

**POLITECNICO DI TORINO**

**Corso di Laurea Magistrale  
in Ingegneria Energetica e Nucleare**

**Tesi di Laurea Magistrale**

**Simulation-based Optimization  
for the Solar Decathlon Contest  
The POLITO-SCUT Prototype House**



**Relatori**

Prof. Enrico Fabrizio

Prof. Mauro Berta

Prof. Yufeng Zhang

Ph.D. Maria Ferrara

**Candidato**

Alessio Messina

**A.A. 2017-18**



## **Acknowledgments**

Firstly, I want to thank all the supervisors, Enrico Fabrizio, Mauro Berta, Yufeng Zhang, and Maria Ferrara, for their patience and efforts spent on this project, helping, teaching, and supporting me during all the time.

Obviously, a big thanks, to my family, my parents and my relatives, for their sacrifices, for their unlimited support, priceless moral support, and economical support, without them, this goal would not have been possible.

Another big thanks, to the team SCUTxPOLITO, both Italian and Chinese teammates, people I can call friends now, after all the time spent together during these years.

Thanks to my friends, they helped me through the difficulties, giving me the strength to face them, straight to the goal.

Thanks to my “travel brothers”, Ciro and Marco, which joined me on this experience in another city, with whom I spent most of the time, sharing happy and sad moments.

A special thanks to my best friend, who knows me from all my life, he is always by my side, and never refuse mine requests of help.

Last, but not least, a special thanks to a special person, Yicheng, for her kindness, her personality, and support, who made my experience in China, the best of my life.





## Index

Figure List.....	iii
Table List .....	vi
Introduction .....	1
1. The Solar Decathlon competition .....	3
1.1 Solar Decathlon China 2018 .....	4
1.2 Team SCUT-POLITO .....	12
2. Team SCUT-POLITO prototype: LONG PLAN.....	17
2.1 Envelope .....	17
2.2 HVAC system .....	20
2.3 Domestic Hot Water .....	24
2.4 PV system .....	24
3. Energy Model.....	27
3.1 Prototype Description and main characteristics .....	28
3.1.1 Requirements and simulation specifications .....	28
3.1.2 Envelope and Architecture .....	29
3.1.3 Systems and Engineering .....	30
3.2 TRNSYS Type for the energy model.....	35
3.2.1 Type 756b – VRV .....	35
3.2.2 Type 698 – Thermostat .....	37
3.2.3 Type 24 – Integrator.....	37
3.2.4 Type 25 – Printer & Type 65d – plot .....	38
3.2.5 Type 571b – Infiltration .....	38
3.2.6 Type 41d – Day.....	39
3.2.7 Type 14h – Schedules and shadings .....	40
3.2.8 Type 14a – Occupancy.....	41
3.2.9 Type 14b – Cooking .....	41
3.2.10 Type 14d – Lighting .....	41
3.2.11 Type 94a – PV .....	42
3.2.12 Type 97 – CONTAM.....	44
3.2.13 Type 760a – ERV .....	45
3.2.14 Type 642 – ERV flow .....	46

3.2.15 Type 15 – Weather file .....	46
3.2.16 Equation .....	47
3.2.17 Type 60d – Water Tank .....	48
3.2.18 Type 73 – Solar Thermal Panel .....	49
3.2.19 Type 654 – Water Pump .....	50
3.2.20 Type 11d – Flow Mixer .....	50
3.2.21 Type 56b – Building .....	51
3.3 Model for the CO <sub>2</sub> and PM 2.5 .....	56
4. Problem statement and implementation of the method .....	60
4.1 Simulation-based Optimization .....	60
4.1.1 General Description of the Problem and Mathematical Reference ..	60
4.1.2 PSO - Particle Swarm Optimization .....	62
4.1.3 Implementation on GenOpt .....	64
4.2 Application to the Prototype .....	70
4.2.1 Objective Function .....	70
4.2.2 Variables .....	70
4.2.3 Process .....	73
5. Results and Discussion .....	74
5.1 Results of the optimization .....	74
5.2 Design Variation .....	80
6. Conclusion .....	82
Appendix .....	83
MATLAB Code .....	83
Contest detailed schedule .....	88
References .....	96

