	8.3	1.05	9.3	1.21	10.3	1.39
		37	5.2	0.67	6.2	0.8	7.2	0.95	7.8	1.03	8.3	1.11	9.3	1.28	10.3	1.47
		39	5.2	0.7	6.2	0.85	7.2	1	7.8	1.09	8.3	1.18	9.3	1.36	10.3	1.56

Figure 31: Example Capacity Table

The combination factor indicates the part load of the system (with the maximum power used). Despite the system having a combination factor of 115%, the amount of max power is the nominal of the system; if the requested power exceeds the nominal one the only internal machine working at maximum will be the one further from the set point with all the others working on part load. From this table, fixing the set point temperature is possible to evaluate the COP:

Table 23: COP table - part load

T in WB [°C]	16.2	% load					
		50%	60.0%	70.0%	80.0%	90.0%	100.0%
T out DB [°C]	10.00	11.95	11.20	10.23	9.25	8.16	7.13
	12.00	11.73	11.03	10.10	9.08	7.99	7.01
	14.00	11.71	10.87	9.88	8.91	7.87	6.86
	16.00	11.49	10.72	9.76	8.76	7.71	6.74
	18.00	11.29	10.56	9.55	8.61	7.55	6.60
	20.00	11.09	10.41	9.35	8.46	7.45	6.49
	21.00	11.07	10.27	9.34	8.39	7.35	6.41
	23.00	10.88	10.13	9.14	8.17	7.05	6.00
	25.00	10.70	9.85	8.76	7.72	6.59	5.62
	27.00	10.31	9.34	8.25	7.21	6.19	5.26
	29.00	9.68	8.79	7.74	6.77	5.80	4.93
	31.00	9.11	8.31	7.28	6.38	5.46	4.62
	33.00	8.60	7.79	6.87	5.99	5.13	4.34
	35.00	8.14	7.40	6.46	5.65	4.82	4.08
	37.00	7.73	6.98	6.10	5.32	4.53	3.83
	39.00	7.28	6.56	5.74	5.00	4.26	3.60

In order to use it directly in the simulation at every timestep, instead of using a linear interpolation the fitting function of the COP has been found through a polylinear regression using a MATLAB code to obtain and test it [15]. The result is:

$$f(x,y) = p_{00} + p_{10}x + p_{01}y + p_{20}x^2 + p_{11}xy + p_{02}y^2 + p_{30}x^3 + p_{21}x^2y + p_{12}xy^2$$

Where x is the Part Load, y is the Outdoor Temperature and the coefficients are:

- p00 = 8.766
- p10 = 17.02

- p01 = 0.2953
- p20 = -28.05
- p11 = -0.5104
- p02 = -0.008196
- p30 = 10.05
- p21 = 0.1791
- p12 = 0.006246

The goodness of fit is:

- R-square: 0.9964
- Adjusted R-square: 0.9961
- RMSE: 0.1329

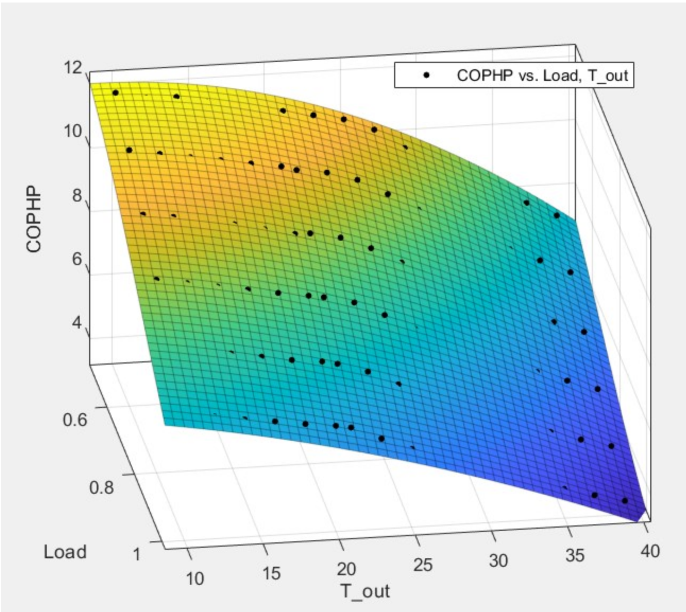


Figure 32: COP evaluation function of Load factor and Outdoor Temperature [°C]

The external unit type read the part load as the sum of all the power used by the internal machines and the outdoor temperature from the weather file and give the COP as an output to evaluate the electrical energy consumption.

Type:

- **VRVs – Type 756**

  The component models an air conditioner for residential or commercial applications. The model requires an external file of performance data that contains the total capacity, sensible capacity and power as a function of the outdoor dry-bulb temperature, the indoor dry-bulb temperature, the indoor wet-bulb temperature, and the evaporator flow rate.

4.4 Simulation Results

Before moving on with the calibration itself the model underwent a "logical behaviour calibration", as suggested by McKenna et al. in [17], to assess if the physics of the simulation worked properly compared with the previous simulation on Design Builder and if trivial modification on the parameters cause the expected results. The simulated periods where both annual and contest weeks. Starting with the latter, the simulation was performed under this hypothesis:

- Contest week period: 5112 hr -5472 hr
- Annual simulation: 0 hr – 8760 hr
- Weather file: Dezhou (Rhaoyang)
- Ventilation schedule:
  - On: 18:00 – 08:00
  - Off: 08:00 – 18:00
- Bathroom schedule: Always off

The simulation during the contest weeks shows that the system is, as expected, capable of overcoming the heat load and works on part load. During the contest period the temperature are maintained flawlessly inside the wanted thresholds. The energy consumption and temperature behaviour are shown below:

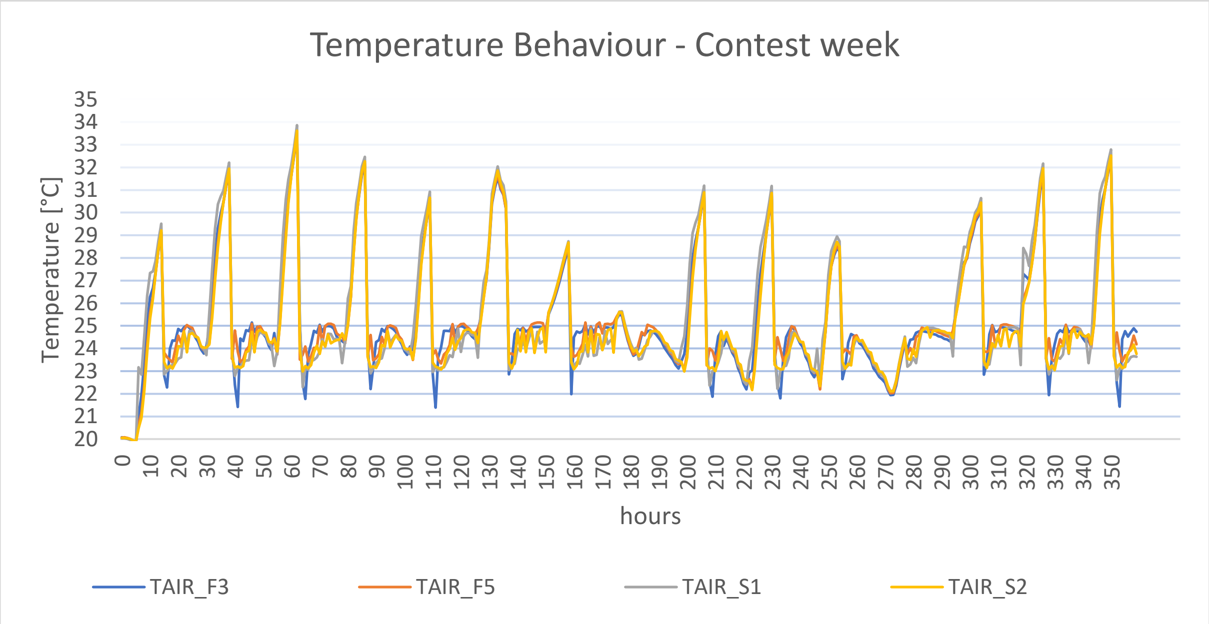


Figure 33: Temperature Behaviour - Contest Week

Table 24: Contest Week Preliminary Simulation

Day	En. Th. cooling [kWh]	En.El. cooling [kWh]
1	25.91	2.30
2	33.46	3.06
3	32.83	3.07
4	28.60	2.61
5	28.16	2.55
6	26.93	2.43
7	18.63	1.68
8	12.63	1.11
9	28.84	2.57
10	30.18	2.69
11	20.03	1.73
12	9.00	0.80
13	27.09	2.40
14	34.00	3.06
15	33.82	3.12
Tot	390.12	35.20

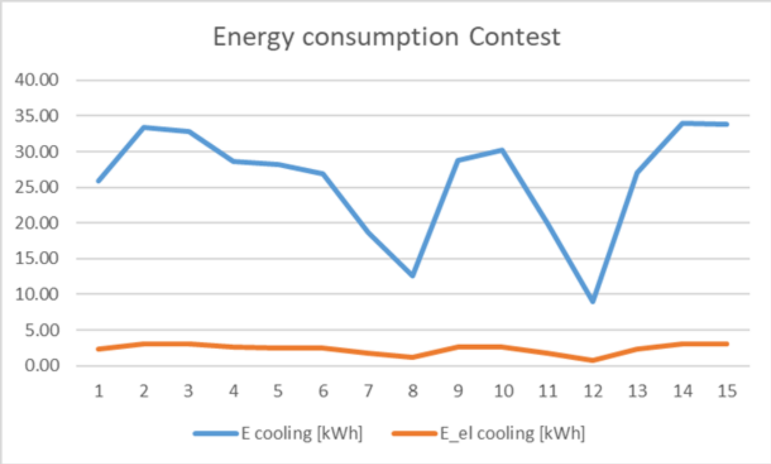


Figure 34: Energy Production-Consumption Contest

Table 25: Contest Week Energy Cumulative

Day	Sum En. Th. cooling [kWh]	Sum En.El. cooling [kWh]
1	25.91	2.30
2	33.46	3.06
3	32.83	3.07
4	28.60	2.61
5	28.16	2.55
6	26.93	2.43
7	18.63	1.68
8	12.63	1.11
9	28.84	2.57
10	30.18	2.69
11	20.03	1.73
12	9.00	0.80
13	27.09	2.40
14	34.00	3.06
15	33.82	3.12
Tot	390.12	35.20

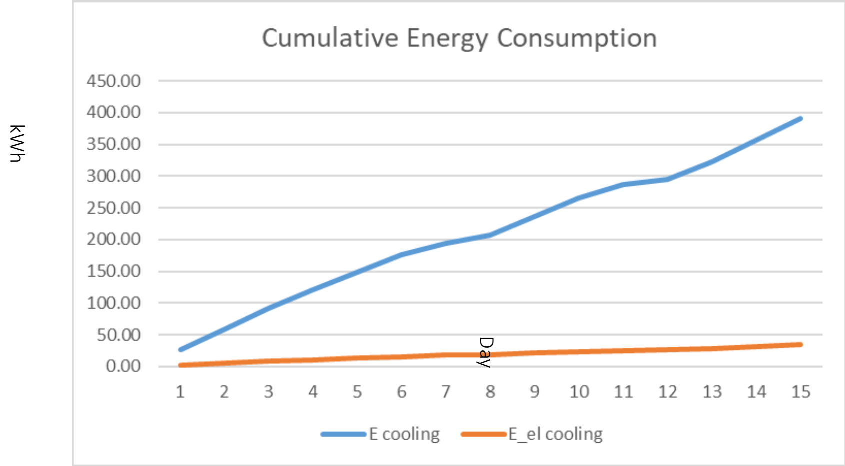
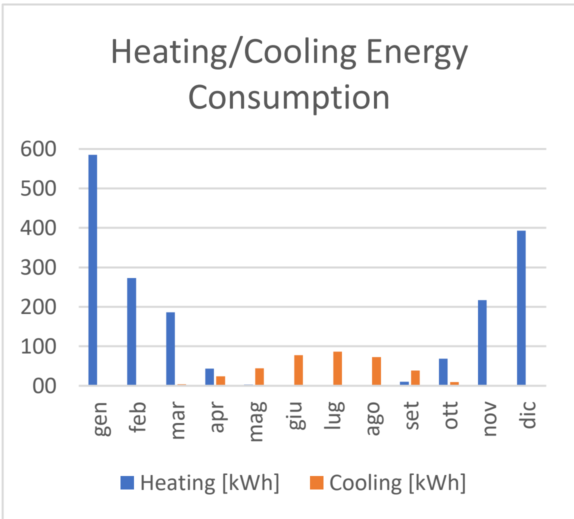


Figure 35: Cumulative Energy Consumption-Production

On a yearly basis the results are perfectly matching the previous simulations and building type expectations [18] with the results expressed in the following graphs:

Table 26: Yearly Simulation Results

Month	Heating [kWh] Th.En–En.El.		Cooling [kWh] Th.En–En.El.	
Jan	2361.6	584.8	0.0	0.0
Feb	1443.0	273.3	0.0	0.0
Mar	1088.9	186.6	42.1	3.6
Apr	296.2	43.3	288.2	24.4
May	23.5	3.3	504.2	44.1
Jun	0.0	0.0	821.2	77.4
Jul	0.0	0.0	944.4	86.6
Aug	0.0	0.0	806.9	72.4
Sept	73.4	10.2	435.6	38.4
Oct	459.7	68.3	107.1	9.1
Nov	1240.8	217.0	12.7	1.1
Dec	1957.3	393.4	0.0	0.0
Tot	8944.5	1780.2	3962.3	357.1



The next step was to perform the logical check of the goodness of the simulation; starting with the following hypothesis:

- Start: 0 hr
- Stop: 8760 hr
- Weather file: Guangzhou
- Ventilation schedule:
    - On: 18:00 – 08:00
    - Off: 08:00 – 18:00
- Bathroom schedule:
    - Always off
- Internal Gain: not set
- Occupancy: not set

The results are then compared to different runs of the same simulation under other condition to check if the logical expectation about the behaviour of the Energy demand are fulfilled. The comparison was done with respect to the following modifications:

A. Shading always off
B. Ventilation always off
C. Ventilation always on

Studying the results will give a first evaluation of the simulation reliability. The several runs under different conditions where then launched to ensure the logical behaviour of the envelope:

- Ventilation On-Off-Schedule

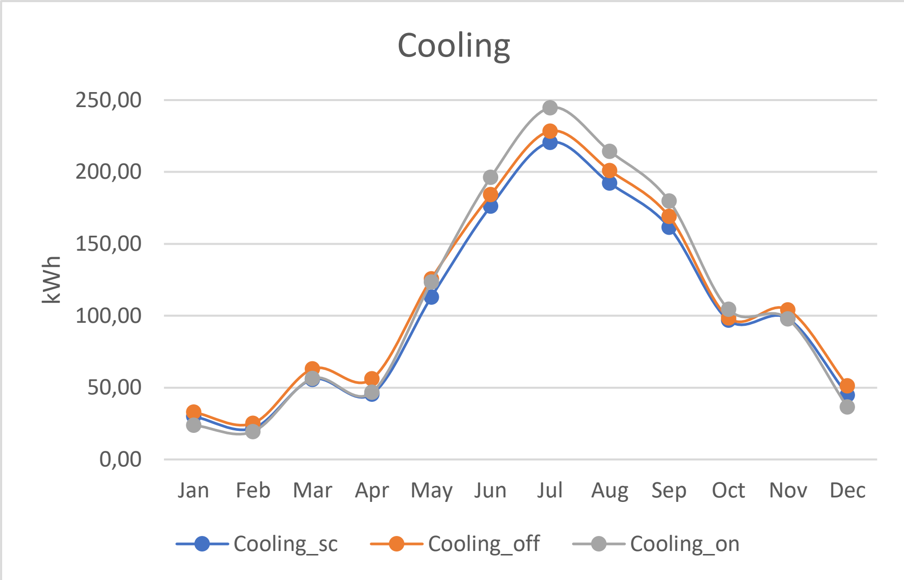


Figure 36: Cooling Energy - Ventilation On/Off

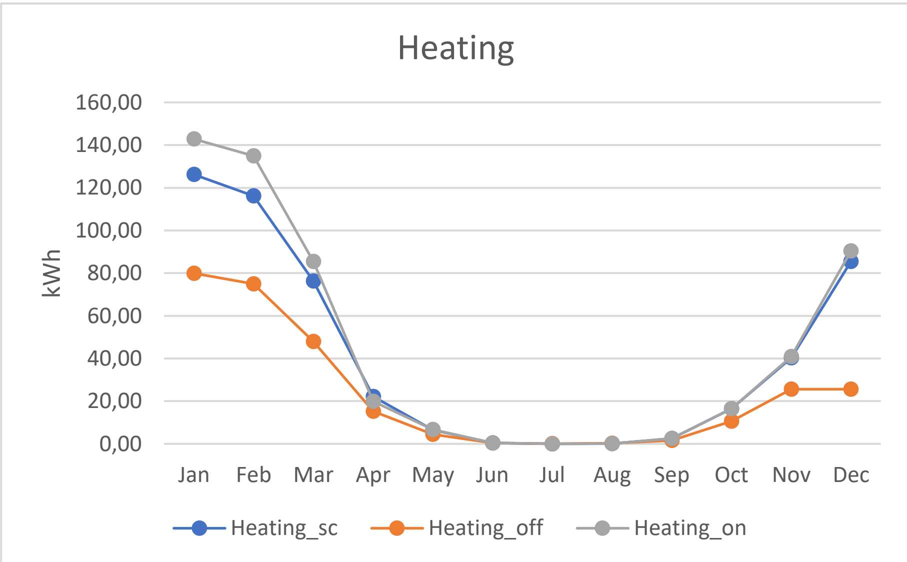


Figure 37: Heating Energy - Ventilation On/Off

The results are consistent with the physics of the simulations; the use of the ventilation system increase the loads on the HVAC system. Remarkably the use of a superior design schedule during summer allows to reach the best energy savings by using the air as much as possible during the coldest hours of the day.

- Shading On-Off

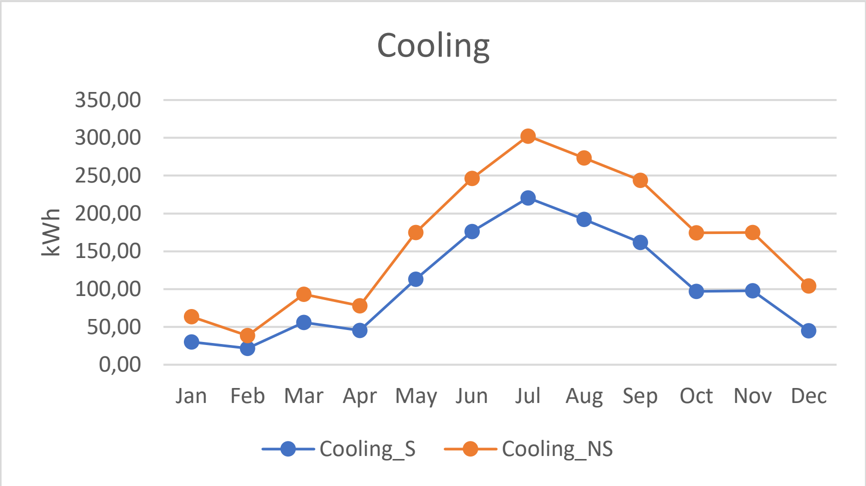


Figure 38: Cooling Load Shading On/Off

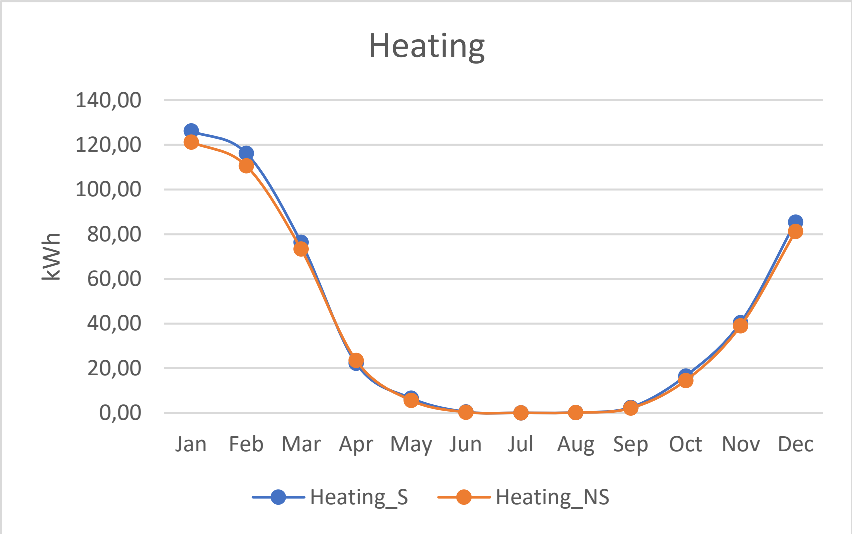


Figure 39: Heating Load Shading On/Off

All the results behaved as expected with the biggest variations on the cooling load with the variation of the shading while the main variation on heating load occurs when ventilation is always on due to the temperature outside being always below the set point.