## Figure List

Figure 1: Temperature Score .....	6
Figure 2: Humidity Score .....	6
Figure 3: CO2 Score .....	6
Figure 4: PM2.5 Score .....	7
Figure 5: Refrigerator Score .....	7
Figure 6: Freezer Score .....	7
Figure 7: Drying Score .....	8
Figure 8: Cooking Score .....	8
Figure 9: Hot Water Score .....	9
Figure 10: Energy Balance Score .....	10
Figure 11: Generating Capacity Score .....	10
Figure 12: Team SCUT-POLITO, patio .....	12
Figure 13: Living belt and Service belt .....	13
Figure 14: Staircase, integrated wall .....	13
Figure 15: Team SCUT-POLITO, opening ceremony .....	14
Figure 16: LONG PLAN, day and evening .....	15
Figure 17: Final award ceremony, first place .....	15
Figure 18: Leaders of the Chinese team .....	15
Figure 19: First Prize for both Engineering and Innovation .....	15
Figure 20: SDC Chronology .....	16
Figure 21: House CAD scheme .....	17
Figure 22: HVAC system .....	20
Figure 23: DHW loop scheme .....	24
Figure 24: Cooling solutions for the PV panels .....	25
Figure 25: Energy consumption .....	26
Figure 26: Energy production and consumption .....	26
Figure 27: TRNSYS Energy Model .....	27
Figure 28: Domestic Hot Water System .....	27
Figure 29: VRV Macro .....	30
Figure 30: ERV Macro .....	31
Figure 31: CONTAM Macro .....	31
Figure 32: Infiltration Macro .....	32
Figure 33: PV Macro .....	32

Figure 34: Shadings Macro .....	33
Figure 35: Schedules Macro .....	33
Figure 36: Type 756 - Parameter.....	35
Figure 37: Type 756 - Input.....	36
Figure 38: Type 698 - Parameter.....	37
Figure 39: Type 698 - Input.....	37
Figure 40: Type 41d - Input.....	39
Figure 41: Type 14h - Function editor .....	40
Figure 42: Type 14h - Parameter.....	41
Figure 43: Type 94a - Parameter.....	42
Figure 44: Type 94a - Input.....	42
Figure 45: CONTAM first floor .....	44
Figure 46: CONTAM second floor .....	44
Figure 47: Type 760a - Parameter .....	45
Figure 48: Type 760a - Input .....	45
Figure 49: Type 642 - Parameter.....	46
Figure 50: Type 642 - Input.....	46
Figure 51: Type 15-3 - Parameter .....	47
Figure 52: Equation tool .....	47
Figure 53: Parameter - Type 60d, tank 1.....	48
Figure 54: Parameter - Type 60d, tank 2.....	48
Figure 55: Input - Type 60d.....	49
Figure 56: Parameter - Type 73.....	49
Figure 57: Input - Type 73 .....	49
Figure 58: Parameter - Type 654.....	50
Figure 59: Input - Type 654.....	50
Figure 60: File Building Homepage.....	52
Figure 61: File Building Zone example .....	52
Figure 62: File Building Wall type manager .....	53
Figure 63: File Building Windows Type Manager.....	53
Figure 64: File Building Cooling Type Manager .....	54
Figure 65: File Building Ventilation Type Manager.....	54
Figure 66: File Building Infiltration Type Manager.....	55
Figure 67: File Building Gains .....	55

Figure 68: PM2.5 Meter .....	57
Figure 69: Zero-filter.....	57
Figure 70: CO2 Meter .....	57
Figure 71: Contest CO <sub>2</sub> .....	58
Figure 72: Contest CO <sub>2</sub> detail.....	58
Figure 73: Contest PM2.5 .....	59
Figure 74: Contest PM2.5 detail .....	59
Figure 75: Von Neumann topology, size 1 .....	63
Figure 76: PSO with Inertia weight in GenOpt.....	64
Figure 77: GenOpt Initialization file syntax .....	67
Figure 78: GenOpt Configuration file syntax .....	67
Figure 79: GenOpt discrete variables syntax.....	68
Figure 80: Batch file.....	73
Figure 81: Optimization Results .....	74
Figure 82: Optimization 5 .....	76
Figure 83: Optimization 7 .....	76
Figure 84: Optimization 8 .....	77
Figure 85: Optimization 9 .....	77
Figure 86: Optimization 10 .....	77
Figure 87: Best points of last optimization .....	79

## Table List

Table 1: External wall section .....	18
Table 2: Ground floor section .....	18
Table 3: Roof section.....	19
Table 4: Mid ceiling-floor section.....	19
Table 5: Daikin outdoor unit data .....	21
Table 6: Daikin indoor VRV data .....	21
Table 7: Capillary radiant floor module.....	22
Table 8: ERV .....	23
Table 9: Second floor bathrooms ventilator .....	23
Table 10: First floor bathroom ventilator.....	23
Table 11: PV panels data, STC .....	25
Table 12: PV panels data and coefficients .....	25
Table 13: VRV Parameters and Inputs .....	36
Table 14: PV panels Parameters and Inputs.....	43
Table 15: Variables names.....	70
Table 16: First values of the variables.....	71
Table 17: Second values of the variables .....	72
Table 18: Results of the simulations 1 - 6.....	75
Table 19: Results of the simulations 7 - 10 .....	78
Table 20: Design variation .....	81

## Introduction

This project is developed for a study about a **NZEB** prototype house designed for the competition **Solar Decathlon China**. The maximum score is 1000 points, divided into different sections [1]. Since a part of the score is linked to some measured parameters, it is possible to make a study about the prototype, building an accurate energy model, testing the performance requested, therefore, optimize it through some optimization algorithm, using the simulation-based optimization, a growing technique about the simulation of the buildings [2]. Usually the Life Cycle Cost is taken into account, as objective function, for this kind of simulation, instead, in this case the aim, is to maximize the obtained score, related to the parameters measured during the contest period [3].

To achieve this result, some coupling between software is needed. **TRNSYS 16** (Transient System Simulation Tool) will be used to create the energy model of the building [4], for both the envelope and the energy system, with the help of **CONTAM** software [5]. Therefore, the energy model should be optimized, varying some structural and management parameters. The traditional way of design relies on the experience of the designer, or on a single parameter check, to study the performance [6][7]. This wastes a lot of time, sometimes spent on useless parameters, sometimes forgetting of other important variables, and could lead even to a wrong solution. That is why the simulation-based optimization, taking advantage from the machine learning algorithms, in the case of this project, the particle swarm optimization [8][9], reduces the computational cost needed to check every single combination, ensuring a considerable improvement of the solution, saving time.

**GenOpt** software (Generic Optimization Program) suits well this need, in fact, it is widely used for this kind of applications [10]. The peculiarity of the objective function, quite different from a traditional simple output of a simulation program, because of the complexity of the time period, and the different scheme of calculation, requires a special evaluation of the outputs, so **MATLAB** will be used for this purpose, thanks to his easy customization.

Some of the results could be used as suggestion for the best operation and monitoring of the systems, during the contest period, while the others, could

be implemented in the future realization of the house, or for other studies about this project.

This tool is quite effective, it can be used for many applications, like other competition of the same level, new design, and to test the house behaviour in different conditions, requirements, or environments for the market appeal of the house.



## **1. The Solar Decathlon competition**

Solar Decathlon is an international competition where the fields about architecture and engineering are mixed together, to give life to a real house prototype. The first edition was held in Washington D.C. on 2002, after the proposal of Richard King, 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 last edition, the contests are Architecture, Market Potential, Engineering, Communication, Innovation, Water, Health and Comfort, Appliances, Home Life, Energy Contest.

## **1.1 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. The total score is 1000 points, divided into 100 points to each sub-contest [1]. It has a main division: 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:

### **a. Architecture (Jury) – 100 points**

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

### **b. Market Appeal (Jury) – 100 points**

- 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.