4.5 List of Parameters

The further step to perform the final calibration is to find the most influent parameters through a sensitivity analysis. In order to perform it is good to have a list of the possible parameters to identify the one that are more prone to errors in the simulation phase due to unknow values or datasheet in test condition with respect to real deployment operations. The parameters set for the simulation have been listed below:

Table 27: Total parameters list

Parameters			
Name	**Value**	**Units**	**Source**
TYPE 56			
Zones/Glazing Size	-	m	Project Data
Materials Thickness	-	mm	Project Data
Materials Conductivity	-	W/m K	Project Data/Standards
Zones Capacitance	-	kJ/K	Standards
Zones Gain	-	-	Standards
Internal Convective Heat Transfer Coefficient	11	kJ/h m^2 K	Standards
External Convective Heat Transfer Coefficient	64	kJ/h m^2 K	Standards
U -Value Windows	-	W/m^2 K	Project Data
G - Value Windows	-	%	Project Data
U-Value Frame	-	kJ /h m^2 K	Project Data
Absorbance Frame	-	%	Project Data
Area frame/Window	-		Project Data
Reflection Coef. Internal Device	-	%	Project Data
Geosurf	-	%	Project Data
Shading Factor	-	%	Project Data
Fraction of Abs Solar Radiation to Zone Air Node	-	%	Project Data
Air coupling zones	-	m^3/s	Evaluation/Mass Balance
Infiltration (only conditioned zones)	-	ach	Type dependent function
Internal Convective Heat Transfer Coefficient_W	11	kJ/h m^2 K	Default
External Convective Heat Transfer Coefficient_W	64	kJ/h m^2 K	Default
Density of air	1.204	kg/m^3	Default
Specific heat of air	1.012	kJ/kg K	Default

Heat of vaporization of water	2454	kJ/kg	Default
Stefan Boltzmann Constant	2.04E-07	kJ/h m^2 K^4	Default
Approx. average surface temp.	293	K	Default
Constant Heated Floor	7.2	kJ /m^2 K	Default
Exponent Heated Floor	0.31		Default
Constant vertical surface	5.76	kJ /m^2 K	Default
Exponent vertical surface	0.3	-	Default
Simulation Studio			
ERV (Type 760)			
Rated Power	169	kJ/h	Datasheet
Exhaust Air Flow Rate	361	kg/hr	Project Data
Fresh Air Flow Rate	421	kg/hr	Project Data
Sensible Effectiveness	-	%	Datasheet
Suction Fan (Type 642)			
Rated Flow Rate	-		Datasheet
Rated Power	-		Datasheet
Infiltration evaluator (Type 571)			
Zone Volume	-	m^3	Project Data
K1 coef.	-	ACH	Standards
K2 coef.	-	ACH/C	Standards
K3 coef.	-	ACH.s/m	Standards
Schedule Management (Type 516)			
On/Off cycle input	-	-	Predicted Value
Weather Data (Type 15-3)			
Dry Bulb Temperature	-	°C	Energy+ Weather File
Effective Sky Temperature	-	°C	Energy+ Weather File
Percent RH	-	%	Energy+ Weather File
Wind Velocity	-	m/s	Energy+ Weather File
Total Horizontal Radiation	-	kJ/h m^2	Energy+ Weather File
Angle of Incidence for Horizontal	-	°	Energy+ Weather File
Horizontal Beam Radiation	-	kJ/h m^2	Energy+ Weather File
Total Tilted Radiation (surfaces)	-	kJ/h m^2	Energy+ Weather File
Beam Radiation (surfaces)	-	kJ/h m^2	Energy+ Weather File
Angle of Incidence (surfaces)	-	°	Energy+ Weather File
Radiant system tank (Type 601)			
Tank loss Coef.	2	kJ/h m^2 K	Standards

Set Point Temperature	35	°C	Project Data
Death band for heating power	3	°C	Project Data
Power Inlet from HP	16	kW	Project Data
Flow rate Radiant floor	20	kg/h m^2	Project Data
Radiant floor (Type653)			
Capacitance of the slab	-	kJ/K	Standards
Slab to ambient loss coefficient	-	kJ/h K	Standards
Slab to zone Heat transfer coef.	-	kJ/h K	Standards
Heat exchanger effectiveness	0.8		Project Data
VRF (Type 756)			
Flow rate external coil	-	l/s	Project Data
Cooling Power	-	kW	Project Data
Sensible Cooling Power	-	kW	Project Data
Electrical Power	-	kW	Project Data
Evaporator Flow rate	-	m^3/s	Project Data
Thermostat controller (Type 698)			
Temperature dead band	2	°C	Project Data
Heating Set Point	20	°C	Project Data
Cooling Set Point	24	°C	Project Data

The total number of used defined parameters is 302 but among them only a certain number can be actively used for calibration due to their source or the use done in the simulation, as highlighted by R. Enriquez at al. [16]. In the next chapter these parameters will be reduced through a Sensitivity Analysis, picking only the ones that have a higher influence on the simulation.

5. Sensitivity Analysis

As seen in the previous chapter, working with Building Energy Models requires quite a high number of parameters to be set. Since the final topic of this project is to calibrate the model through the variation of these parameters, the computational cost would be impossible to be handled. This problem is easily overcome by the identification of those parameters that have the biggest impact on the simulation results [19]. The most used technique to select the parameters is based on the experience of the modeller, which uses previous projects and technical literature to pick the right set; the only possibility to check the results is to set up different simulations manually and compare the results. This method could lead to many errors, firstly because it is strictly connected to the user's experience, secondly because it does not check evenly the possible interaction between the parameters. More rigorous methods are offered by Sensitivity Analysis; it is a branch of the Uncertainty Analysis focussed on the evaluation of the weight of the inputs on the output of a mathematical model. Since many years, these methods are used to increase models' reliability in many fields such as economics, medicine and engineering.

5.1 Selection of Sensitivity Analysis method

Several Sensitivity Analysis methods could be applied to a model giving different information about the input parameters, as suggested by Nguyen and Reiter [2]. Different methodologies have to be studied to find the one that fits better the study. The main classification, according to the study of Saltelli&Sobol [20], divides between local and global methods:

- **Local:** local methods rely on the effect of the different parameters on the model outcome, without studying their effect on the variance, following the evaluation of the partial derivatives. They allow the analyst to easily sort the parameters according to the variation caused to the results. The structure of this methods is based on the One-At-Time sampling, with the evaluation of the model at every step; the result of the analysis is expressed in terms of "Sensitivity Indices", basically a comparison between the results at the sorted point in the space of solution and a baseline value properly definite. These methods are relatively faster than global ones but with the main drawback of *lacking information about unexplored space unless the problem is proven linear* (Saltelli and Annoni, 2010).

- **Global:** the global methods explore the whole parameter's hypercube through linear regression and correlation between them at every step by assuming to know the exact value of a parameters. They are variated all at the same time and selected consequently to a pre-defined probability density function. These methods are used when the analyst lacks any information about one or more parameters. Among these the most common are Sobol's method (variance based), FAST method (Fourier's amplitude sensitivity test) [21].

Being the matter of this study a calibrated simulation the focus has been set on the most important parameters among the ones previously listed. This would have led to the choice of an OAT method, but this require a linearity assumption that difficulty fit a BES, mostly because the high number of parameters inserted. A good compromise has been found in the Morris method. This procedure shares some characteristics from both local and global methods. Listed above are the main pros of this technique:

- Provide the influence sorting of the parameters
- Does not depend on properties and does not require linearity assumption
- The hyperspace could be explored evenly without defining parameters' probability density functions in advance
- Graphical interpretation of the results
- Reduced computational time
- Easy implementation

5.2 Mathematica Structure of Morris Method

Morris Method (MM) [22] works using “trajectories”: from a first step in the hypercube of possible values the coordinates move variating only one parameter at each step [3]. It relies on the evaluation of a Sensitivity Index several times for every parameter. Suppose to have a system composed by k parameter Xi, the used SI is called Elementary Effect and is defined as:

$$EE_i(\underline{X}^j) = \frac{Y(X_1^j, \dots, X_{i-1}^j, X_i^j + \Delta, X_{i-1}^j, \dots, X_k^j) - Y(\underline{X}^j)}{\Delta}$$

Where *Y* represent the system’s output before and after the variation of the i^{th} parameter of the quantity Δ. This is an incremental effect proportional to *p*, where *p* is defined as the number of parameters’ variation studied: indeed, the field of variation for each of them is {0;1} divided in the following set:

$$\left\{0; \frac{1}{p-1}; \dots; \frac{n}{p-1}; \dots; \frac{p-2}{p-1}; 1\right\}$$

The Elementary effect is computed for *r [j= 1,… ,r]* trajectories: one variation for every parameter plus one base value; after that, the mean value and the standard deviation are evaluated to allow the sorting of the parameters:

$$\mu_i = \frac{\sum_{j=1}^{r} EE_i(\underline{X}^j)}{r}$$

$$\sigma_i = \sqrt{\frac{\sum_{j=1}^{r} \left[EE_i(\underline{X}^j) - \mu_i\right]^2}{r}}$$

The results are then plotted, and the parameters can be sorted. Since the Elementary Effect could assume negative values, to avoid cancellation errors it is good practice to also evaluate the mean value of the Elementary Effect:

$$\mu_i^* = \frac{\sum_{j=1}^{r} \left|EE_i(\underline{X}^j)\right|}{r}$$

According to Morris and Campolongo et Al. valid values for the EE method's parameters are:

$$p = an\ even\ number$$

$$\Delta = \frac{p}{2(p-1)}$$

While the choice of the number of trajectories r is led to the exploration level wanted, but always directly proportional to the number of possible level p.

5.2.1 Enhancing the method efficiency

The main drawback of the method, as reported in [4] is that, in order to maintain the computational cost low, only *r(k+1)* values of Elementary effect are evaluated, with a high part of the parameters space unexplored. There are several sampling methods to decrease this effect [23], in this study two of them are reported.

Radial Latin Hypercube Sampling: This procedure relies on the lesser probability to have repetition if the sampling space is "spherical". For every trajectory, a starting point is randomly selected, its value is then fixed, and the variation of the parameters starts from the starting value. The implementation of this sampling strategies is simple, and many examples are provided for free online, so the code was not developed. This will be used as a baseline sampling strategy since is better than the purely random one, but it is still prone to superpositions errors.

Optimized Latin Hypercube Sampling: First developed by Campolongo at Al. (2007) and applied to chemical reactors modelling this procedure uses a brute force approach to generate *M>>r* trajectories, evaluating the geometrical distance between every possible set of *r* trajectory and then sorting them to identify the one with the highest spread among the hypercube.

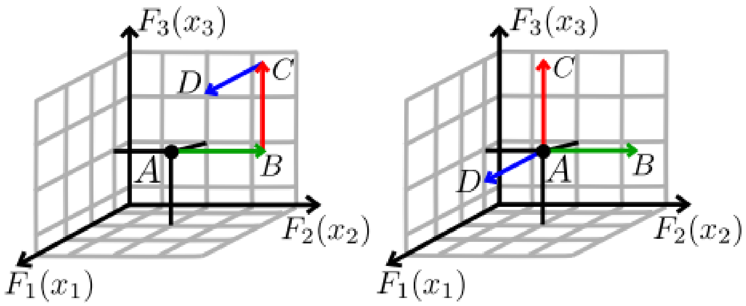


Figure 40: Trajectory vs. Radial Sampling

This work was developed according to the latter sampling strategy whose implementation will be explained in the next chapter.

5.3 Implementation of the method

The platform chosen for the implementation was MATLAB® R2017b due to the complete and precise array management of the software [24].

5.3.1 Optimized sampling

The first step of implementation is to set the constants *k* and *p*. These must be set accordingly to the study and will partially affect the optimization computational cost. Then M, the total number of trajectories to be generated, and r, the number of trajectories to use for Sensitivity analysis, are set; this step is the one that will affect the most the computational cost of the process since the total number of distance to be computed are given by the possible combination of r elements out of M.

E.g.) r= 4 M= 10

$$\#\text{Dist} = \binom{M}{r} = \binom{10}{4} = 210$$

r=10 M=100

$$\#\text{Dist} = \binom{M}{r} = \binom{100}{10} = 17'310'309'456'440$$

The operation is highly time consuming, suggested level of M are even higher (i.e. 500) but they require several weeks to be done. The level of precision will be higher the higher is the value of M but, since the number of trajectories are still the same it is possible to decide the wanted level of precision reducing the computational cost according to the analyst's needs [25].

The next step is to generate the randomized trajectories; one of the easiest ways is through the matrix:

$$B^* = \left(J_{k+1,1}x^* + \frac{\Delta}{2}\left[\left(2B - J_{k+1,k}\right)D^* + J_{k+1,k}\right]\right)P^*$$

Where:

$$J_{k+1,k}: k + 1 byk \ ones \ matrix$$
$$x^*: random \ baseline \ value$$
$$D^*: k \ by \ k \ diagonal \ matrix \ of \ random \pm 1$$
$$P^*: k \ by \ k \ matrix, one \ element \ per \ raw = 1; no \ coloumn \ has \ 2 \ value = 1$$

This sampling is repeated for M different trajectories.

To optimize the choice of the trajectories, following the procedure described by Campolongo, the spread between all the pairs must be computed. There are several methods to evaluate it, like Manhattan distance or Euclidian distance, in this study the latter is used. The distance is evaluated as:

$$d_{ml} = \Sigma_{i=1}^{k+1} \Sigma_{j=1}^{k+1} \sqrt{\Sigma_{z=1}^{k} \left(X_z^i(m) - X_z^j(l)\right)^2}$$

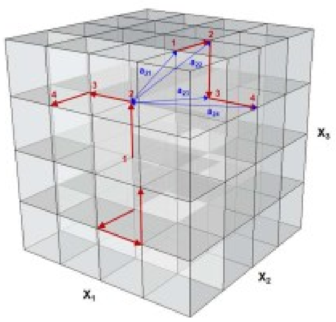


Figure 41: Example of distance Evaluation

Where *m* and *l* are generic trajectories (if $m=l$ $d_{ml}=0$). Then, after assessing all the distances the step forward is to compute the total spread of all the combinations of r possible trajectories among the generated M ones:

E.g.) r=3 {x,y,z}

$$D_{x,y,z} = \sqrt{d_{x,y}^2 + d_{x,z}^2 + d_{z,y}^2}$$

The best trajectories to be studied will be the ones with the highest cumulative distance Dx,y,z.

5.3.2 Sensitivity Analysis run

The stored best r trajectories are then called in the SA function with also the number of parameters k and the number of step p and the function to be evaluated. The code will take step by step by step every trajectory and for each it will compute the function with the set of prescribed parameters storing the result to be used as baseline value for the next step until all the *k+1* runs occur. At every run, the current value and the previous one is used to evaluate the Elementary effect that will be print together with the information about the coordinates. At the end of the *r* runs of the code it is possible to evaluate the mean value and standard deviation for the elementary effect of every parameters. The results are then plotted and printed for further evaluations.

5.4 Parameters Choice

Among the parameters listed in the previous chapter only the ones with a known high influence in BEM results were considered [26]. For a first selection level previous projects have been studied to evaluate the best parameters to run in sensitivity analysis. After that for every parameter was defined a lower and an upper bound; the written code would modify the value after every simulation dividing the probability of picking on value or another evenly. In order to explore both the “ideal” calibration and the one that would actually be performed, two different sets have been developed. The first one, the theoretical one, list all the parameters that could be possibly calibrated in a building in fully operational conditions, while the second set explores the possible parameters to be implemented in a construction site calibration; these second set offers the possibility to improve the knowledge of the building envelope as well as the performance of some mechanical equipment with the possibility to operate them on a fixed schedule during the off-work hours. The first set is listed in the table below:

Table 28: Total Parameters

#	Parameters SA	Min	Max	Units	Source
1	Internal Convective Heat Transfer Coefficient_W	5	9	kJ/h m^2 K	Standards
1	External Convective Heat Transfer Coefficient_W	54	74	kJ/h m^2 K	Standards
1	Approx. average surface temp.			K	Default
4	Infiltration flow rate (percentage modifier)	-0.1	0.1	m^3/s	Evaluation
6	Zones Capacitance (percentage modifier)	0	0.15	kJ/K	Standards
1	Internal Convective Heat Transfer Coefficient	5	9	kJ/h m^2 K	Standards
1	External Convective Heat Transfer Coefficient	54	74	kJ/h m^2 K	Standards
1	Phenolic Conductivity			kJ/h m K	Project Data
1	VIP Thermal resistance			h m^2 K/kJ	Project Data
1	ERV Sensible Effectiveness (percentage modifier)	-0.1	0.1	%	Datasheet
14	Air coupling zones	-0.1	0.1	%	Evaluation
4	Reflection Coef. Internal Device	0	0.4	%	Project Data
4	Shading Factor	0	0.8	%	Project Data
40	Tot				

Many parameters depend from calculation and not just from inputs, for them the variation is inserted as a percentage modifier. The next table lists the second set, the one that, because of the building site progress, will be used for the actual calibration:

Table 29: Sensitivity Analysis Parameters

Parameter	Min	Max	Unit	Note
Internal Convective Heat Transfer Coefficient_W	5	9	kJ/h m^2 K	Literature
External Convective Heat Transfer Coefficient_W	54	74	kJ/h m^2 K	Literature
Approx. average surface temp.	293	303	K	Default
Infiltration flow rate F3	-0.1	0.1	%	Type evaluation
Infiltration flow rate F5	-0.1	0.1	%	
Infiltration flow rate S1	-0.1	0.1	%	
Infiltration flow rate S2	-0.1	0.1	%	
Zones Capacitance F3/Volume	0	0.15	%	Evaluation
Zones Capacitance F5/Volume	0	0.15	%	
Zones Capacitance S1/Volume	0	0.15	%	
Zones Capacitance S2/Volume	0	0.15	%	
Internal Convective Heat Transfer Coefficient	5	9	kJ/h m^2 K	Standards
External Convective Heat Transfer Coefficient	54	74	kJ/h m^2 K	Standards
Phenolic Conductivity	-0.05	0.05	%	Project Data
VIP Thermal resistance	-0.05	0.05	%	Project Data
ERV Sensible Effectiveness (percentage modifier)	-0.1	0.1	%	Datasheet
Shading Factor Horizontal	0	0.1	-	Project data
Air coupling zones F1-S4	-0.1	0.1	%	Evaluation/Mass Balance
Air coupling zones F7-S4	-0.1	0.1	%	
U-Value Frame Windows type #1	-0.1	0.1	%	Project Data
Absorbance Frame Windows type #1	-0.1	0.1	%	
Area frame/Window Windows type #1	-0.1	0.1	%	
U-Value Frame Windows type #2	-0.1	0.1	%	
Absorbance Frame Windows type #2	-0.1	0.1	%	
Area frame/Window Windows type #2	-0.1	0.1	%	
U-Value Frame Windows type #3	-0.1	0.1	%	
Absorbance Frame Windows type #3	-0.1	0.1	%	
Area frame/Window Windows type #3	-0.1	0.1	%	
Coupling Open house	-0.1	0.1	%	Contam Evaluation

5.5 Sensitivity Analysis results

After the definition of the parameters the following step is to set up the template of the Simulation studio's .dck file and Type-56's .bui file; the templates have to be updated in the SA function to allow the iterative procedure. After the set-up of all the different sections the Trajectory generation, their optimization and Sensitivity Analysis are called in sequence trough a script: the settings used are listed above:

Table 30: Sensitivity Analysis settings

Trajectories	Parameters	Variation Steps
10	27	4

In the next table the results obtained are shown:

Table 31: Sensitivity Analysis results

#	Parameter	mu [kWh]	mu^* [kWh]	sigma [kWh]
1	ERV	0.0363	0.1650	0.0369
2	H_in	0.3077	0.3137	0.0534
3	H_out	-0.2274	0.2683	0.0752
4	HW_in	0.2174	0.2509	0.0576
5	HW_out	-0.0710	0.1711	0.0444
6	Inf_f3	0.0547	0.1672	0.0441
7	Inf_f5	-0.0026	0.0859	0.0120
8	Inf_s1	-0.0949	0.2568	0.1211
9	Inf_s2	-0.1001	0.2095	0.0557
10	AC_14	0.0337	0.1851	0.0803
11	AC_17	-0.0194	0.2181	0.1089
12	Sh_hor	-0.5973	0.5973	0.0432
13	AC_od	-2.0583	2.0583	0.0177
14	U_fr_fac	0.0510	0.1622	0.0399
15	Rat_fr_fac	-0.2487	0.2539	0.0568
16	U_fr_RP	-0.0414	0.1217	0.0394
17	Rat_fr_RP	-0.0062	0.1532	0.0366
18	U_fr_RS	0.0811	0.1491	0.0387
19	Rat_fr_RS	0.0981	0.2335	0.1240
20	Cap_f3	1.1619	1.1619	0.2946
21	Cap_f5	0.0577	0.2020	0.0773
22	Cap_s1	-0.0155	0.2207	0.0726
23	Cap_s2	0.0724	0.1288	0.0196
24	Phen_Cond	0.5109	0.5109	0.0652
25	Vip_resi	-0.0500	0.1052	0.0150
26	T_ground	-0.0640	0.1231	0.0245
27	Abs_fram_fac	0.0937	0.1355	0.0243
28	Abs_fram_RP	0.0055	0.0697	0.0117
29	Abs_fram_RS	-0.0862	0.1544	0.0332

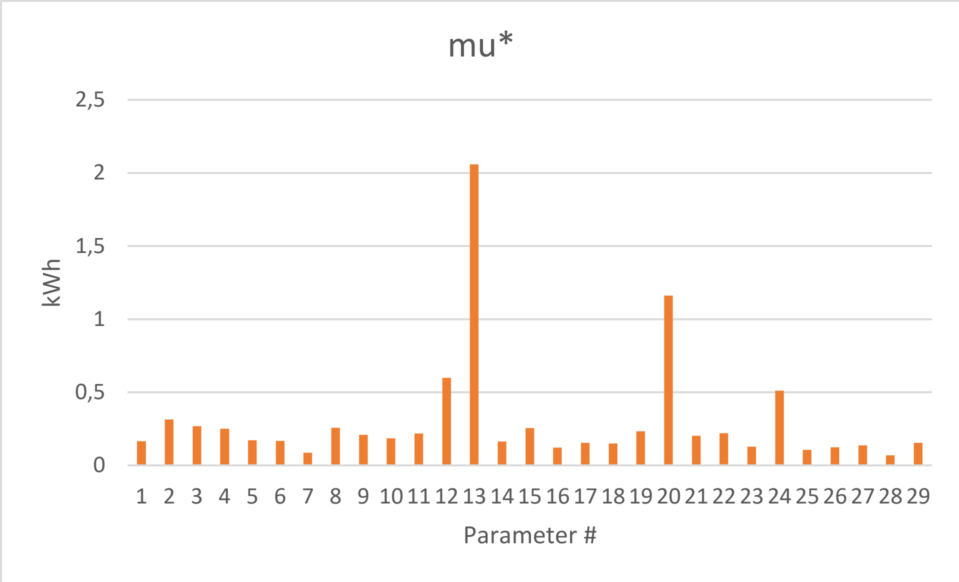


Figure 42: Mean Value Sensitivity Analysis

To assess the most influent parameters, the results are then ordered with respect to the highest Elementary Effect mean value (the absolute value has been used to remove the cancellation error) taking also into account the standard deviation [27]. The parameters will be picked up in two different sets; one will be used before the installation of the mechanical systems and will be used to calibrate a "free floating" model while the rest are going to be used for the complete calibration. The free-floating set will focus on the envelope, actual size of some openings and main zone characteristic. In the graph below the results have been plotted on the μ^*- σ plane. The orange ones represent the set used for complete calibration, the green ones the one for the free-floating model and the blues one the parameter discarded that will be fixed to a pre-determined value [28]. The red one, nevertheless quite important has been discarded for practical reasons since the horizontal shading has been stuck during a storm. Using this configuration, the 18 most important parameters (listed below) out of the 29 selected can be calibrated on two different models to be launched in sequence; this will obtain a higher match between the model and the prototype, with a lower number of parameters arbitrarily set.