### **c. Engineering (Jury) – 100 points**

- 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.

**d. Communication (Jury) – 100 points**

- 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.

**e. Innovation (Jury) – 100 points**

- 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.

## f. Comfort Zone

- Temperature – 40 points

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

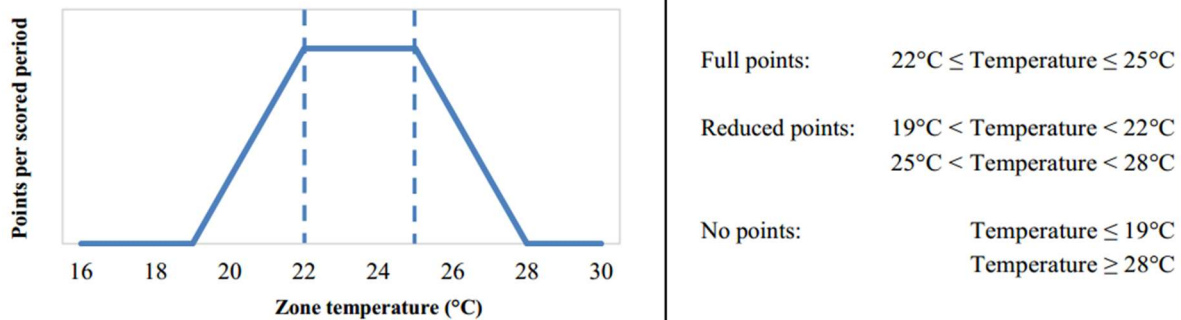


Figure 1: Temperature Score

- Humidity – 20 points

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

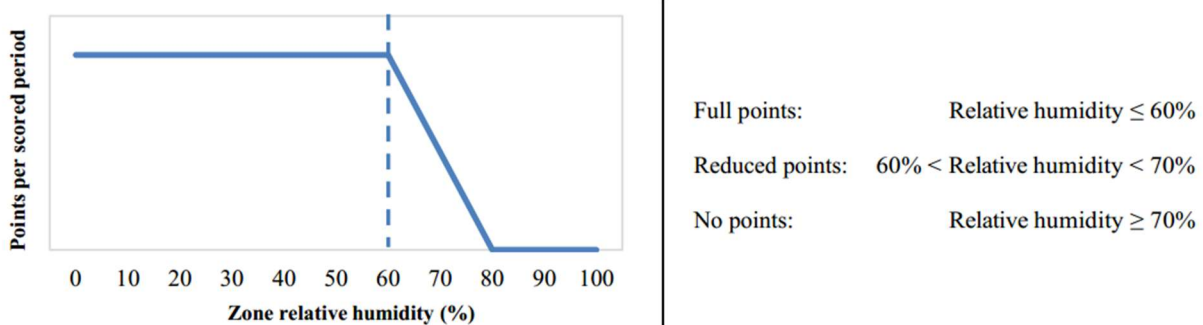


Figure 2: Humidity Score

- CO<sub>2</sub> Level – 20 points

The CO<sub>2</sub> concentration should be below 1000 ppm to earn the maximum points, reduced points are earned from 1000 to 2000 ppm.

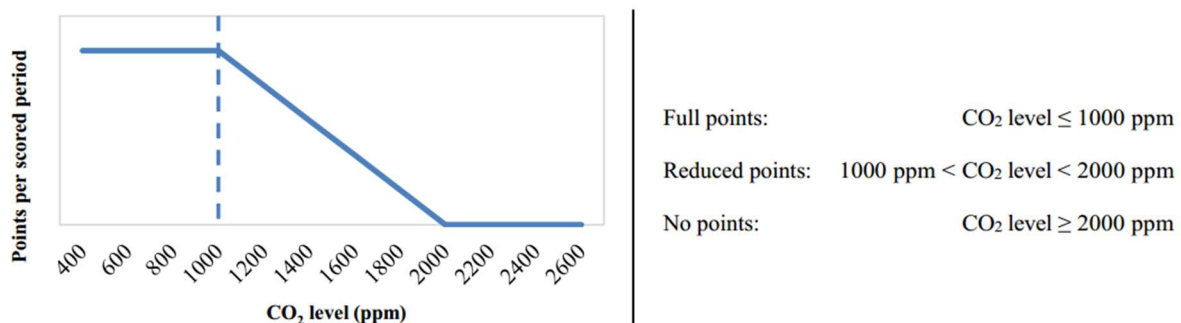


Figure 3: CO<sub>2</sub> Score

- PM 2.5 Level – 20 points

The PM 2.5 concentration should be below  $35 \mu\text{g}/\text{m}^3$  to earn the maximum points, reduced points are earned from 35 to  $75 \mu\text{g}/\text{m}^3$ .

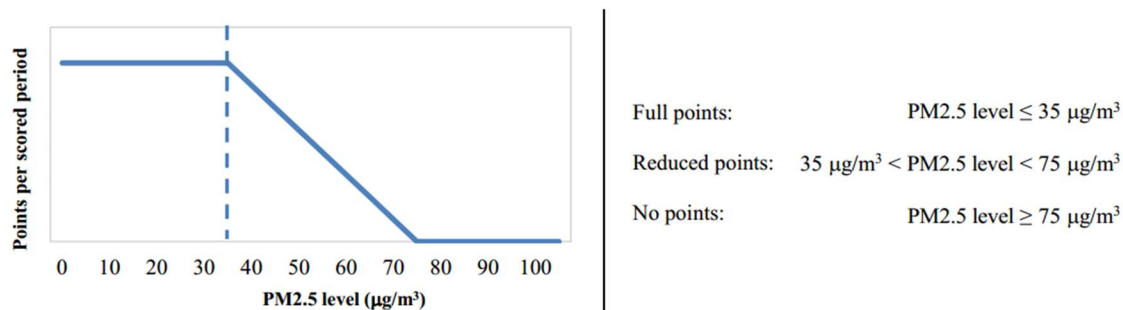


Figure 4: PM2.5 Score

### g. Appliances

- Refrigerator – 10 points

The internal temperature must be inside the range  $1 \div 4^\circ\text{C}$  to earn the maximum points, reduced points are earned from  $1^\circ\text{C}$  to  $0^\circ\text{C}$ , and from  $4^\circ\text{C}$  to  $5^\circ\text{C}$ .

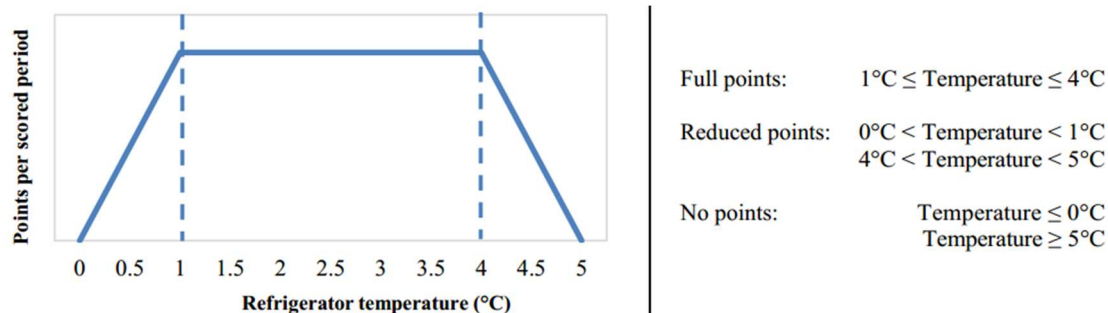


Figure 5: Refrigerator Score

- Freezer – 10 points

The internal temperature must be inside the range  $-30 \div -15^\circ\text{C}$  to earn the maximum points, reduced points are earned from  $-30^\circ\text{C}$  to  $-35^\circ\text{C}$ , and from  $-15^\circ\text{C}$  to  $-10^\circ\text{C}$ .