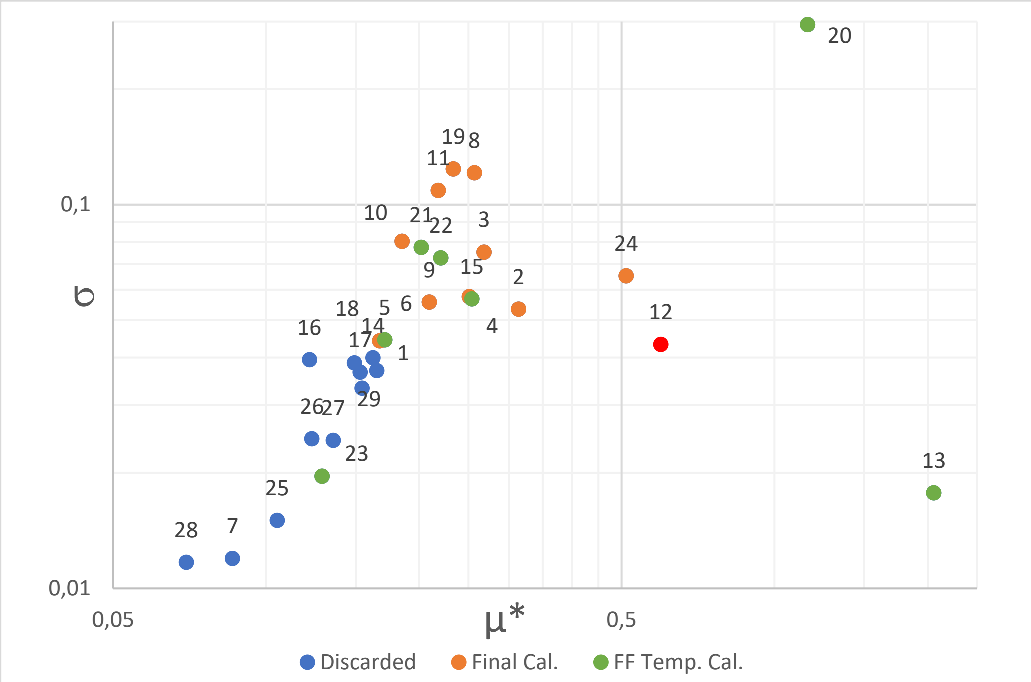


Figure 43: Sensitivity Analysis scatterplot

The two sets are show below:

Table 32: Free Floating Sensitivity Analysis

Free Floating Calibration				
#	Parameter	mu [kWh]	mu* [kWh]	sigma [kWh]
13	AC_od	-2.0583	2.0583	0.0177
15	Rat_fr_fac	-0.2487	0.2539	0.0568
21	Cap_f5	0.0577	0.2020	0.0773
22	Cap_s1	-0.0155	0.2207	0.0726
20	Cap_f3	1.1619	1.1619	0.2946
23	Cap_s2	0.0724	0.1288	0.0196
5	HW_out	-0.0710	0.1711	0.0444

Table 33: Full Operation Sensitivity Analysis

Full operation Calibration				
#	Parameters	mu [kWh]	mu*[kWh]	sigma[kWh]
6	Inf_f3	0.0547	0.1672	0.0441
19	Rat_fr_RS	0.0981	0.2335	0.1240
8	Inf_s1	-0.0949	0.2568	0.1211
24	Phen_Cond	0.5109	0.5109	0.0652
3	H_out	-0.2274	0.2683	0.0752
4	HW_in	0.2174	0.2509	0.0576
2	H_in	0.3077	0.3137	0.0534
11	AC_74	-0.0194	0.2181	0.1089
9	Inf_s2	-0.1001	0.2095	0.0557
10	AC_14	0.0337	0.1851	0.0803

6. Calibration

Since the Sensitivity Analysis has given clear results it was possible to set up and launch the Calibrations accordingly with the progress of the construction site [30]. On building phase, which lasted a couple of weeks, the focus was on the measurement architecture, sensors placement and model updating with the actual prototype configuration.

6.1 Calibration process

The calibration of a model can reach different levels of details depending on the length of observation and the data obtained by the modeller. The main accepted differentiation, as provided in [3], divides them in five possible levels:

Table 34: Calibration Levels

Calibration levels	Building Input Data Available					
	Utility bills	As-Built Data	Inspection	Detailed Audit	Short-Term Monitoring	Long-Term Monitoring
Level 1	x	x				
Level 2	x	x	x			
Level 3	x	x	x	x		
Level 4	x	x	x	x	x	
Level 5	x	x	x	x	x	x

Despite the fact that the nature of the project does not allow having any utility bills, this lack is overcome by the details given in the as-built data and a construction-time long inspection. Being the measured campaign of 3 days for the free-floating calibration this work can be considered a Level 4 Calibration. As previously introduced the Calibration procedure that has been selected is the Optimization Based one; unlikely the standard methods, the Optimization-based calibration does not rely on the experience of the modeller to match the models to the real building but depends on "an automated approach based on numerical simulation and mathematical optimization" through the coupling of a Building Energy Modelling Software with an Optimization one. As all the other Calibration even, the Optimization-Based one needs a set of measured data to allow the comparison with the simulated ones; in this study, due to the high dependency of the model to the outdoor conditions, the data collection focussed on the weather too. Another feature to be set is the objective function: this is usually set to the numerical difference between the measured and the simulated data set. In this work the optimization objective function was instead set according to the standards for considering a calibration validated; this was done in order to achieve within the same operation both the calibration and its validation. The standard used for reference is the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14 [31]. The validation of the calibration is based mainly on two statistical indices:

Mean Bias Error (MBE)

$$MBE(\%) = \frac{\Sigma_{Period}(S - M)_{interval}}{\Sigma_{Period} M_{interval}} \cdot 100\%$$

- Measures how close are the simulated and measured data
- M represents the measured data set
- S represents the simulated data set
- The interval is the lowest observation period (1 min, 1 hour)
- The Period indicates the length of the observation/calibration time
- Prone to cancellation error due to reduction given from positive and negative values

Coefficient of Variation of the Root Mean Square Error (Cv(RMSE))

$$Cv(RMSE_{Period}) = \frac{RMSE_{Period}}{A_{Period}} \cdot 100$$

$$RMSE_{Period} = \sqrt{\frac{\Sigma(S - M)^2_{interval}}{N_{interval}}}$$

$$A_{period} = \frac{\Sigma_{Period} M_{interval}}{N_{intervl}}$$

- The RMSE measures the deviation of the differences between the measured values and the simulated values
- The Cv(RMSE) is the RMSE normalized with respect to the mean of the observed values

- Gives a good measurement on the overall uncertainty in the outcome of the simulation
- $N_{interval}$ is the number of time interval considered for the monitored period

The threshold limits [6] for both MBE and Cv(RMSE) are:

Table 35: Calibration Validation Threshold

Statistical indices	ASHRAE Guideline 14	
	Monthly Calibration	Hourly Calibration
MBE (%)	±5	±10
Cv(RMSE) (%)	15	30

The cost function was then written as:

$$CF = MBE \cdot 0.5 + Cv(RMSE) \cdot 0.5$$

Giving to both the MBE and the Cv(RMSE) the same statistical weight to define the goodness of the calibration [32].

The process for the calibration, as expressed in [5], will be organized through the following steps:

- A measurement campaign will gather data on the envelope and weather
- Implementation of the measured data into the BEM
- BEM handling to create the coupling with the optimization software
- Iterative Optimization
- Data Post Processing with possibility of active intervention on the prototype

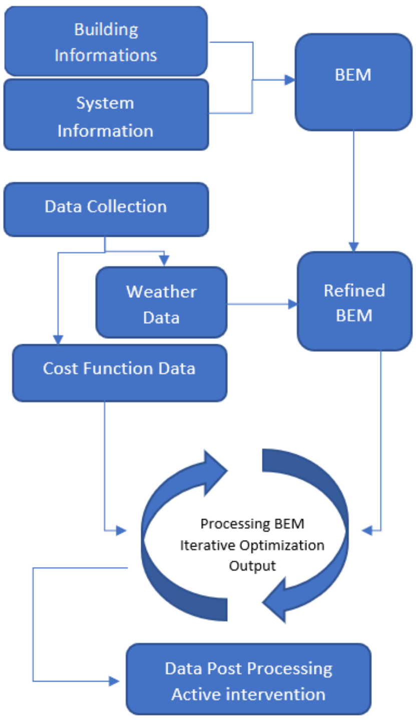


Figure 44: Calibration Flowchart

As said before the BEM was developed using TRNSYS. The software choice for Optimization was GenOpt.

GenOpt (general optimization) software is a Java-developed optimization environment produced by the Berkeley Nation Laboratory of the University of California to offer a cost function minimizer able to connect with many modelling software as EnergyPlus, TRNSYS, Dymola, IDA-ICE or DOE-2 and others. The software has an internal library with both global and local optimization algorithm offering nevertheless the possibility to implement an own designed algorithm.

6.2 Measurements architecture and data logging

To perform the calibration different data-set have to be collected for various reason:

- Data to be used for definition of the cost function
- Model refining
- Weather data definition

To perform the calibration it is possible to compare different data, accordingly with the availability on the studied building. To perform this calibration different possibilities have been studied and then matched with the availability of measurement devices; in the end, the choice was to proceed with a Temperature calibration [1]. In the following paragraphs this aspect will be clarified.

6.2.1 Weather data collection

Collecting weather files *in situ* allows to implement them in the simulation [33]; this will highly reduce error connected with the mismatch between actual weather data and the weather file written in the past years. To implement the collected data in the simulation Type-109(User defined) will be used; the requested input will lead the choice of the measurement devices. The input file format (*Filename.109*) has the following template:

```
<userdefined>
<longitude>     -113.16                                                                     ! east of greenwich: negative
<latitude>      23.08
<gmt>           8                                                                           ! time shift from GMT, east: positive (hours) - if solar time-> write "solar"
<interval>      0.08333                                                                     ! Data file time interval between consecutive lines
<firsttime>     3142                                                                        ! Time corresponding to first data line (hours)
<var>   IBEAM_H <col>   0   <interp>    0   <add>   0   <mult>  1   <samp>  0   !...to get radiation in W/m²
<var>   IBEAM_N <col>   0   <interp>    0   <add>   0   <mult>  1   <samp>  0   !...to get radiation in W/m²
<var>   IDIFF_H <col>   0   <interp>    0   <add>   0   <mult>  1   <samp>  0   !...to get radiation in W/m²
<var>   IGLOB_H <col>   5   <interp>    0   <add>   0   <mult>  1   <samp>  0   !...to get radiation in W/m²
<var>   TAMB    <col>   3   <interp>    2   <add>   0   <mult>  1   <samp>  0   !...to get °C
<var>   RHUM    <col>   4   <interp>    1   <add>   0   <mult>  1   <samp>  0   !...to get relative humidity in %
<var>   WSPEED  <col>   2   <interp>    1   <add>   0   <mult>  1   <samp>  0   !...to get wind speed in m/s
<var>   WDIR    <col>   1   <interp>    1   <add>   0   <mult>  1   <samp>  0   !...to get wind direction in degree
<var>   PRESS   <col>   6   <interp>    1   <add>   0   <mult>  1   <samp>  0   !...to get pressure in hPa
<var>   udef2   <col>   0   <interp>    1   <add>   0   <mult>  1   <samp>  0   !...to get ... in ...
<var>   udef3   <col>   0   <interp>    1   <add>   0   <mult>  1   <samp>  0   !...to get ... in ...
<var>   udef4   <col>   0   <interp>    0   <add>   0   <mult>  1   <samp>  0   !...to get ... in ...
<data>
0       0       25.8    84      0       1008.7                          !       3142
```

Figure 45: Type 109 template

Other than latitude and longitude the simulation will require to set the time shift, the interval of measurement (5 min, 0.833h), when the first timestep will occur and the name of the variable. The format offers some slots for user defined data. Since the measured solar radiation is the global one on the horizontal surface the script has already implemented the Perez model for the calculation of direct and diffuse radiation. To obtain all the requested data the chosen measurement devices have been:

- Davis Vantage Pro2 weather station
- Delta Ohm HD2102 Solar Flux Datalogger
- LP Pyra02 Pyranometer

Their data are reported in the table:

Table 36: Weather stations data

Variable	Resolution	Range	Accuracy (+/-) Nominal
Barometric Pressure	0.1 hPa	540 to 1100 hPa	1.0 hPa
Outside Humidity	1%	1 to 100%	4%
Solar Radiation	0,1 W/m2	0 to 2000 W/m2	5%
Outside Temperature	0.1°C	-40° to +65°C	0.5°C
Time	1 min	24 hours	8 sec./mon.
Wind Direction	1°	0 to 360°	3°
Compass Rose	0.3 compass pt	16 compass pts	-
Wind Speed	0,4 m/s	0 to 322 m/s	1 m/s

Figure 46:Vantage PRO 2 Weather station

Figure 47:Delta Ohm Datalogger + LP Pyra02 Pyranometer

The position of the sensors has been decided to reduce the effect of nearby building or environment and maintain the sensors safe from the building site operation. The weather station was placed on the north-west corner, with the wind probe at the height of 3 meter (first floor). The Pyranometer was placed on top of the workers stall to reduce the horizontal interaction with other structures and avoid any kind of shading (allowed <5° on the horizontal).

The control centre was placed in the workers' stall and connected with a laptop to be remotely operated and allow the data collection even without direct interaction. The direct measurement showed a huge difference with the weather file provided for the region, thus the comparison will no longer be affected by this mismatch error.

6.2.2 Measurement on the prototype

The measurement performed on the model were organized dividing the thermometers according to their timestep (2 minutes- Therm. A and 5 minutes - Therm. B) and placing them in couples in the main thermal zones and with just the Therm. B one in the connection zones. The Term. B have been placed atop of the walls and would be used just to check the temperature fluctuation between zones. The Term. A would be used for the actual measurements and will be placed at the geometrical centre of the zone at a height of 1.5 m as shown in the next image:

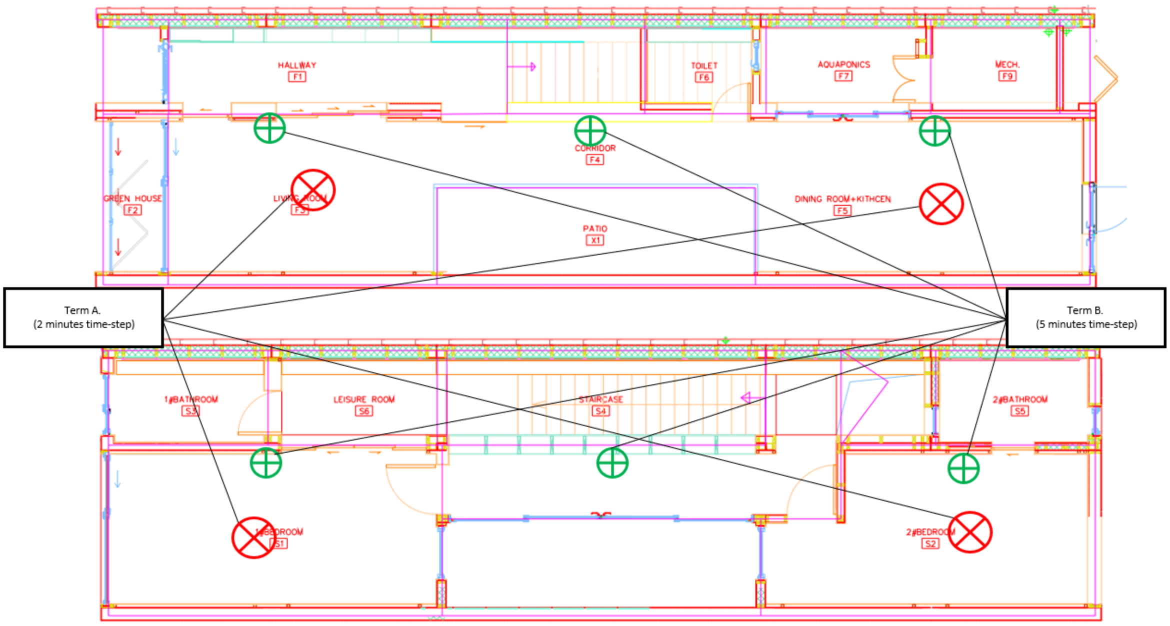


Figure 48: Sensor Placement Section Plan

The optimized calibration procedure relies on the evaluation of the distance between the model's and the studied building's results to determine its goodness [34]. Since the software to be coupled are mainly Trnsys and GenOpt this "distance" is expressed in term of a cost function that GenOpt will reduce trough iterations. Usually, in order to achieve a better exploration of the behaviour of a building, different data are gathered form the building such as the temperature inside main thermal zones, the energy consumption in terms of electricity, gas or thermal load. Due to the highly changing situation of a construction site the collected data for the first set has been focussed just on the temperature behaviour inside the envelope. The analysis of the temperature evolution can highlight the accuracy of the simulation and is easily gatherable. The instrument used for it is the HOBO U23-001, whose main specifications are listed below:

Table 37: HOBO U23-001 specifications

Modello Hobo:	**U23-001**
Memory	42,000 meas.
Sampling rate	1 second to 18 hours
Internal Temperature	
Measurement range	-40° to 70°C
Accuracy	± 0.21°C over 0° to 50°C
Resolution (12-bit)	± 0.02°@ 25°C
Stability (drift)	< 0.1°C per year
Relative Humidity (U23-001 & U23-002 only)	
Measurement range	0 to 100% RH, -40° to 70°C
Accuracy	±2.5% from 10%RH to 90%RH
Resolution (12-bit)	0.05%RH

Figure 49: HOBO pro-V2 U23-001

Figure 50: Sensor placement

For the measurement campaign the sensors have been placed in the 4 conditioned rooms, each of whose is a thermal zone. In the first phase, during the data collection for the free-floating temperature calibration one sensor was placed in each zone, with a logging time of 5 minutes; after the electrical system has been done a second sensor was placed in each room, with a 2 minutes time-step, to increase the precision during the transient phase with the conditioning equipment on. For further studies other 2 sensors were placed in the thermal zones that connects the 4 conditioned ones.

6.3 Integrating data in the BEM

The only data effectively usable to refine the precision of the simulations resulted to be the weather data, the manual creation of a weather files from various sources needs to be consistent when including all the collected data.