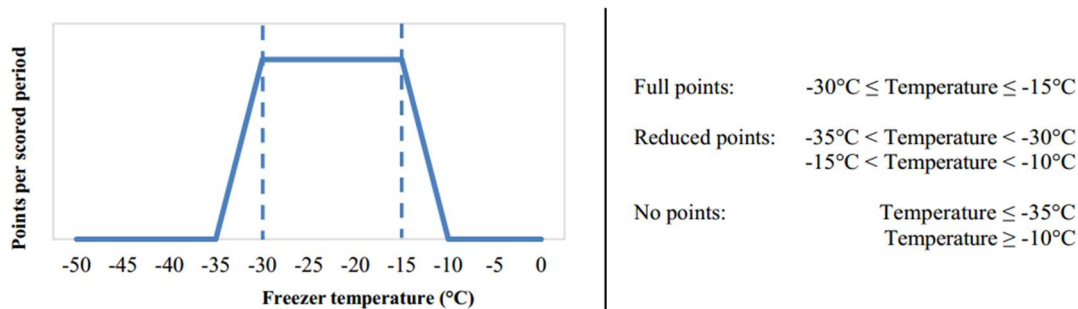


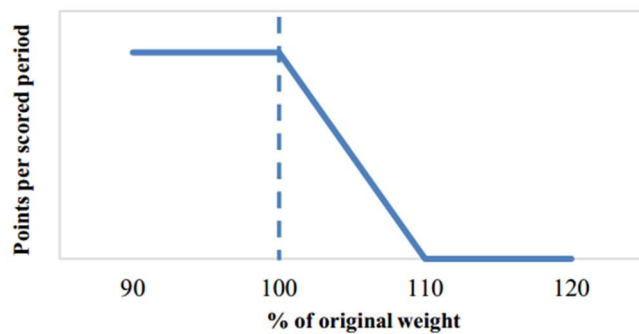
Figure 6: Freezer Score

- Clothes washer – 16 points

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

- Clothes drying – 32 points

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  $\leq 100$   
 Reduced points:     $100 < \text{% of original weight} < 110$   
 No points:                      % of original weight  $\geq 110$

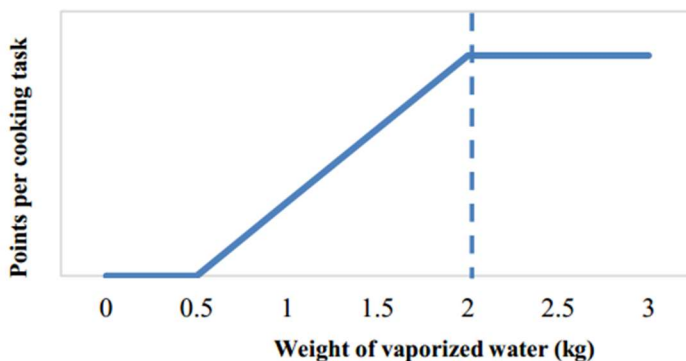
Figure 7: Drying Score

- Dishwasher – 17 points

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

- Cooking – 15 points

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  $\geq 2$  kg  
 Reduced points:     $0.5 \text{ kg} < \text{Weight} < 2 \text{ kg}$   
 No points:                      Weight  $\leq 0.5 \text{ kg}$

Figure 8: Cooking Score

#### h. Home Life

- Lighting – 25 points

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

- Hot water – 50 points

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.