6.3.1 Weather data implementation

Data from Davis Vantage Pro2 weather station and data from Delta Ohm HD2102 Solar Flux Datalogger need to be merged in a single excel file before being implemented in the weather file format:

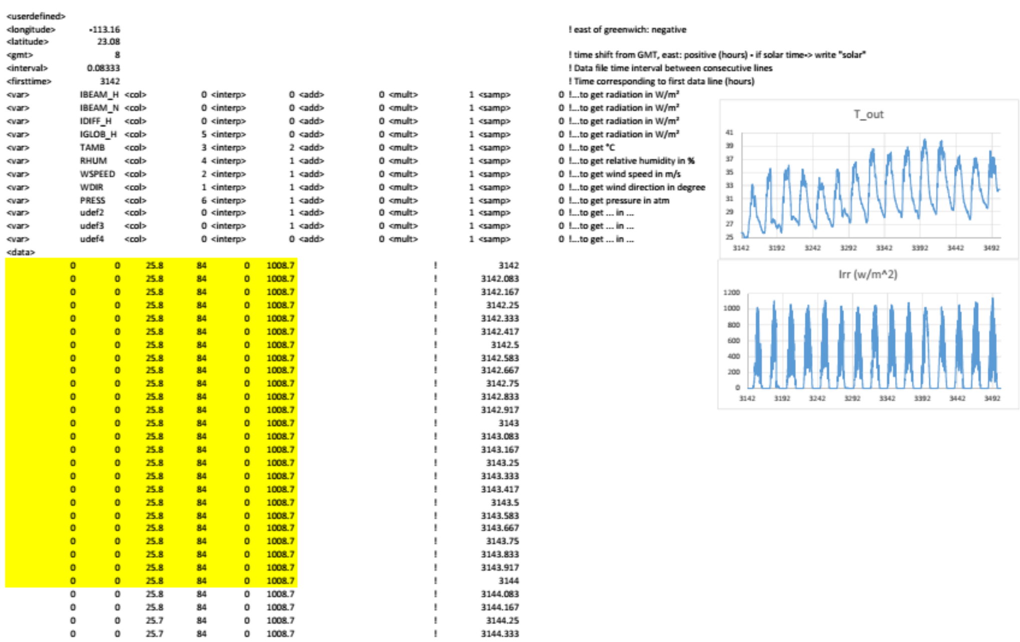


Figure 51: Weather file report

The highlighted part is the "head" of the weather file: it is good practice to add a "head" and a "tail" in self-written weather files in order to avoid that different reading procedures could miss some data about the start of the simulation. The highlighted part reports the same reading of the first measured data. After the creation of the weather file (.109) it is good to perform some tests on it. They have been carried out for 15 days (time interval: 3144 – 3500 h), and the comparison between the measured and given data is shown below:

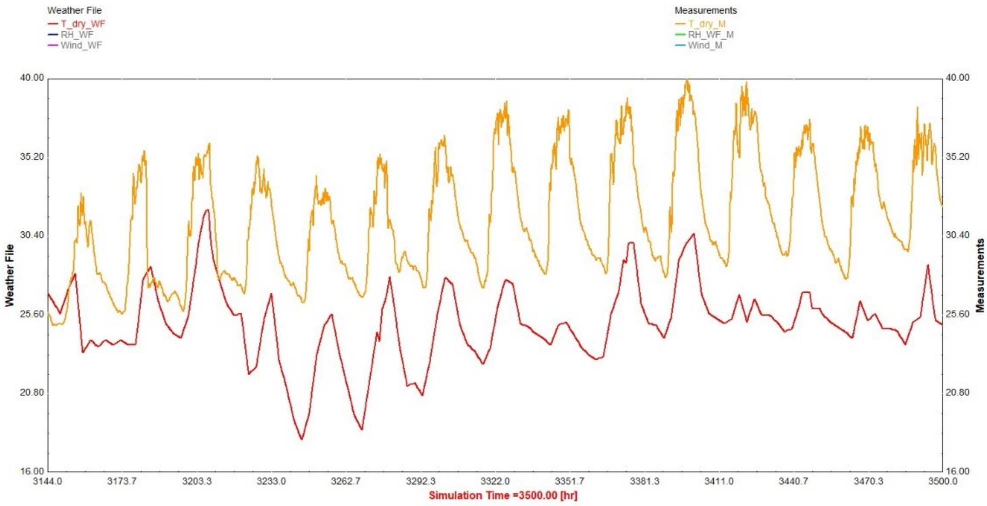


Figure 52: Measured vs Simulated outdoor temperature

It is clear how the measured temperature is constantly higher than the one reported in the weather file. This mismatch was probably caused by the location of the building site and the variation in the microclimate of the city with a higher solar irradiance:

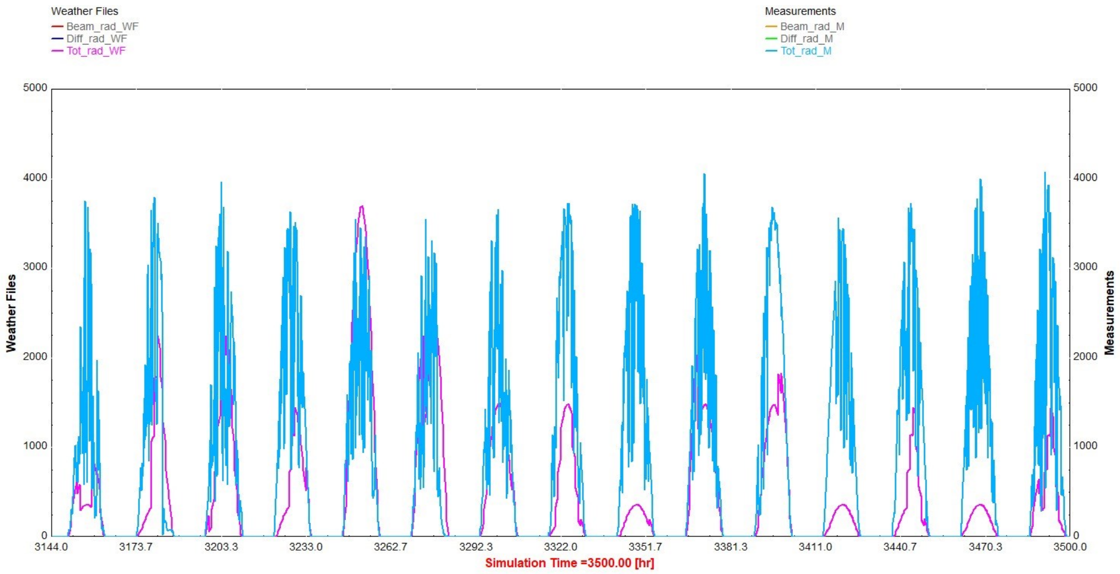


Figure 53:Measured vs Simulated Irradiance

And a lower Relative Humidity level:

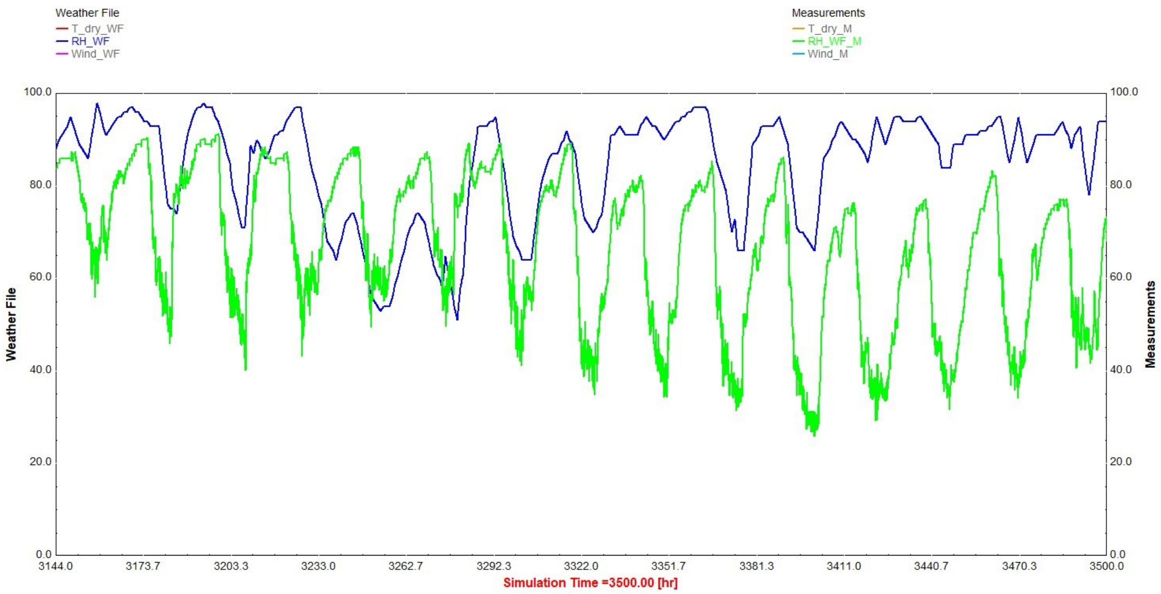


Figure 54:Measured vs Simulated Relative Humidity

The windspeed plot shows a constant higher level on the measured file, this is due to the lesser roughness in the construction area (in the suburbs) with respect to the city centre:

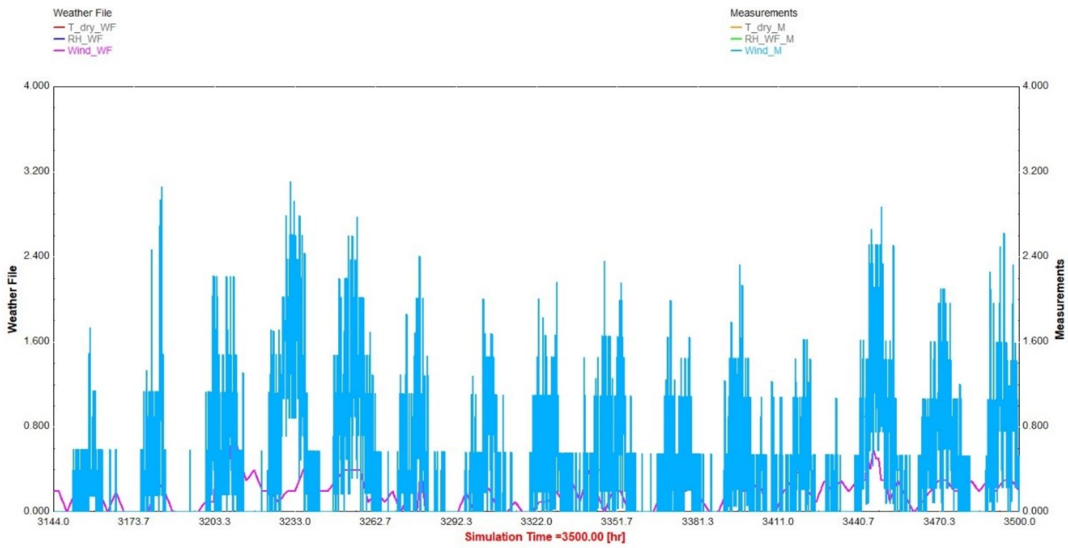


Figure 55: Measured vs Simulated Windspeed

This data will have a high impact on the calibration of the airflow in natural ventilation.

6.4 Selection of the Optimization Algorithm

One of the main advantages of GenOpt is the fact of having a wide range of optimization algorithms already included in its script. The choice of the right one has to be led by both the kind of results wanted and the model itself. The main characteristic to be checked is whether or not the parameters have to be considered continuous or discrete; another valuable information to be collected is the weight of the parameters with respect to the others. The considered algorithms for this study were the Particle Swarm Optimization and the Generalized Pattern Search.

6.4.1 Model characteristics

The parameters picked up for the first calibration set were:

Table 38: Optimized Calibration Parameters

Free Floating Calibration					
#	Parameter	Description	Range	Unit	Type
13	AC_od	Air Flow Natural Ventilation	0 - 700	m^3/h	Continue
15	Rat_fr_fac	Ratio Frame/Glass	0.1 - 0.2	%	Continue
21	Cap_f5	Capacitance thermal zone	50 - 70	kJ/K	Continue
22	Cap_s1		50 - 70		Continue
20	Cap_f3		35 - 55		Continue
23	Cap_s2		45 - 60		Continue
5	HW_out	Outdoor convective heat transfer wind.	55 - 75	$kJ/h\ m^2\ K$	Continue

All of them are continuous parameters with range variation of varied sizes with respect to the used steps. Both The methods evaluated where able to manage both continuous and discrete parameters.

6.4.2 Particle Swarm Optimization

These are algorithms, based on the population-based probabilistic optimization, are used in field in which the cost function could have discontinuous behaviour. It exploits a set (Population) of potential solutions (Particle) that are initialized with a random number generator to spread the solution in the user-defined hypercube and then update the position of the particles through an equation modelled on the social behaviour of members of bird flocks or fish schools.

For continuous variables, the PSO algorithm is defined below:

Let them be:

- $k \in N$ *Generation Number*
- $n_P \in N$ *Number of particles in each generation*
- $x_i(k) \in R^{nc}$, $i \in \{1,..., n_P\}$, *the i-th particle of the k-th generation*
- $vi(k) \in R^{nc}$ *Velocity*
- $c1, c2 \in R+$
- $\rho 1(k), \rho 2(k) \sim U(0, 1)$, *uniformly distributed random numbers between 0 and 1*

the update equation is, for all $i \in \{1,..., n_P\}$ *and all* $k \in N$:

$$v_i(k+1) = v_i(k) + c_1\,\rho_1(k)\left(p_{l,i}(k) - x_i(k)\right) + c_2\,\rho_2(k)p_{g,i}(k) - x_i(k))$$

$$x_i(k+1) = x_i(k) + v_i(k+1)$$

Where:

$$p_{l,i}(k) \triangleq \underset{x \in \{x_i(j)\}_{j=0}^{k}}{arg\,min} f(x)$$

$$p_{g,i}(k) \triangleq \underset{x \in \left\{\{x_i(j)\}_{j=0}^{k}\right\}_{i=1}^{n_P}}{arg\,min} f(x)$$

$$v_i(0) \triangleq 0$$

- $p_{l,i}(k)$ *is the location that for the i-th particle yields the lowest cost over all generations*
- $p_{g,i}(k)$ *is the location of the best particle over all generations*
- $c_1\,\rho_1(k)\,(p_{l,i}(k) - x_i(k))$ *is a term associated with the cognition*
- $c_2\,\rho_2(k)\,(pg_{,i}(k) - x_i(k))$ *is a term associated with social interaction*
- c_1: *cognitive acceleration constant*
- c_2 *is called social acceleration constant.*

The model for the PSO algorithm is listed below:

- **Data:** Constraint set on the parameters X with and upper and lower bound. Definition of number of particle n_p and number of generation n_g
- **Step 0:** Initialize the first population through a Random number generator and take into account the neighbourhood
- **Step 1:** Evaluate the solutions on the randomly selected populations
- **Step 2:** For the selected neighbourhood evaluate the local best and the global best using the data in memory
- **Step 3:** Update the particles location
- **Step 4:** If reached the predicted number of generations stop, Else go to Step 2
- **Step 5:** Pass to the next set of generation and go to Step 1

The main advantage of this algorithm is the finite number of operations, the number of which are known *a priori* and selected accordingly with the available computational power and precision requested. The method is a global one and does not require gradients for the cost functions. On the other hand, due to the handling method of the parameters the PSO is predisposed to find a local minimum without exploring the closest neighbourhood of the local minimum. This could be a problem in simulation with fast variation of the solutions within a single step.

6.4.3 Generalized Pattern Search

Generalized Pattern Search (GPS) algorithms are derivative-free optimization algorithms for the minimization of both continuous and mixed problems. They are used where the cost function does not have an exact evaluation but an approximate one under the assumption that it is continuously differentiable. The peculiarity of this model is that the variation step changes in size according to the value evaluated in the neighbourhood. On the other hand, the methods behave like a while loop so no *a priori* evaluations are suitable for the calibration.

- **Data:** Initial iteration to the starting parameters, dividing of the mesh and selections of the exponents
- **Maps:** Creation of the search map with a pattern that is strictly monotone decreasing
- **Step 0:** Initializing the first simulation
- **Step 1:** Global Search until the global precision is reached
- **Step 2:** Local Search untill the local precision is reached
- **Step 3:** Parameters update
- **Step 4:** Pass to the next simulation and go to step 1

To solve the problems related to both the proposed methods the choice was to apply a third one, a hybrid model that allows to have a known number of steps with a good search for global minimum. It will be explained in detail in the next paragraph.

6.4.4 Hybrid GPS with PSO GPSPSOCCHJ

The hybrid global optimization algorithm starts with a Particle Swarm Optimization (PSO) on a mesh, for a number of generations nG defined by the user. Afterwards, it initializes the Generalized Pattern Search (GPS) algorithm using the continuous independent variables of the particle with the lowest cost function value. If the optimization problem has continuous and discrete independent variables, then the discrete independent variables will, for the GPS algorithm, be fixed at the value of the particle with the lowest cost function value. Since the PSO algorithm is a global optimization algorithm, the hybrid algorithm is, compared to the Hooke-Jeeves algorithm (GPS), less likely to be attracted by a local minimum that is not global. Thus, the hybrid algorithm combines the global features of the PSO algorithm with the provable convergence properties of the GPS algorithm.

6.5 Mathematical structure of the algorithm

The algorithm works with continuous and mixed problems, but since this work has only continuous parameters the mathematical structure will be explained just for continuous problems.

As for the PSO, the parameters need some constraint, upper and lower. The constraint is defined as:

$$X \subset \mathbb{R}^{\boldsymbol{n}_c}$$

$$l_i, u_i \in \mathbb{R} \, for \, all \, i \in \{1, \ldots, n_c\}$$

The PSO is then run with initial iterate $x_0 \in X$ U (defined later) for a user-specified number of generation $n_G \in \mathbb{N}$ with the following mesh:

$$\mathcal{M}(x_c, 0, \Delta, s) \triangleq \{ x_{c,0} + \Delta \Sigma_{i=1}^{n} m^i s^i e_i \,|m \in \mathbb{Z}^{n_c} \}$$

and the same algorithm listed above.

Then the GPS is launched as the Hooke-Jeeves GPS Algorithm):

- parameters D, r, s_0, and t_k are defined as in the Coordinate Search algorithm:
  - $D \triangleq [+s^1 e_1, -s^1 e_1, \ldots, +s^n e_n, -s^n e_n]$ where $s_i \in R$, $i \in \{1, \ldots, n\}$, is a scaling for each parameter
  - $r \in N$, $r > 1$
  - $s_0 \in N$
  - t_k is, for the iterations that do not reduce the cost, defined by the parameter **MeshSizeExponentIncrement**
- Ek: $R^n \times Q_+ \times R^q{}_+ \rightarrow 2^{M}{}_k$, is the map that defines the "exploratory moves"
- global search set map γ_k is defined as γ_k ($\underline{x_k}$, Δ_k, $\in$) = G_k following these steps:
  - **Map:** Map for "exploratory moves" $E_k : R_n \times Q_+ \times R_{q\,+} \rightarrow 2_{M_k}$.

- **Input:** Previous and current iterate, $x_{k-1} \in R^n$ and $x_k \in R^n$. Mesh divider $\Delta_k \in Q_+$. Solver precision $\varrho \in R^q_+$
- **Output:** Global search set G_kOutput: Global search set G_k
- **Step 1:** Set $x = x_k + (x_k - x_{k-1})$
- **Step 2:** Compute $G_k = E_k(x, \Delta_k, \varrho)$.
- **Step 3:** If $\min_{x \in G_k,} f^*(\in, x) > f_*(\in, x_k)$ Set $G_k \leftarrow G_k \cup E_k(x_k, \Delta_k, \in)$.
- **Step 4:** Return G_k.

- If the global search, as defined has failed in reducing $f^*(\in, \cdot)$, then has constructed a set G_k that contains the set $\{x_k + \Delta_k D_{ei} \mid i = 1, . . . , 2n\}$ that is a local search set:
  - L_k, $\{x_k + \Delta_k D\, e_i \mid i = 1, . . . , 2n\} \subset G_k$

The search starts with the initial iterate x0 equal to the location of the lowest cost function value's particle:

$$x_0 \triangleq p \triangleq \underset{x \in \{xj(k) \mid j \in \{1,\dots,nP\},\, k \in \{1,\dots,nG\}\}}{\arg min} f(x)$$

Where $n_P \in \mathbb{N}$ represents the number of particles and $x_j(k)$, with $j \in \{1,\dots, n_P\}$ the number of particles of the generation $k \in \{1,\dots, n_G\}$ among the total generations. Since the PSO algorithm stops after a finite number of iterations, all convergence results of the GPS algorithm hold. In particular, if the cost function is once continuously differentiable, then the hybrid algorithm constructs accumulation points that are feasible and stationary points of problem.

6.6 Implementation and software coupling

Being the algorithm already pre-loaded in the GenOpt scripts, it only needs some simple commands to perform the optimization; part of them to prepare the TRNSYS simulation [35], part to write the GenOpt configuration and command files.

6.6.1 TRNSYS operations

With respect to the BEM used in the previous chapters the simulation has to be modified to be ready to be called iteratively by GenOpt and evaluate the cost function in a proper way.

First of all, the weather file should be built with the collected data and connected with the needed type(s). The selected format is, as previously said, the Type109-Userdefined. The Data handling was performed through and Excel file in order to increase the length of the weather data accordingly to the length of the simulation.

Then the temperature measured in the zones has to be read by the simulation to evaluate the deviation of the calculated data from the real ones. The format used is the simple Type9a: this type allows to create a simple tab with interpolating features and user-defined time interval. For the first calibration only the temperature in the four conditioned rooms has been inserted in the simulation.

The handling of the results has been performed through a MATLAB script to evaluate the cost function on hourly-averaged values provided by a TRNSYS .out files. The script handles the temperatures, measured and simulated ones, of all the 4 different zones separately, and going ahead with the evaluation of the cost function using the worst condition (the data set that are on average on the biggest distance). The cost function is evaluated as a multi-objective one with the weighting values equal for the Mean Bias Error and the Coefficient of Variation of Root Mean Square Error according to the ASHRAE 14 guidelines standards.

6.6.2 GenOpt and TRNSYS set up and coupling

After the set-up of the simulation there are some steps to be performed in order to successfully generate templates for GenOpt. The actual simulation files from TRNSYS, the .DCK and .BUI (respectively the Simulation Studio and TRNBuild files), have to be edited according to the parameters that will be handled by GenOpt. The editing requires to create two template files in which is needed to change the values of the parameters with a variable name consistent with the other files expressed between the "%" symbol, and an example is shown below:

```
* EQUATIONS "Calibr.Par."
*
EQUATIONS 3
AC_OD = %AC_OD%
Rat_wf_Facade = %RWFF%
HW_out = %HW_out%
*$UNIT_NAME Calibr.
```

Figure 56: Calibration Parameters in .DCK files

Another step is to link the right .BUI and .DCK files together; this is achieved by changing the link of the external files to the file that will be created at every GenOpt run. For convenience it is good to disable the graphical output in order to speed up the simulation.

The following step is to create the project files for GenOpt:

<u>Configuration file (.cfg)</u>

Contain the command for the simulation start and the location of the objective function in the following format:

```
SimulationStart {
    Command = "cmd /x /c \"start /WAIT C:\\Users\\asus\\Desktop\\Calibration_FF\\Run.bat";
    WriteInputFileExtension = true;
}

ObjectiveFunctionLocation {

    Name1       = "Result";
    Delimiter1 = "1.2340000e+03" ;
}
```

Figure 57: Example of configuration file

The command for the simulation start calls a file in the windows command windows; to achieve the right order and timing the file was organized as a BATCH (.bat) file containing a code string to be printed in the command shell:

```
C:\Trnsys16\Exe\TRNExe.exe C:\Users\asus\Desktop\Calibration_FF\Run.dck /n
matlab -nodisplay -nosplash -nodesktop -r "run('C:\Users\asus\Desktop\Calibration_FF\Run2.m')";exit;"
cd C:\Users\asus\Desktop\Calibration_FF
:Check
forfiles /m CostFunction.txt /d 0 && (
  EXIT
) || (
  TIMEOUT /t 2 /nobreak
  GOTO :Check
)
```

Figure 58: Optimization Batch file

In order are then launched the TRNSYS simulation, the MATLAB function to create the cost function, and the file-check code that made the simulation go further only if all the right files have been created.

The ObjectiveFunctionLocation reads the file *Result.txt* and identifies as cost function the first uninterrupted script after the imposed Delimiter.

GenOpt project initialization file (.ini)

This script contains:

- Template files path and the name to be read by GenOpt
- Input file and Log file paths and names to be written by GenOpt
- Cost Function Location
- Configuration file location
- Optimization Commands file location

GenOpt optimization commands (.txt)

This file gives information about the parameters to be optimized and the required data about them; an example is shown below:

```
Parameter {
    Name     = AC_OD;
    Min      = 0;
    Ini      = 100;
    Max      = 700;
    Step     = 25;
    Type     = CONTINUOUS;
}
```

Figure 59: Example Parameters ID

Then the settings about the Optimizations are written as parameters:

```
OptimizationSettings {
    MaxIte = 1000;
    MaxEqualResults = 10;
    WriteStepNumber = false;
}
```

Figure 60:Example Optimization Settings

This tells the software how many iterations to perform on a single point and how many equal results are allowed before moving onto another generations; this parameter is important in simulations that risk being stuck due to repetitions. A higher number allows to explore the hypercube on a deeper level even if the results are the same or not.

The last feature of the file is the Algorithm identification and settings:

```
Algorithm{
  Main = GPSPSOCCHJ;
  NeighborhoodTopology = vonNeumann;
  NeighborhoodSize = 7;
  NumberOfParticle = 35;
  NumberOfGeneration = 100;
  Seed = 1;
  CognitiveAcceleration = 2.8;
  SocialAcceleration = 1.3;
  MaxVelocityGainContinuous = 0.5;
  MaxVelocityDiscrete = 4;
  ConstrictionGain = 1;
  MeshSizeDivider = 2;
  InitialMeshSizeExponent = 0;
  MeshSizeExponentIncrement = 1;
  NumberOfStepReduction = 4;
}
```

Figure 61: Example of Algorithm Settings

The different parameters keywords are defined below:

- **Main:** Codename of the Algorithm
- **NeighborhoodTopology:** handling method for the neighbourhood particles. It could be extended to include the g-best (global best), the l-best (local best) or use the VonNeumann notation
- **NeighborhoodSize**: usually equal to $N_S = 0.2\ N_P$
- **NumberofParticle** (N_P): equal to $N_P = 5\ N_{parameters}$
- **NumberofGeneration** (N_G):
- **Seed**: Random number initialization
- **CognitiveAcceleration**: equal to $c_1 \in R_+$ used in the PSO / 2.8
- **SocialAcceleration**: equal to $c_2 \in R_+$ used in the PSO /1.3
- **MaxVelocityGainContinuous**: equal to $\lambda \in R_+$
- **MaxVelocityDiscrete**: equal to the $v_{max} \in R_+$
- **ConstrictionGain**: equal to $\kappa \in (0, 1]$
- **MeshSizeDivider**: equal to $r \in N$, with $r > 1$, used by the PSO algorithm and used by the GPS algorithm to compute Δk. Usually set to $r = 2$.

- **InitialMeshSizeExponent**: equal to s ∈ N used by the PSO and GPS algorithm. A common value is s0 = 0.
- **MeshSizeExponentIncrement**: value for t_k ∈ N (fixed for all k ∈ N) used by the GPS algorithm. A common value is tk = 1.
- **NumberOfStepReduction**: the maximum number of step reductions before the GPS algorithm stops. A common value is m = 4.

With this file the configuration of the simulation is complete, and it can be launched. The obtained results are discussed in the next paragraph.

6.7 Calibration Results

After the input data had been all completed the calibration were launched for the first discussed configuration. The next paragraphs report the pre-calibration behaviour of the simulation, the results of the calibration and the behaviour after the results were implemented in the model.

6.7.1 Free Floating Calibration

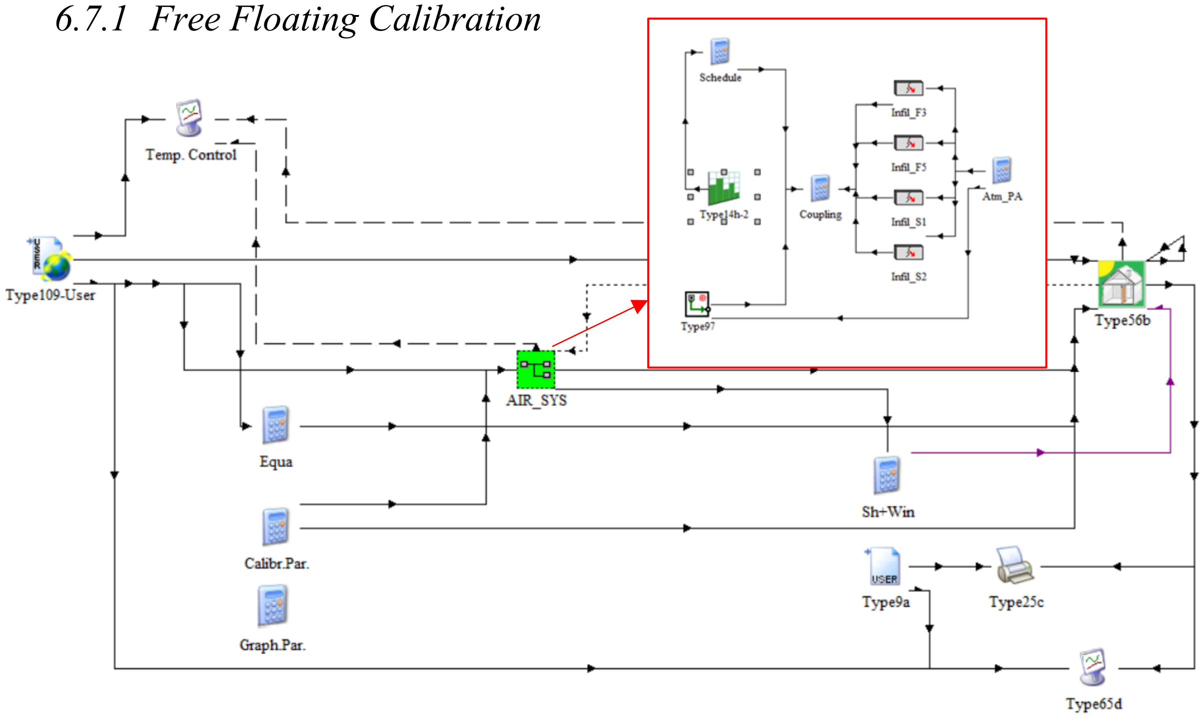


Figure 62: TRNSYS scheme for F.F. Calibration

For the free-floating calibration, the simulation was rearranged to speed up the runs, removing the systems that, due to the building site operation, have not been used. The resulting reduced simulation maintains the infiltration handlers, the air coupling simulation in CONTAM. The simulation would be launched with the following characteristics:

- Simulation Start time: 3144 hr
- Simulation Stop time 3216 hr
- Simulation timestep: 1 min
- Weather file: User defined

The results clearly show a mismatch between the real temperature and the simulated ones:

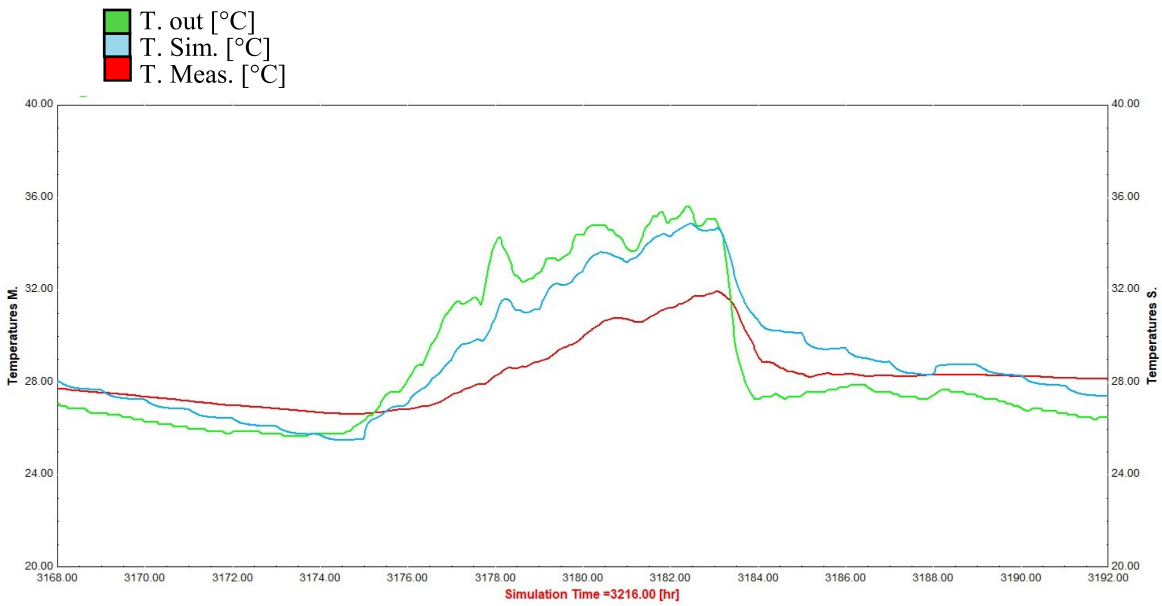


Figure 63: Temperature behaviour before calibration – [°C]

The simulated temperature follows the outdoor temperature, showing little weight on the building thermal inertia and a high dependence on the solar radiation effects. Then the Calibration was launched; the results, as shown below, highlight the behaviour of one of the parameters that has a higher weight than the others, creating a sudden drop that after the PSO is explored to find the global minimum of the simulation:

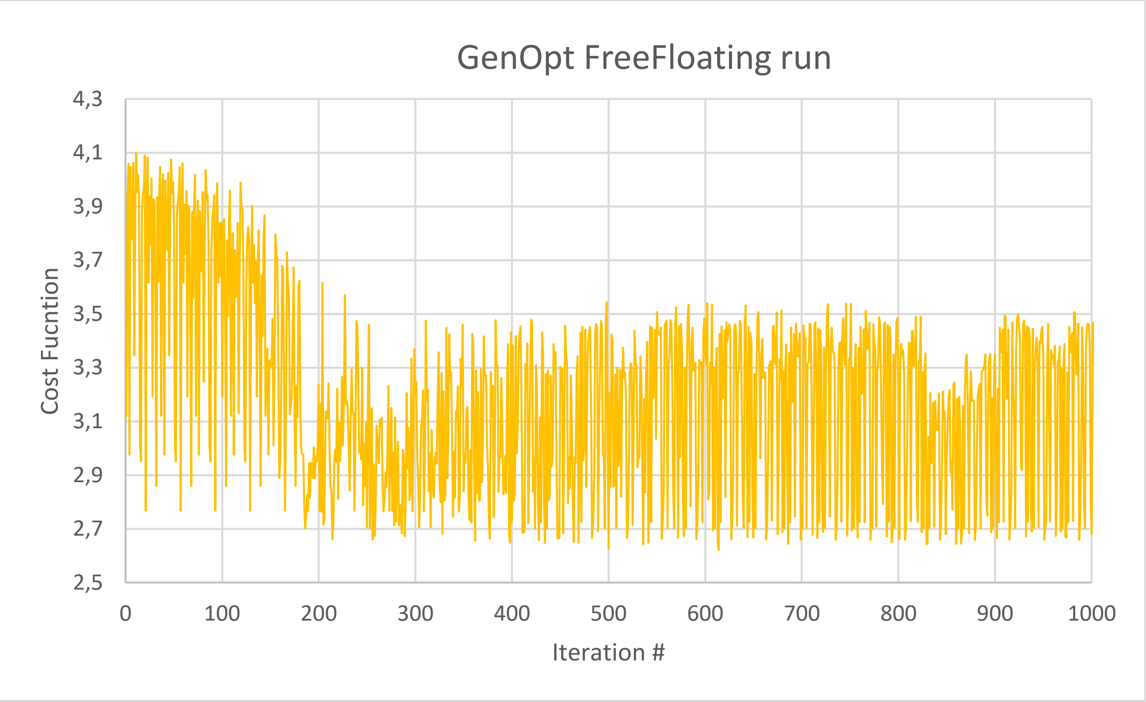


Figure 64: GenOpt Free Floating run

Figure 65: Cost Function Evolution

The total reduction of the cost function is from 4.1 to 1.65 with the selected calibrated parameters:

Table 39: Free Floating Calibration Results

Free Floating Calibration					
#	Parameter	Description	Value	Unit	Type
13	AC_od	Air Flow Natural Ventilation	25	m^3/h	Continue
15	Rat_fr_fac	Ratio Frame/Glass	0.2	%	Continue
21	Cap_f5	Capacitance thermal zone	51	kJ/K	Continue
22	Cap_s1		69		Continue
20	Cap_f3		69		Continue
23	Cap_s2		58		Continue
5	HW_out	Outdoor convective heat transfer wind.	59	$kJ/h\ m^2\ K$	Continue
-	Cost Function	Value of the cost function	2.6216	-	-

The temperature behaviour after the calibration shows a closer match between the measured and simulated data:

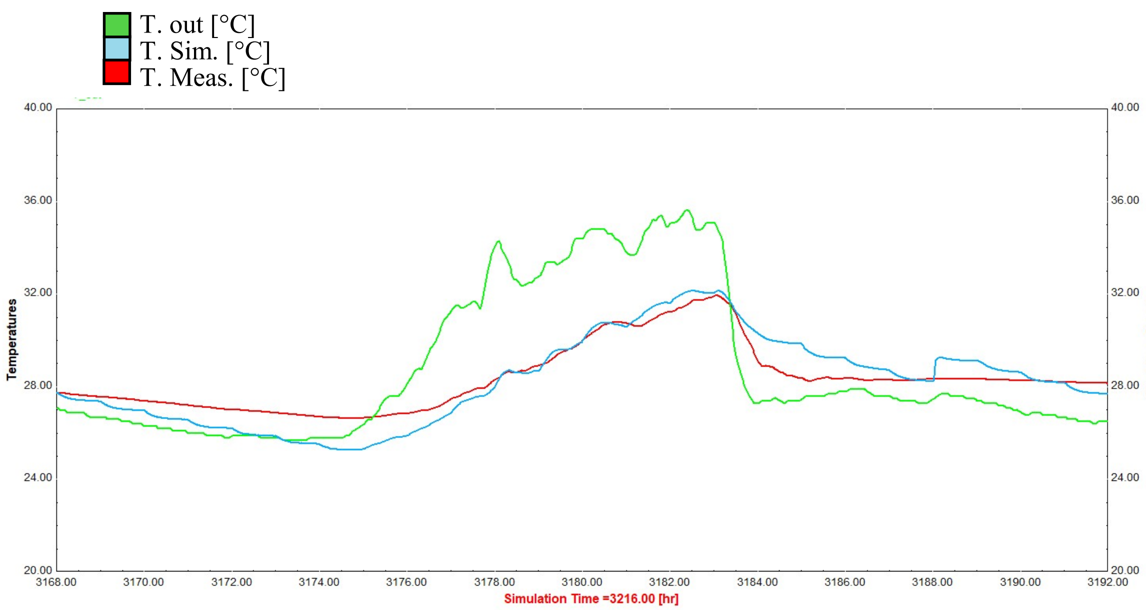


Figure 66: Temperature behaviour after calibration – Measured vs. Simulated [°C]

The biggest deviations occur during the switch between the nigh time and the day time. This is probably caused by the management of the solar radiation in some of the glazed surfaces. The reduction in the deviation has been proved on the same model in another day without an active calibration but using measured data for the weather files as well:

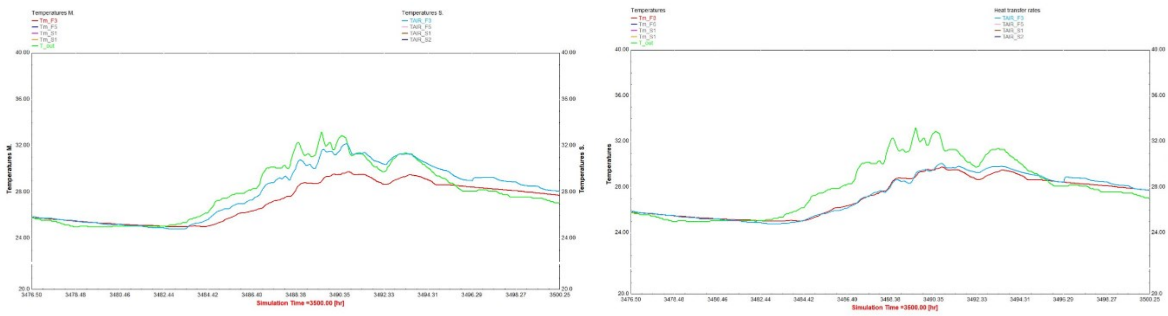


Figure 67: Improvements on a Test day aided by measure [°C]

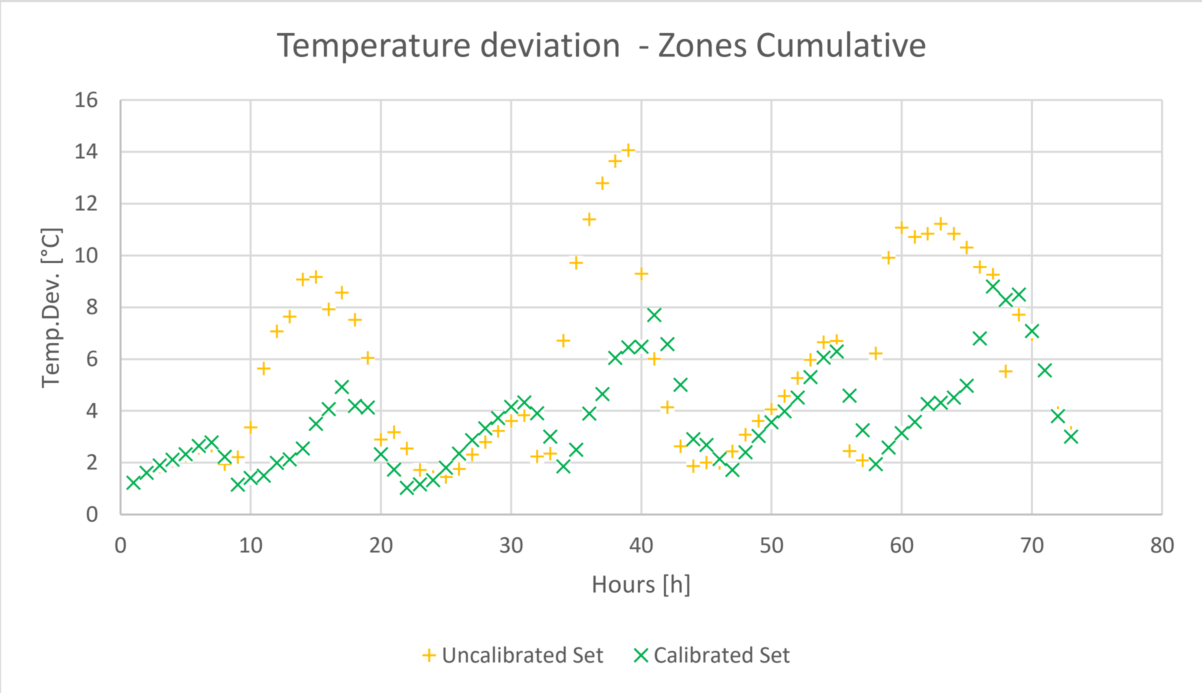
The deviation during daytime is almost totally reduced and differences in the behaviour during nigh time appear just in presence of sudden change in outdoor conditions.

About the statistical parameters for assessing the goodness of the calibration the results were widely within the calibration thresholds given by ASHRAE guideline 14 and even stricter standards:

Table 40: Free Floating Calibration Validation

	Obtained value	Threshold	Validated
Cost function	+2.62	-	-
MBE (%)	+4.27	±10	x
Cv(RMSE) (%)	+4.88	30	x

Despite the value of the cost function being weighted on the internal volumes for the threshold check, only the worst values have been considered. The temperature deviation was checked on the total for all the 4 zones, showing the highest deviation on midday and almost the same during the night.



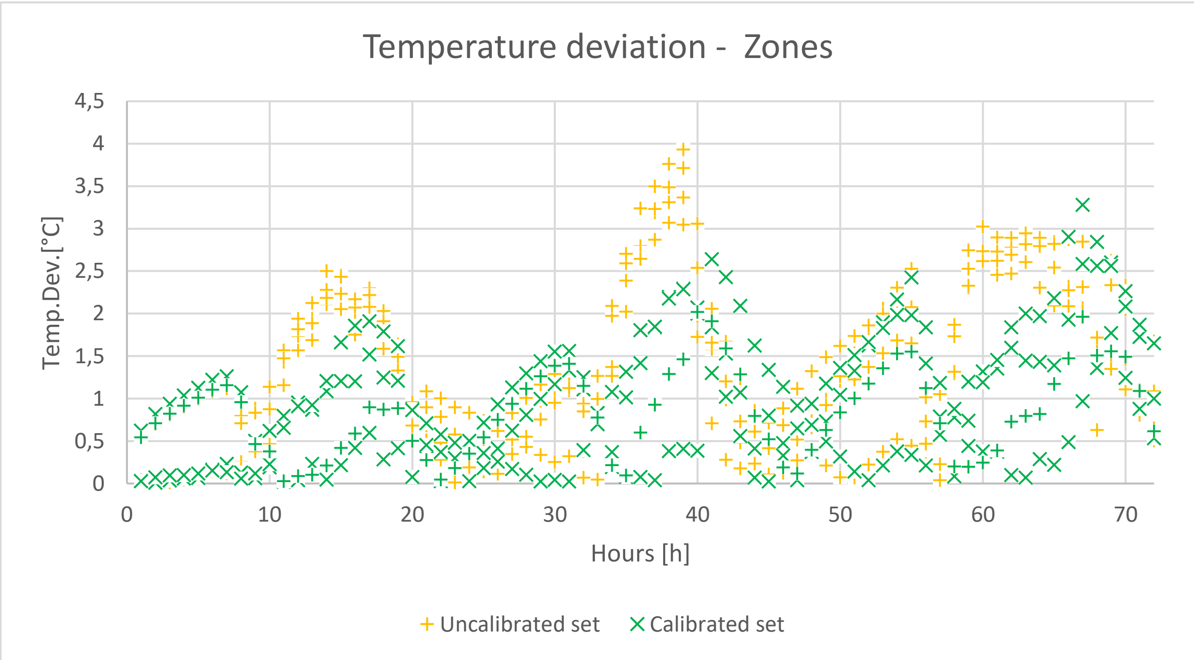


Figure 68:Temperature deviation scatterplots

The calibrated parameters have been then implemented on the complete simulation to go ahead with the full operation calibration.

6.7.2 Final Calibration

As for the first level calibration, the BEM has been rearranged to match the actual usage of the systems and speed as much as possible the simulation:

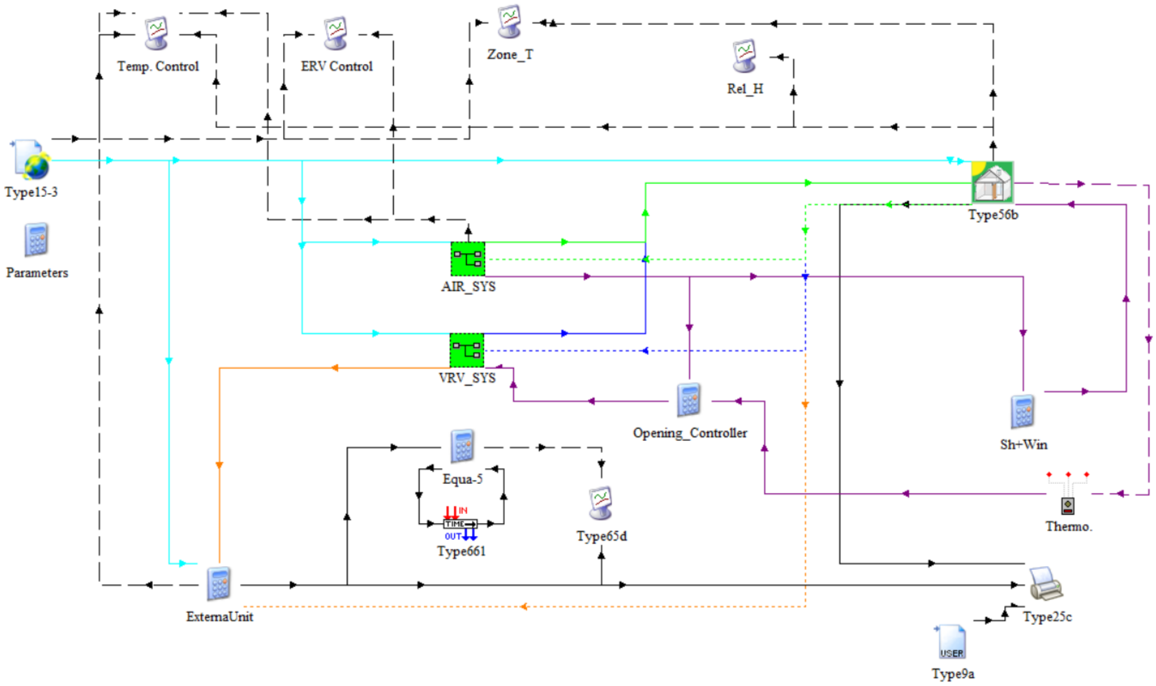


Figure 69: TRNSYS scheme for Final Calibration

Due to the use in summer season only the heating system has been removed. the data reading has been implemented to consider the measured values. Due to the building site's operational status it was possible to collect usable data only for night time and then go ahead with an evidence-based calibration during the pre-competitions test days. The expected behaviour, simulation based, on the performed night time test in Guangzhou are reported below:

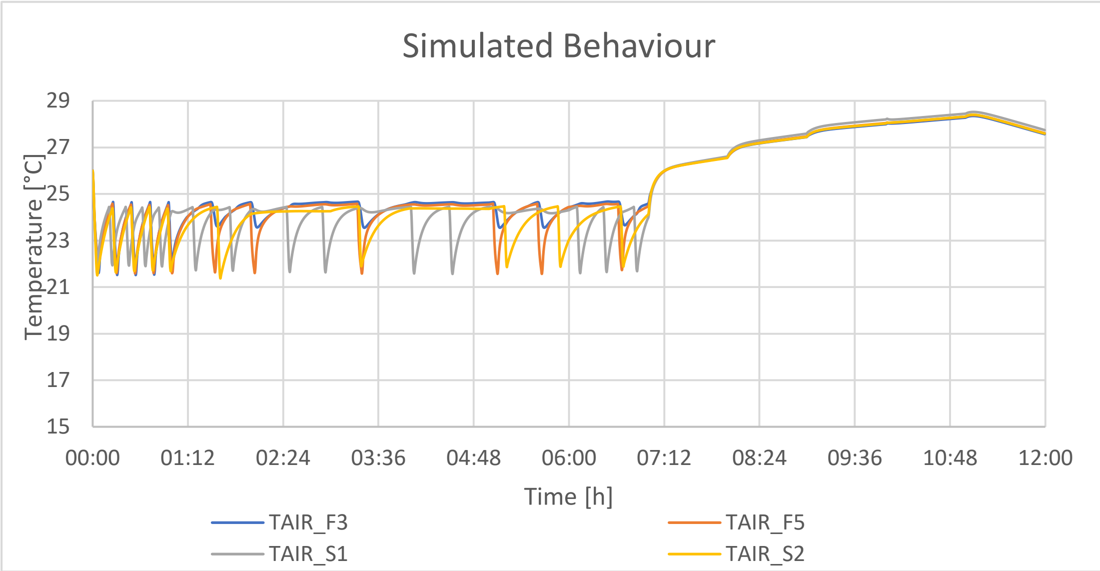


Figure 70: Calibrated model temperature simulated behaviour

Which shows the on-off switch of the different machines. The set-point was set to 22°C with a 2°C dead-band level. The actual behaviour instead showed that, due to an error in the placement of the thermostat, the temperature inside the rooms falls way below the set point, with the kitchen (F5) not be able to reach it:

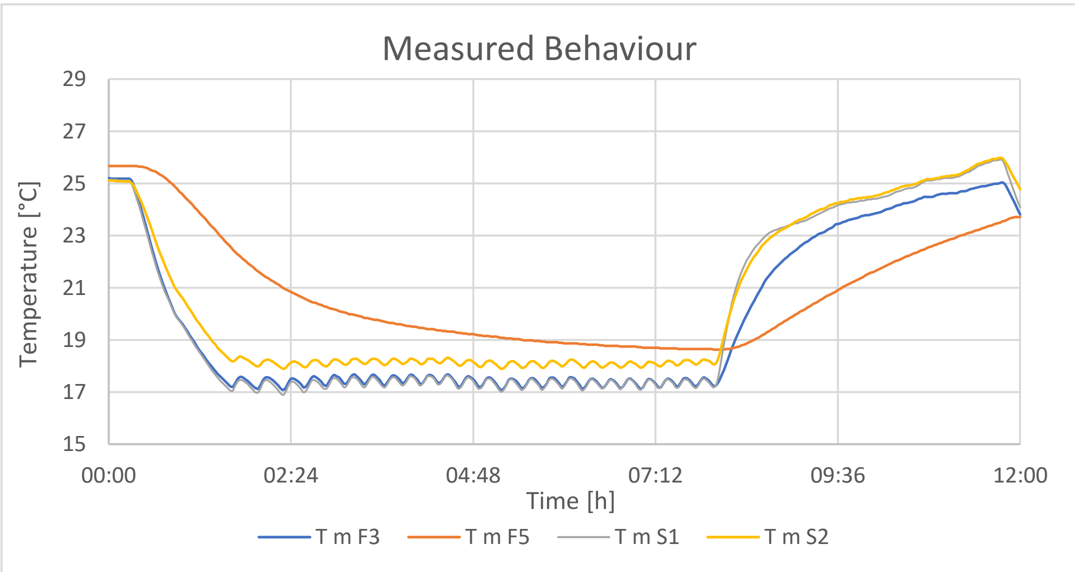


Figure 71: Measured Temperature Behaviour – Test 0

It was then decided to change the cooling mode and re-evaluate the set point to find out the virtual set point to maintain the right level inside the environment. Due to the construction schedule the set point matching was done after the construction in Dezhou. The mismatch was gradually reduced by adjusting the set point in the rooms according to the simulation mismatch till the convergence in the hourly averaged results was obtained. Originally the deviation was about 5°C for each thermal zone but, due to the higher temperature outside, the new set point was moved from 22°C to 24°C, and the cooling mode was modified in all the zones, except that of for the dining room (which was not allowed by the machine), to the stabilized mode: instead of the on-off cycle the machine used the internal inverter to maintain Temperature and Humidity stable. The results, thus improved, were not completely inside the needed thresholds for all the zones:

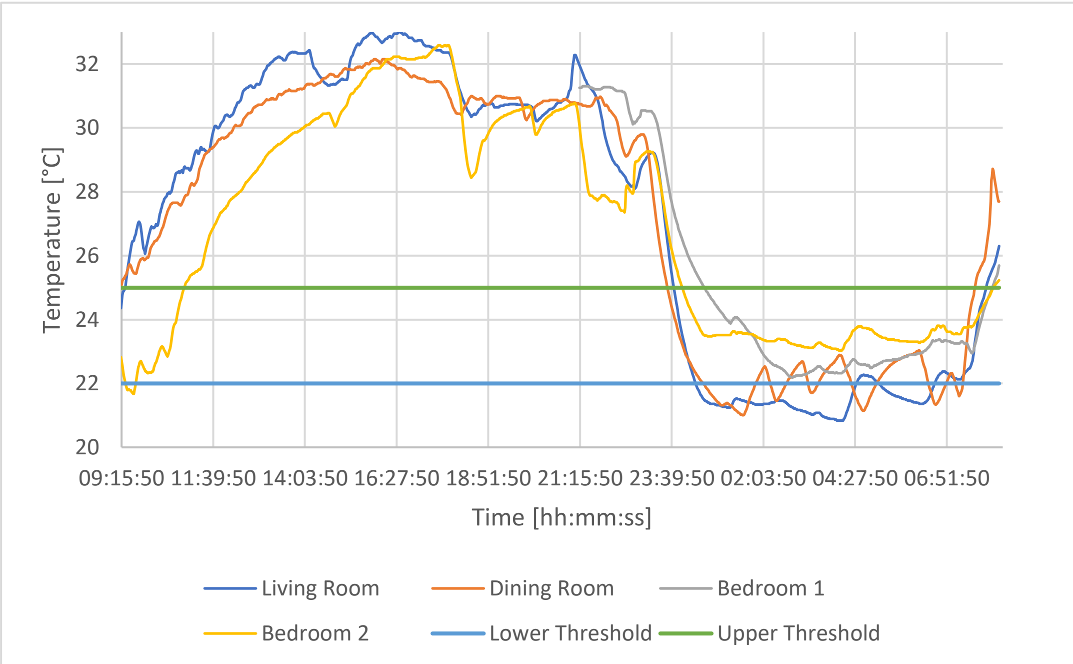


Figure 72: Measured Temperature behaviour- Test 1

The collected data have been inserted in the simulation with the right outdoor conditions and the set point for the Living Room and the Dining Room have been modified from 22°C to 26°C. After another night of testing the results were all inside the threshold both in the real operation and in the simulation too:

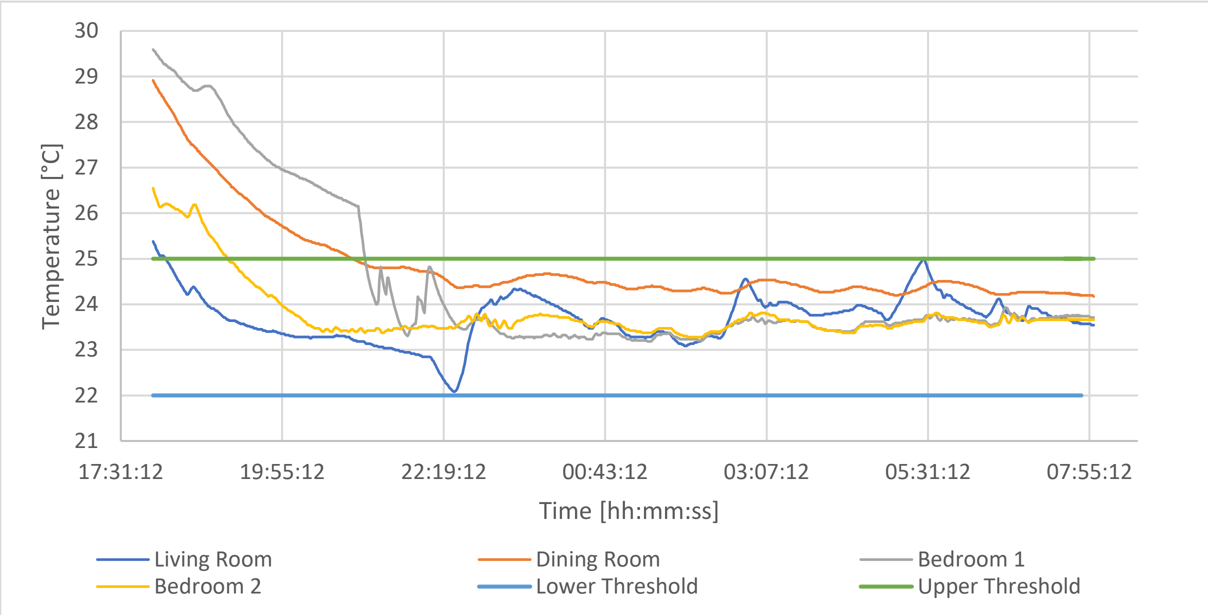


Figure 73: Temperature behaviour - Test 9

The comparison on an hourly basis is reported below:

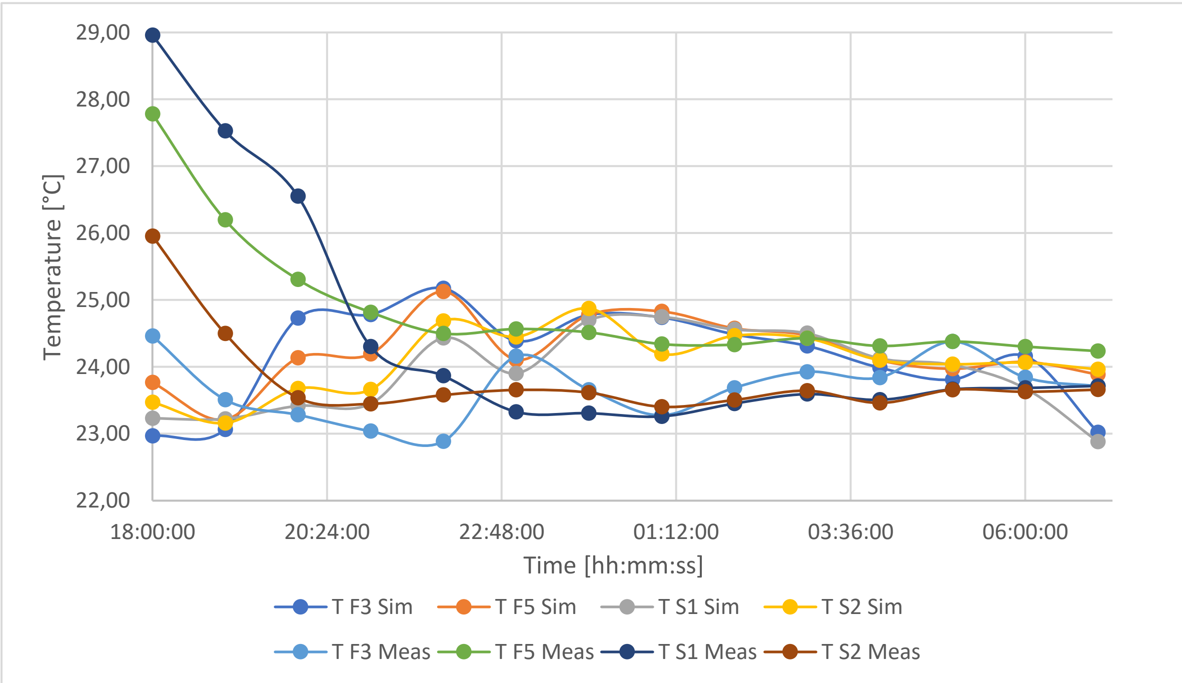


Figure 74: Simulation-Measurement hourly comparison

Table 41: Simulated vs Measured Temperature – Final Calibration

Time	T F3 Sim	T F5 Sim	T S1 Sim	T S2 Sim	T F3 Meas.	T F5 Meas.	T S1 Meas.	T S2 Meas.
18:00	22.97	23.77	23.23	23.47	24.46	27.78	28.96	25.96
19:00	23.07	23.21	23.22	23.16	23.51	26.20	27.53	24.50
20:00	24.73	24.13	23.42	23.67	23.28	25.31	26.55	23.54
21:00	24.78	24.19	23.45	23.66	23.04	24.82	24.30	23.45
22:00	25.18	25.13	24.43	24.69	22.89	24.50	23.87	23.58
23:00	24.39	24.11	23.90	24.45	24.16	24.57	23.33	23.65
00:00	24.78	24.78	24.70	24.87	23.66	24.52	23.31	23.62
01:00	24.74	24.83	24.75	24.19	23.28	24.34	23.26	23.40
02:00	24.49	24.58	24.56	24.47	23.69	24.33	23.45	23.50
03:00	24.31	24.47	24.50	24.43	23.93	24.43	23.59	23.64
04:00	23.99	24.10	24.13	24.10	23.84	24.31	23.51	23.46
05:00	23.81	23.97	24.03	24.04	24.38	24.38	23.67	23.66
06:00	24.16	24.07	23.68	24.06	23.84	24.30	23.68	23.63
07:00	23.02	23.89	22.88	23.96	23.71	24.24	23.72	23.66

Using this dataset, the simulation has been validated according to the standards requirement with these results:

Table 42: Validation of the Final Calibration

	Obtained values (%)				Threshold	Validated
	Zone F3	Zone F5	Zone S1	Zone S		
MBE	3.96	3.48	6.39	3.49	±10	x
Cv(RMSE)	4.78	5.70	9.13	4.27	30	x

In all the thermal zones the behaviour of the BEM has been validated. This allowed its use for the comfort zone contest planning during the competition with a good precision for the medium/short range monitoring. The results obtained during the competition will be discussed in the next Chapter.

7. Final considerations

The calibration was not only performed for a study purpose, but it was part of a bigger procedure to obtain the maximum available score during the contest. This meant working both on a short-term monitoring and on a long-term planning. This was obtained developing two models: the first, the one designed in this study, has the aim of creating a calibrated Building Energy Models and to use it as a base for the second one, consisting of a computational-aided optimization of many parameters during the competition and on a real-life operation prevision [37]. They have been both used for the settings of the systems for almost all the tasks to be performed with different objectives: the calibrated simulation was used as a predictive item with a 5-8 hours timespan; the optimized simulation gave a benchmark on the operational mode to be maintained in the building throughout the competition. The results obtained and the further advancements to be performed are discussed in the next paragraphs.

7.1 Competition Results

The project overall scores earned it the victory of the competition with the results for the engineering, innovation and comfort zone stacked on top of the board. The final scores are listed below:

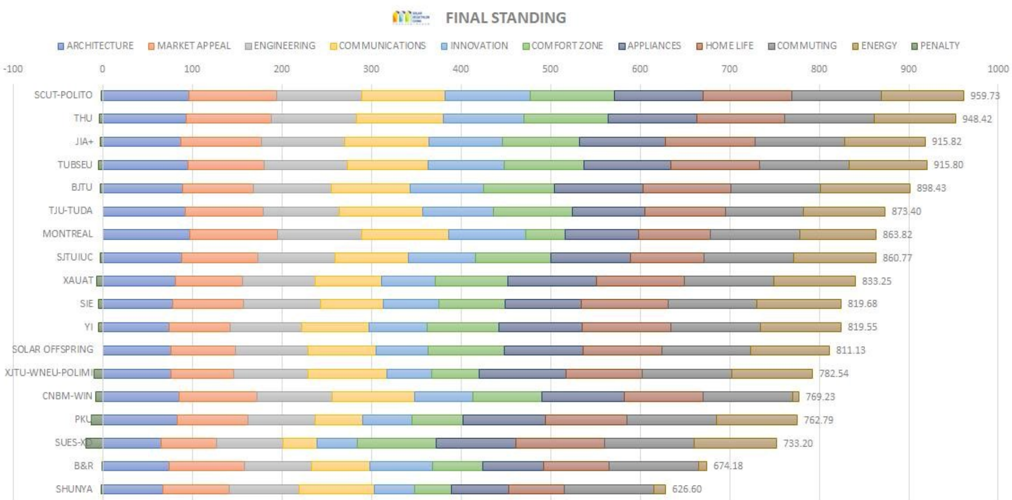


Figure 75: Final Overall Score

Table 43: Task score by Type

Team	Team SCUTxPoliTo		
Task	Type	Score	Position
Architecture	Jury	96.0	2
Market Appeal	Jury	97.7	2
Engineering	Jury	96.0	1
Communication	Jury	92.6	4
Innovation	Jury	95.0	1
Comfort zones	Measured	94.1	1
Appliances	Measured	98.7	4
Home Life	Measured	99.2	2
Commuting	Measured	100	1
Energy	Measured	91.9	3

The results were calculated as explained in Chapter 2 using a real time monitoring system placed in 3 zones (Living Room, Bedroom 1 and Bedroom 2) and taking into account only the values that are the farthest from the full-point zone. The scoring platform, remotely reachable, recorded the values with a 15 minutes timestep with a live update. Before the start of the monitoring period each day (usually 18:00 – 8:00) a simulation with the expected fluctuation in the temperature was launched to apply some changes at the optimized set point.

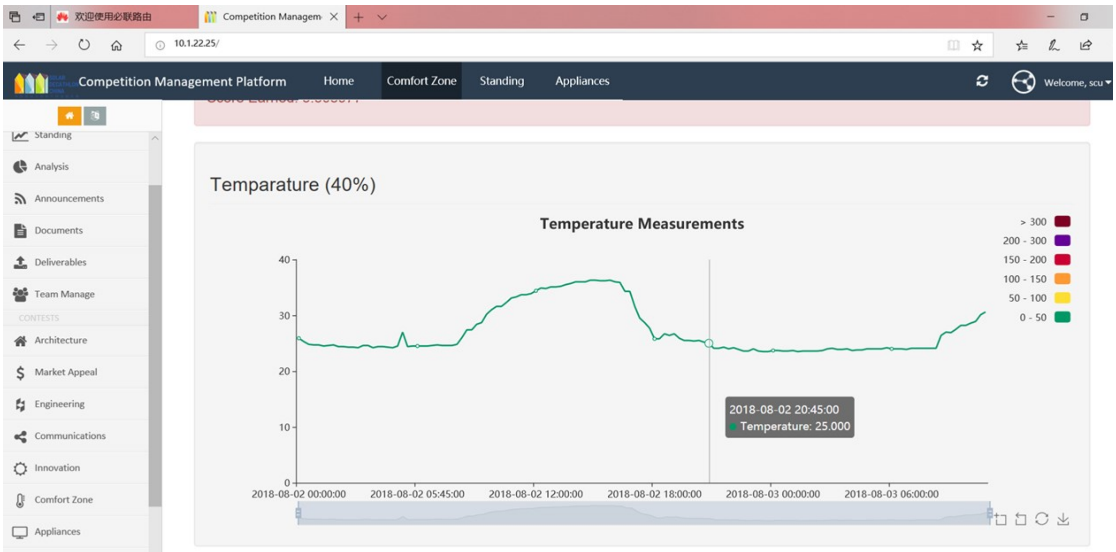


Figure 76: Scoring system evaluation

At the same time, a real time energy monitoring system was implemented to maximize the score in the energy balance contest. To perform this, the contest schedule was merged with the expected energy consumption of all the systems and appliances (with the HVAC covering the 60% of consumption). All the efforts payed off with the most stable behaviour for the comfort zone where the project obtained full marks for the whole contest period except one night in which the house was left on purely passive strategies as a demonstration for the Juries. The energy balance scored a +32 kWh mark, being awarded with the 3th place (the loss points are all on the weighted PV panels efficiency). The results of the competition were a success not only for the final victory but mostly for the level of accuracy obtained in the management of the prototype, considering the elevated level of the other contestant. Due to the simulations it was possible to control the commercial systems as system designed *ad hoc*.

7.2 Further Development

After the end of the contest and having the prototype fully operational it will be possible to complete the calibration using the optimization aided method even for the system calibration. Other advancements to add the study could be the use of power loggers to calibrate the energy consumption on the longer period. These features could be implemented in the domestic automation application: this software, self-developed by the Information Technologies (IT) group, integrates a SCADA/EMS system able to operate actively on the energy system. The ability to predict the behaviour of the house with a real-time monitoring and free online forecast could bring a significant improvement in the energy savings and integration with passive strategies. Further modifications on the software could focus on a calibration of the heating system and the integration of the adaptive comfort set-point selection that was developed by the IT team.

8. Conclusion

The study brought useful results to the competition developing. The creation of a BEM worked properly as a double-check and enhanced simulations of the HVAC efficiency. The implementation of the capacity tables allowed a dynamic evaluation of the energy consumption and the possibility to study the effect of distinct set-ups. The working connection between TRNSYS and CONTAM made it possible to evaluate both energy and pollutants flow paths in the contest operations. The performing of a Sensitivity Analysis gave meaningful focus on certain parameters that, in other ways, would have been left behind. This, together with the optimization of the pattern searched, increased the reliability of the calibration maintaining the computational cost affordable. The optimization-aided calibration offered a good range of available codes for performing the final simulation, giving the opportunity to pick the one that better suits the simulation and to tailor it to the specifics of the wanted calibration. The results, even if incomplete, give a substantial help to the monitoring and planning system and have shown the flexibility of the calibration procedure in reshaping itself according to the building site and operational needs. The outcome of the competition proved the goodness of this results by maximizing the possible results and offering further development for a calibration on the energy consumption to be implemented in the SCADA/EMS system for the full operation of the house in a smart, energy saving, mode.

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To my team I want to devote my final thanks. We have been through all of this together and we made it to the final victory. In these two years I grew up professionally and personally and part of this I owe to you. I sincerely wish you all the best. You are great professionals and wonderful people and I want to thank you for making me feel like at home even when I was really far away from it.

加油

Appendix A

Sensitivity Analysis MATLAB Codes

Campolongo Trajectory Listing

```
clear all
close all
clc
tic
kk= 27;
pp= 4;
%% Constant
delta= pp/(2*(pp-1));
BB= tril(ones(kk+1,kk),-1);
JJ= ones(kk+1,kk);

%% Random Generated array to develop a single trajectory
% They are nested in a for loop to create M different trajectories
% Among this we will tool the r trajectories with the higest spread
MM= 22;
BBtot= [];v
for jj= 1:MM

    xx= ((randi(2,kk,1)-ones(kk,1))/(pp-1))';

    DD= rand(1,kk)*2;
    for ii=1:kk
        if DD(ii)>0
            DD(ii)= 1;
        else
            DD(ii)= -1;
        end
    end
    DD= diag(DD);
    PP= zeros(kk);
    loc= 1:length(PP);
    pic= loc(randi(length(loc)));
    for ii=1:kk
        PP(ii,pic)=1;
        loc(loc==pic)=[];
        if ~isempty(loc)
            pic= loc(randi(length(loc)));
        end
    end
    BBstar= (JJ(:,1)*xx + (delta/2)*((2*BB-JJ)*DD+JJ))*PP;

    BBtot= [BBtot; BBstar];
end
%% Calculatin the distance between pair of trajectories
clear ii jj
dist= [];

for ww= 1:MM
    for yy= (ww+1):MM
        %Storing the results
        %Trajectoriy A
```

```
        ll= ww;
        T_i= BBtot((kk+1)*(ll-1)+1:(kk+1)*(ll-1)+1+kk,:);
        %Trajectory B
        mm= yy;
        T_j= BBtot((kk+1)*(mm-1)+1:(kk+1)*(mm-1)+1+kk,: );
        aa= [];

        for ii= 1:kk+1
            for jj= 1:kk+1

                for nn= 1:kk
                    x_i= T_i(ii,kk);
                    x_j= T_j(jj,kk);
                end
                aa= [aa sqrt((x_i-x_j)^2)];
            end
        end
        dist= [dist; ll , mm , sum(aa)];
    end
end

%% Selecting the best trajectories
rr= 10;
tot_trajectory= 1:MM;

DD= nchoosek(tot_trajectory,rr);
for ss=1:length(DD)
    dd= nchoosek(DD(ss,:),2);
    euc_dis= [];
    for gg= 1:length(dd)
        coord= find((dd(gg,1)==dist(:,1))+( dd(gg,2)==dist(:,2))==2);
        euc_dis= [euc_dis dist(coord,3)^2];
    end
    DDr(ss,:)= [DD(ss,:), sqrt(sum(euc_dis))];
end
[~,idx]= sort(DDr(:,rr+1),'descend');
DD_ordered= DDr(idx,:);
rr_f= DD_ordered(1,1:end-1);

%%Printing the Best Trajectories
RR_final= [];
for nn= 1:length(rr_f)
RR_final= [RR_final ;BBtot((kk+1)*(nn-1)+1:(kk+1)*(nn-1)+1+kk,:)];
end
save RR_final RR_final
%%Chapeaux to myself
toc
```

Standard Trajectory Listing

```
tic
clear all
close all
clc
kk= 27;
pp= 4;
%% Constant
delta= pp/(2*(pp-1));
BB= tril(ones(kk+1,kk),-1);
JJ= ones(kk+1,kk);

%% Random Generated array to develop a single trajectory
% They are nested in a for loop to create M different trajectories
% Among this we will tool the r trajectories with the higest spread
RR= 10;
BBtot= [];
for jj= 1:RR

    xx= ((randi(2,kk,1)-ones(kk,1))/(pp-1))';

    DD= rand(1,kk)*2;
    for ii=1:kk
        if DD(ii)>0
            DD(ii)= 1;
        else
            DD(ii)= -1;
        end
    end
    DD= diag(DD);


    PP= zeros(kk);
    loc= 1:length(PP);
    pic= loc(randi(length(loc)));
    for ii=1:kk
        PP(ii,pic)=1;
        loc(loc==pic)=[];
        if ~isempty(loc)
            pic= loc(randi(length(loc)));
        end
    end
    BBstar= (JJ(:,1)*xx + (delta/2)*((2*BB-JJ)*DD+JJ))*PP;

    BBtot= [BBtot; BBstar];
end
RR_final= BBtot;
save RR_final RR_final
toc
```

Template Editing and TRANSYS calling

```
function [E_con]= Calling_CL (XX)
%XX= zeros(1,27);  %Test
%% Parameters Setting
%DCK
ERV= (0.9 +XX(1)*0.2);
h_in= 5+XX(2)*4;
h_out= 54+XX(3)*20;
hwin_in= 5+XX(4)*4;
hwin_out= 54+XX(5)*20;
Inf_f3= (0.9 +XX(6)*0.2);
Inf_f5= (0.9 +XX(7)*0.2);
Inf_s1= (0.9 +XX(8)*0.2);
Inf_s2= (0.9 +XX(9)*0.2);
AC_f31= (0.9 +XX(10)*0.2);
AC_f32= (0.9 +XX(11)*0.2);
AC_f34= (0.9 +XX(12)*0.2);
AC_f54= (0.9 +XX(13)*0.2);
AC_f57= (0.9 +XX(14)*0.2);
AC_s16= (0.9 +XX(15)*0.2);
AC_s14= (0.9 +XX(16)*0.2);
AC_s24= (0.9 +XX(17)*0.2);
AC_s25= (0.9 +XX(18)*0.2);
Sh_hor=  0 +XX(19)*0.1;
Sh_ver=  0 +XX(20)*0.1;
%BUI
Cap_F3= 47.64*(1+XX(21)*0.15);
Cap_F5= 59.28*(1+XX(22)*0.15);
Cap_S1= 59.16*(1+XX(23)*0.15);
Cap_S2= 53.16*(1+XX(24)*0.15);
Phen_con= 0.108*(0.9 +XX(25)*0.2);
VIP_res= 1*(0.9 +XX(26)*0.2);
T_ground= 293+ XX(27)*3;
fid = fopen('SA_template.dck','rt') ;
X = fread(fid) ;
fclose(fid) ;
%% Variables to string
%DCK
X = char(X.') ;
ERV= num2str(ERV);
h_out= num2str(h_out);
hwin_out= num2str(hwin_out);
h_in= num2str(h_in);
hwin_in= num2str(hwin_in);
Inf_f3= num2str(Inf_f3);
Inf_f5= num2str(Inf_f5);
Inf_s1= num2str(Inf_s1);
Inf_s2= num2str(Inf_s2);
AC_f31= num2str(AC_f31);
AC_f32= num2str(AC_f32);
AC_f34= num2str(AC_f34);
AC_f54= num2str(AC_f54);
AC_f57= num2str(AC_f57);
AC_s16= num2str(AC_s16);
AC_s14= num2str(AC_s14);
AC_s24= num2str(AC_s24);
AC_s25= num2str(AC_s25);
```

```
Sh_hor= num2str(Sh_hor);
Sh_ver= num2str(Sh_ver);
Y = strrep(X, "%ERV%", ERV) ;
Y = strrep(Y, "%h_out%", h_out) ;
Y = strrep(Y, "%hwin_out%", hwin_out) ;
Y = strrep(Y, "%h_in%", h_in) ;
Y = strrep(Y, "%hwin_in%", hwin_in) ;
Y = strrep(Y,"%Inf_f3%", Inf_f3 );
Y = strrep(Y,"%Inf_f5%", Inf_f5 );
Y = strrep(Y,"%Inf_s1%", Inf_s1 );
Y = strrep(Y,"%Inf_s2%", Inf_s2 );
Y = strrep(Y,"%AC_f31%",AC_f31 );
Y = strrep(Y,"%AC_f32%",AC_f32 );
Y = strrep(Y,"%AC_f34%",AC_f34 );
Y = strrep(Y,"%AC_f54%",AC_f54 );
Y = strrep(Y,"%AC_f57%",AC_f57 );
Y = strrep(Y,"%AC_s16%",AC_s16 );
Y = strrep(Y,"%AC_s14%",AC_s14 );
Y = strrep(Y,"%AC_s24%",AC_s24 );
Y = strrep(Y,"%AC_s25%",AC_s25 );
Y = strrep(Y,"%Sh_hor%",Sh_hor );
Y = strrep(Y,"%Sh_ver%",Sh_ver );
fid2 = fopen('SA_run.dck','wt') ;
fwrite(fid2,Y) ;
fclose (fid2) ;
%BUI
fid3 = fopen('SA_template.bui','rt') ;
Z = fread(fid3) ;
fclose(fid3) ;
Z = char(Z.') ;
Cap_F3= num2str(Cap_F3);
Cap_F5= num2str(Cap_F5);
Cap_S1= num2str(Cap_S1);
Cap_S2= num2str(Cap_S2);
Phen_con= num2str(Phen_con);
T_ground= num2str(T_ground);
VIP_res= num2str(VIP_res);
G = strrep(Z, "%Cap_F3%", Cap_F3) ;
G = strrep(G, "%Cap_F5%", Cap_F5) ;
G = strrep(G, "%Cap_S1%", Cap_S1) ;
G = strrep(G, "%Cap_s2%", Cap_S2) ;
G = strrep(G, "%Phen_con%", Phen_con) ;
G = strrep(G, "%T_ground%", T_ground) ;
G = strrep(G, "%VIP_res%", VIP_res) ;
fid4 = fopen('SA_run.bui','wt') ;
fwrite(fid4,G) ;
fclose (fid4) ;
!C:\Trnsys16\Exe\TRNExe.exe C:\Users\asus\Desktop\SA_Finale\SA_run.dck /n
Results = 'type28_energy.sum';
delimiterIn= ' ';
headerlinesIn = 2;
[RR] = importdata(Results,delimiterIn,headerlinesIn);
RR= RR.data;
E_con= sum(RR(end,2:3));
```

Sensitivity Analysis Launcher

```
%Sensitivity Analysis run
clear all
close all
clc

kk= 27; %Number of parameters to be tested
pp= 4; %Number of variation assumed for every step

RR_final=load('RR_final.mat'); %Optimied traje ctories matrix
RR_final=RR_final.RR_final;
delta= pp/(2*(pp-1)); %Delta between steps
zz= length(RR_final)/(kk+1); %Number of trajectories
func= @(x) Calling_CL(x); %The function that will launch trnsys
counter= 0;
EE= zeros(zz,kk); %Pre-allocation of the Elementary Effect matrix
for ii= 1:zz
    traj= RR_final((kk+1)*(ii-1)+1:(kk+1)*(ii-1)+1+kk,:); %Traj. to be studied
    base= func( traj(1,:)); % Func. value for the first EE
    for jj= 2:kk+1
        last= func( traj(jj,:)); % Actual value of the function
        coord= find(traj(jj,:)~=traj(jj-1,:)); %Checking the position of the variation
        EE(ii,coord)= (last-base)/delta;  %Evaluating the EE
        base= last; %Updating the trajectory value
        counter= counter +1 %#ok<*NOPTS>
    end
end
mu= sum(EE)/zz; %Mean Value
mu_star= sum(abs(EE))/zz; %Absolute value of the Mean Value

for mm= 1:kk
sigma(mm)= (sum((EE(:,mm)-mu(mm)).^2))./(zz-1);
end

%Export
save sigma.mat
save mu.mat
save mu_star.mat
```

Appendix B

Capacity Table Heat Pump

RBZQ6AAV

制冷容量

组合 (%)（容量系数）	室外气温 ℃ DB	室内气温℃ WB													
		14.0		16.0		18.0		19.0		20.0		22.0		24.0	
		TC	PI	TC	PI	TC	PI	TC	PI	TC	PI	TC	PI	TC	PI
		kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW
130% 20.15kW	10	13.6	1.93	16.2	2.36	18.8	2.81	19.5	2.87	19.8	2.81	20.3	2.69	20.7	2.57
	12	13.6	1.96	16.2	2.41	18.8	2.86	19.3	2.85	19.5	2.79	20.0	2.67	20.5	2.63
	14	13.6	2.00	16.2	2.45	18.8	2.90	19.0	2.84	19.3	2.78	19.8	2.76	20.2	2.78
	16	13.6	2.04	16.2	2.50	18.5	2.88	18.8	2.86	19.0	2.88	19.5	2.90	20.0	2.93
	18	13.6	2.08	16.2	2.55	18.3	2.99	18.5	3.01	18.8	3.02	19.2	3.05	19.7	3.08
	20	13.6	2.12	16.2	2.72	18.0	3.14	18.3	3.16	18.5	3.17	19.0	3.20	19.5	3.23
	21	13.6	2.18	16.2	2.81	17.9	3.21	18.1	3.23	18.4	3.25	18.9	3.28	19.4	3.31
	23	13.6	2.34	16.2	3.02	17.6	3.36	17.9	3.38	18.1	3.39	18.6	3.43	19.1	3.46
	25	13.6	2.50	16.2	3.23	17.4	3.51	17.6	3.53	17.9	3.54	18.4	3.58	18.9	3.62
	27	13.6	2.67	16.2	3.45	17.1	3.65	17.4	3.67	17.6	3.69	18.1	3.73	18.6	3.77
	29	13.6	2.85	16.2	3.69	16.9	3.80	17.1	3.82	17.4	3.84	17.9	3.88	18.4	3.93
	31	13.6	3.04	16.1	3.91	16.6	3.95	16.9	3.97	17.1	3.99	17.6	4.04	18.1	4.08
	33	13.6	3.24	15.9	4.06	16.4	4.10	16.6	4.12	16.9	4.15	17.4	4.19	17.8	4.24
	35	13.6	3.45	15.6	4.20	16.1	4.25	16.4	4.28	16.6	4.30	17.1	4.35	17.6	4.40
	37	13.6	3.67	15.4	4.35	15.9	4.40	16.1	4.43	16.4	4.45	16.9	4.50	17.3	4.55
	39	13.6	3.91	15.1	4.50	15.6	4.55	15.9	4.58	16.1	4.61	16.6	4.66	17.1	4.71
120% 18.60kW	10	12.6	1.76	15.0	2.15	17.4	2.56	18.6	2.77	19.5	2.88	19.9	2.78	20.4	2.67
	12	12.6	1.79	15.0	2.19	17.4	2.61	18.6	2.82	19.2	2.87	19.7	2.76	20.1	2.65
	14	12.6	1.83	15.0	2.24	17.4	2.66	18.6	2.87	19.0	2.85	19.4	2.74	19.9	2.76
	16	12.6	1.86	15.0	2.28	17.4	2.71	18.5	2.89	18.7	2.86	19.2	2.88	19.6	2.91
	18	12.6	1.90	15.0	2.32	17.4	2.80	18.2	2.99	18.4	3.01	18.9	3.03	19.4	3.06
	20	12.6	1.94	15.0	2.42	17.4	3.01	18.0	3.14	18.2	3.15	18.7	3.18	19.1	3.21
	21	12.6	1.96	15.0	2.50	17.4	3.12	17.8	3.21	18.1	3.23	18.5	3.26	19.0	3.29
	23	12.6	2.09	15.0	2.68	17.4	3.34	17.6	3.36	17.8	3.37	18.3	3.40	18.7	3.44
	25	12.6	2.23	15.0	2.87	17.1	3.49	17.3	3.50	17.6	3.52	18.0	3.55	18.5	3.59
	27	12.6	2.38	15.0	3.07	16.9	3.63	17.1	3.65	17.3	3.67	17.8	3.70	18.2	3.74
	29	12.6	2.54	15.0	3.28	16.6	3.78	16.8	3.80	17.1	3.82	17.5	3.86	18.0	3.89
	31	12.6	2.71	15.0	3.50	16.4	3.93	16.6	3.95	16.8	3.97	17.3	4.01	17.7	4.05
	33	12.6	2.89	15.0	3.73	16.1	4.08	16.3	4.10	16.6	4.12	17.0	4.16	17.5	4.20
	35	12.6	3.07	15.0	3.98	15.9	4.22	16.1	4.25	16.3	4.27	16.8	4.31	17.2	4.36
	37	12.6	3.27	15.0	4.24	15.6	4.37	15.8	4.40	16.1	4.42	16.5	4.47	17.0	4.51
	39	12.6	3.48	14.9	4.47	15.3	4.52	15.6	4.55	15.8	4.57	16.3	4.62	16.7	4.67
110% 17.05kW	10	11.5	1.60	13.7	1.95	15.9	2.31	17.1	2.50	18.2	2.69	19.6	2.86	20.0	2.76
	12	11.5	1.63	13.7	1.99	15.9	2.36	17.1	2.55	18.2	2.74	19.3	2.84	19.7	2.74
	14	11.5	1.66	13.7	2.02	15.9	2.40	17.1	2.60	18.2	2.80	19.1	2.83	19.5	2.74
	16	11.5	1.69	13.7	2.06	15.9	2.45	17.1	2.65	18.2	2.85	18.8	2.87	19.2	2.89
	18	11.5	1.72	13.7	2.10	15.9	2.50	17.1	2.72	18.1	2.99	18.6	3.01	19.0	3.04
	20	11.5	1.76	13.7	2.14	15.9	2.65	17.1	2.93	17.9	3.13	18.3	3.16	18.7	3.19
	21	11.5	1.77	13.7	2.21	15.9	2.74	17.1	3.03	17.8	3.21	18.2	3.23	18.6	3.26
	23	11.5	1.86	13.7	2.37	15.9	2.94	17.1	3.25	17.5	3.35	17.9	3.38	18.3	3.41
	25	11.5	1.98	13.7	2.53	15.9	3.15	17.1	3.48	17.3	3.50	17.7	3.53	18.1	3.56
	27	11.5	2.11	13.7	2.70	15.9	3.37	16.8	3.63	17.0	3.64	17.4	3.68	17.8	3.71
	29	11.5	2.25	13.7	2.89	15.9	3.60	16.5	3.78	16.8	3.79	17.2	3.83	17.6	3.86
	31	11.5	2.40	13.7	3.08	15.9	3.84	16.3	3.92	16.5	3.94	16.9	3.98	17.3	4.01
	33	11.5	2.55	13.7	3.28	15.8	4.05	16.0	4.07	16.2	4.09	16.7	4.13	17.1	4.17
	35	11.5	2.72	13.7	3.49	15.6	4.20	15.8	4.22	16.0	4.24	16.4	4.28	16.8	4.32
	37	11.5	2.89	13.7	3.72	15.3	4.35	15.5	4.37	15.7	4.39	16.2	4.43	16.6	4.48
	39	11.5	3.07	13.7	3.96	15.1	4.49	15.3	4.52	15.5	4.54	15.9	4.59	16.3	4.63
100% 15.50kW	10	10.5	1.44	12.5	1.75	14.5	2.07	15.5	2.24	16.5	2.41	18.5	2.75	19.6	2.85
	12	10.5	1.47	12.5	1.78	14.5	2.11	15.5	2.28	16.5	2.46	18.5	2.81	19.3	2.84
	14	10.5	1.50	12.5	1.82	14.5	2.15	15.5	2.33	16.5	2.50	18.5	2.86	19.1	2.82
	16	10.5	1.52	12.5	1.85	14.5	2.20	15.5	2.37	16.5	2.55	18.5	2.90	18.8	2.87
	18	10.5	1.55	12.5	1.89	14.5	2.24	15.5	2.42	16.5	2.60	18.2	2.99	18.6	3.01
	20	10.5	1.58	12.5	1.92	14.5	2.31	15.5	2.54	16.5	2.79	18.0	3.14	18.3	3.16
	21	10.5	1.60	12.5	1.94	14.5	2.39	15.5	2.63	16.5	2.89	17.8	3.21	18.2	3.23
	23	10.5	1.64	12.5	2.07	14.5	2.56	15.5	2.82	16.5	3.10	17.6	3.36	18.0	3.38
	25	10.5	1.75	12.5	2.21	14.5	2.74	15.5	3.02	16.5	3.32	17.3	3.50	17.7	3.53
	27	10.5	1.86	12.5	2.36	14.5	2.92	15.5	3.23	16.5	3.55	17.1	3.65	17.5	3.68
	29	10.5	1.98	12.5	2.52	14.5	3.12	15.5	3.45	16.4	3.77	16.8	3.80	17.2	3.83
	31	10.5	2.11	12.5	2.69	14.5	3.33	15.5	3.68	16.2	3.91	16.6	3.95	16.9	3.98
	33	10.5	2.24	12.5	2.86	14.5	3.55	15.5	3.93	15.9	4.06	16.3	4.10	16.7	4.13
	35	10.5	2.38	12.5	3.04	14.5	3.79	15.5	4.19	15.7	4.21	16.1	4.25	16.4	4.28
	37	10.5	2.53	12.5	3.24	14.5	4.04	15.2	4.34	15.4	4.36	15.8	4.40	16.2	4.44
	39	10.5	2.69	12.5	3.45	14.5	4.30	15.0	4.49	15.2	4.51	15.6	4.55	15.9	4.59

90% 13.95kW	10	9.4	1.14	11.2	1.37	13.0	1.62	14.0	1.75	14.9	1.88	16.7	2.15	18.5	2.42
	12	9.4	1.16	11.2	1.40	13.0	1.65	14.0	1.78	14.9	1.91	16.7	2.19	18.5	2.47
	14	9.4	1.18	11.2	1.42	13.0	1.68	14.0	1.81	14.9	1.95	16.7	2.23	18.5	2.51
	16	9.4	1.20	11.2	1.45	13.0	1.71	14.0	1.85	14.9	1.99	16.7	2.27	18.5	2.55
	18	9.4	1.22	11.2	1.48	13.0	1.75	14.0	1.89	14.9	2.03	16.7	2.32	18.2	2.63
	20	9.4	1.24	11.2	1.50	13.0	1.78	14.0	1.92	14.9	2.10	16.7	2.49	17.9	2.76
	21	9.4	1.25	11.2	1.52	13.0	1.81	14.0	1.99	14.9	2.18	16.7	2.58	17.8	2.83
	23	9.4	1.28	11.2	1.58	13.0	1.94	14.0	2.13	14.9	2.33	16.7	2.77	17.6	2.95
	25	9.4	1.35	11.2	1.69	13.0	2.07	14.0	2.28	14.9	2.50	16.7	2.96	17.3	3.08
	27	9.4	1.43	11.2	1.80	13.0	2.21	14.0	2.44	14.9	2.67	16.7	3.17	17.1	3.21
	29	9.4	1.52	11.2	1.92	13.0	2.36	14.0	2.60	14.9	2.85	16.5	3.32	16.8	3.34
	31	9.4	1.62	11.2	2.04	13.0	2.52	14.0	2.77	14.9	3.04	16.2	3.45	16.6	3.47
	33	9.4	1.72	11.2	2.17	13.0	2.68	14.0	2.96	14.9	3.25	16.0	3.58	16.3	3.61
	35	9.4	1.83	11.2	2.31	13.0	2.86	14.0	3.15	14.9	3.46	15.7	3.71	16.1	3.74
	37	9.4	1.94	11.2	2.46	13.0	3.04	14.0	3.36	14.9	3.69	15.5	3.84	15.8	3.87
	39	9.4	2.06	11.2	2.61	13.0	3.24	14.0	3.57	14.9	3.93	15.2	3.97	15.6	4.00
80% 12.40kW	10	8.4	0.90	10.0	1.08	11.6	1.27	12.4	1.37	13.2	1.47	14.8	1.67	16.4	1.89
	12	8.4	0.92	10.0	1.10	11.6	1.29	12.4	1.39	13.2	1.49	14.8	1.70	16.4	1.92
	14	8.4	0.93	10.0	1.12	11.6	1.32	12.4	1.42	13.2	1.52	14.8	1.74	16.4	1.96
	16	8.4	0.95	10.0	1.14	11.6	1.34	12.4	1.45	13.2	1.55	14.8	1.77	16.4	2.00
	18	8.4	0.96	10.0	1.16	11.6	1.37	12.4	1.47	13.2	1.58	14.8	1.81	16.4	2.04
	20	8.4	0.98	10.0	1.18	11.6	1.39	12.4	1.50	13.2	1.61	14.8	1.87	16.4	2.18
	21	8.4	0.99	10.0	1.19	11.6	1.41	12.4	1.52	13.2	1.65	14.8	1.94	16.4	2.26
	23	8.4	1.01	10.0	1.22	11.6	1.47	12.4	1.62	13.2	1.76	14.8	2.08	16.4	2.42
	25	8.4	1.04	10.0	1.29	11.6	1.57	12.4	1.73	13.2	1.88	14.8	2.22	16.4	2.59
	27	8.4	1.11	10.0	1.38	11.6	1.68	12.4	1.84	13.2	2.01	14.8	2.38	16.4	2.77
	29	8.4	1.18	10.0	1.47	11.6	1.79	12.4	1.96	13.2	2.15	14.8	2.54	16.4	2.96
	31	8.4	1.25	10.0	1.56	11.6	1.91	12.4	2.09	13.2	2.29	14.8	2.71	16.2	3.08
	33	8.4	1.33	10.0	1.66	11.6	2.03	12.4	2.23	13.2	2.44	14.8	2.89	15.9	3.19
	35	8.4	1.41	10.0	1.76	11.6	2.16	12.4	2.37	13.2	2.60	14.8	3.08	15.7	3.31
	37	8.4	1.49	10.0	1.87	11.6	2.30	12.4	2.53	13.2	2.77	14.8	3.28	15.4	3.43
	39	8.4	1.58	10.0	1.99	11.6	2.44	12.4	2.69	13.2	2.94	14.8	3.50	15.2	3.54
70% 10.85kW	10	7.3	0.72	8.7	0.85	10.1	0.99	10.9	1.07	11.6	1.14	13.0	1.30	14.4	1.46
	12	7.3	0.73	8.7	0.86	10.1	1.01	10.9	1.09	11.6	1.16	13.0	1.32	14.4	1.49
	14	7.3	0.74	8.7	0.88	10.1	1.03	10.9	1.11	11.6	1.18	13.0	1.35	14.4	1.52
	16	7.3	0.75	8.7	0.89	10.1	1.05	10.9	1.13	11.6	1.21	13.0	1.37	14.4	1.55
	18	7.3	0.76	8.7	0.91	10.1	1.07	10.9	1.15	11.6	1.23	13.0	1.40	14.4	1.58
	20	7.3	0.78	8.7	0.93	10.1	1.09	10.9	1.17	11.6	1.25	13.0	1.43	14.4	1.62
	21	7.3	0.78	8.7	0.93	10.1	1.10	10.9	1.18	11.6	1.27	13.0	1.45	14.4	1.68
	23	7.3	0.80	8.7	0.95	10.1	1.12	10.9	1.22	11.6	1.33	13.0	1.55	14.4	1.80
	25	7.3	0.81	8.7	0.99	10.1	1.19	10.9	1.30	11.6	1.42	13.0	1.66	14.4	1.92
	27	7.3	0.86	8.7	1.05	10.1	1.27	10.9	1.39	11.6	1.51	13.0	1.77	14.4	2.05
	29	7.3	0.91	8.7	1.12	10.1	1.35	10.9	1.48	11.6	1.61	13.0	1.89	14.4	2.19
	31	7.3	0.96	8.7	1.19	10.1	1.44	10.9	1.57	11.6	1.72	13.0	2.02	14.4	2.34
	33	7.3	1.02	8.7	1.26	10.1	1.53	10.9	1.67	11.6	1.83	13.0	2.15	14.4	2.50
	35	7.3	1.08	8.7	1.34	10.1	1.63	10.9	1.78	11.6	1.94	13.0	2.29	14.4	2.66
	37	7.3	1.15	8.7	1.42	10.1	1.73	10.9	1.89	11.6	2.07	13.0	2.43	14.4	2.83
	39	7.3	1.21	8.7	1.51	10.1	1.83	10.9	2.01	11.6	2.20	13.0	2.59	14.4	3.02

60% 9.3kW	10	6.3	0.57	7.5	0.67	8.7	0.77	9.3	0.83	9.9	0.88	11.1	1.00	12.3	1.12
	12	6.3	0.58	7.5	0.68	8.7	0.79	9.3	0.84	9.9	0.90	11.1	1.02	12.3	1.14
	14	6.3	0.59	7.5	0.69	8.7	0.80	9.3	0.86	9.9	0.91	11.1	1.03	12.3	1.16
	16	6.3	0.59	7.5	0.70	8.7	0.81	9.3	0.87	9.9	0.93	11.1	1.05	12.3	1.18
	18	6.3	0.60	7.5	0.71	8.7	0.83	9.3	0.89	9.9	0.95	11.1	1.07	12.3	1.21
	20	6.3	0.61	7.5	0.72	8.7	0.84	9.3	0.90	9.9	0.97	11.1	1.09	12.3	1.23
	21	6.3	0.62	7.5	0.73	8.7	0.85	9.3	0.91	9.9	0.97	11.1	1.11	12.3	1.24
	23	6.3	0.63	7.5	0.74	8.7	0.86	9.3	0.93	9.9	0.99	11.1	1.15	12.3	1.32
	25	6.3	0.64	7.5	0.76	8.7	0.90	9.3	0.98	9.9	1.06	11.1	1.23	12.3	1.41
	27	6.3	0.66	7.5	0.80	8.7	0.96	9.3	1.04	9.9	1.12	11.1	1.31	12.3	1.51
	29	6.3	0.70	7.5	0.85	8.7	1.02	9.3	1.10	9.9	1.20	11.1	1.39	12.3	1.61
	31	6.3	0.74	7.5	0.90	8.7	1.08	9.3	1.17	9.9	1.27	11.1	1.48	12.3	1.71
	33	6.3	0.78	7.5	0.96	8.7	1.15	9.3	1.25	9.9	1.35	11.1	1.58	12.3	1.82
	35	6.3	0.83	7.5	1.01	8.7	1.22	9.3	1.32	9.9	1.44	11.1	1.68	12.3	1.94
	37	6.3	0.88	7.5	1.07	8.7	1.29	9.3	1.40	9.9	1.53	11.1	1.78	12.3	2.06
	39	6.3	0.93	7.5	1.14	8.7	1.37	9.3	1.49	9.9	1.62	11.1	1.90	12.3	2.19

组合 (%) （容量系数）	室外气温 ℃ DB	室内气温℃ WB													
		14.0		16.0		18.0		19.0		20.0		22.0		24.0	
		TC	PI	TC	PI	TC	PI	TC	PI	TC	PI	TC	PI	TC	PI
		kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW
50% 7.75kW	10	5.2	0.45	6.2	0.52	7.2	0.59	7.8	0.63	8.3	0.67	9.3	0.76	10.3	0.84
	12	5.2	0.46	6.2	0.53	7.2	0.60	7.8	0.64	8.3	0.68	9.3	0.77	10.3	0.86
	14	5.2	0.46	6.2	0.53	7.2	0.61	7.8	0.65	8.3	0.70	9.3	0.78	10.3	0.87
	16	5.2	0.47	6.2	0.54	7.2	0.62	7.8	0.67	8.3	0.71	9.3	0.80	10.3	0.89
	18	5.2	0.47	6.2	0.55	7.2	0.63	7.8	0.68	8.3	0.72	9.3	0.81	10.3	0.91
	20	5.2	0.48	6.2	0.56	7.2	0.64	7.8	0.69	8.3	0.73	9.3	0.83	10.3	0.92
	21	5.2	0.48	6.2	0.56	7.2	0.65	7.8	0.69	8.3	0.74	9.3	0.83	10.3	0.93
	23	5.2	0.49	6.2	0.57	7.2	0.66	7.8	0.71	8.3	0.75	9.3	0.85	10.3	0.95
	25	5.2	0.50	6.2	0.58	7.2	0.67	7.8	0.72	8.3	0.78	9.3	0.89	10.3	1.02
	27	5.2	0.51	6.2	0.60	7.2	0.71	7.8	0.77	8.3	0.83	9.3	0.95	10.3	1.08
	29	5.2	0.54	6.2	0.64	7.2	0.75	7.8	0.81	8.3	0.88	9.3	1.01	10.3	1.15
	31	5.2	0.57	6.2	0.68	7.2	0.80	7.8	0.86	8.3	0.93	9.3	1.07	10.3	1.23
	33	5.2	0.60	6.2	0.72	7.2	0.85	7.8	0.92	8.3	0.99	9.3	1.14	10.3	1.30
	35	5.2	0.63	6.2	0.76	7.2	0.90	7.8	0.97	8.3	1.05	9.3	1.21	10.3	1.39
	37	5.2	0.67	6.2	0.80	7.2	0.95	7.8	1.03	8.3	1.11	9.3	1.28	10.3	1.47
	39	5.2	0.70	6.2	0.85	7.2	1.00	7.8	1.09	8.3	1.18	9.3	1.36	10.3	1.56