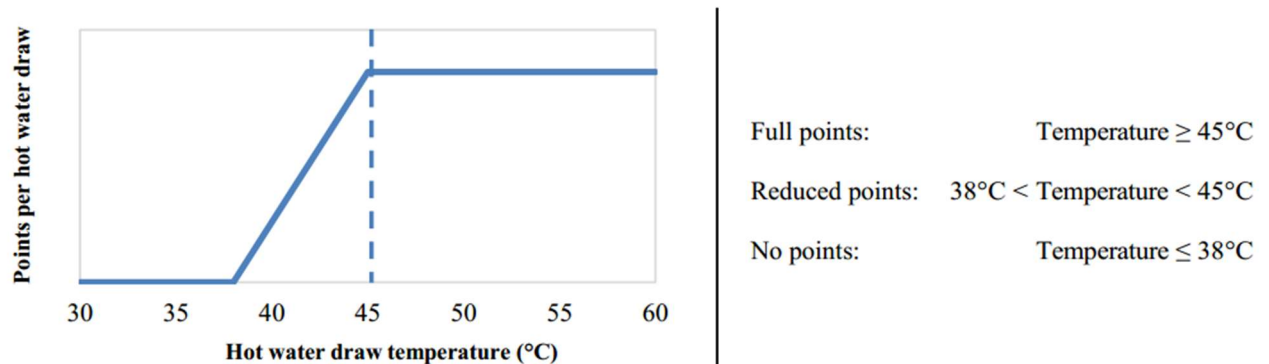


Figure 9: Hot Water Score

- Home electronics – 10 points

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

- Dinner party – 10 points

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

- Movie night – 5 points

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

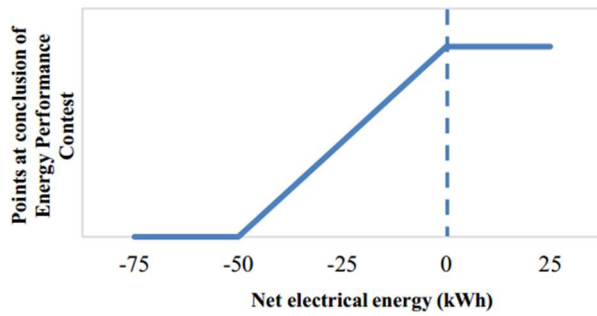
#### i. Commuting – 100 points

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.

## j. Energy

- Energy balance – 80 points

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.

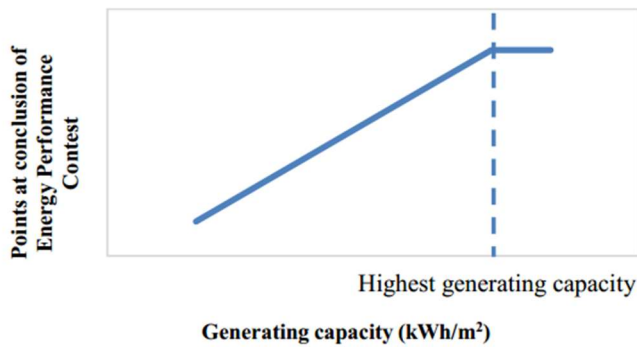


Full points: Net electrical energy  $\geq 0$  kWh  
 Reduced points:  $-50 \text{ kWh} < \text{Net electrical energy} < 0 \text{ kWh}$   
 No points: Net electrical energy  $\leq -50 \text{ kWh}$

Figure 10: Energy Balance Score

- Generating capacity – 20 points

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.



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

Figure 11: Generating Capacity Score



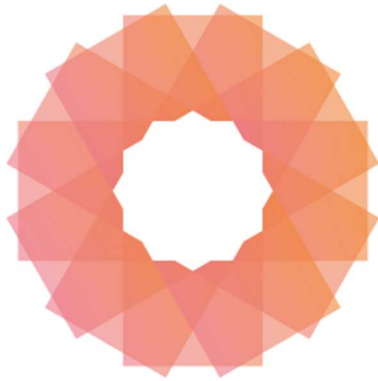
For this edition, the participating teams are:

- 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 (Winner of the competition)*
- 21) **Team UNNC Alpha\*\*:** *University of Nottingham Ningbo China*
- 22) **Team Israel\*\*:** *College of Management Academic Studies / Afeka College of Engineering*

\*Exhibition only

\*\*Withdraw

## 1.2 Team SCUT-POLITO



TEAM  
SCUTxPOLITO  
SDC2018

The team **SCUT-POLITO** is a joint team between the two universities from China and Italy: **South China University of Technology (SCUT)**, which participated on the first edition of the SDC (2013), reaching the second position, and **Politecnico di Torino (POLITO)**. 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 will be pre-built on Guangzhou, for testing, and then, shipped and assembled at the competition site, in Dezhou.



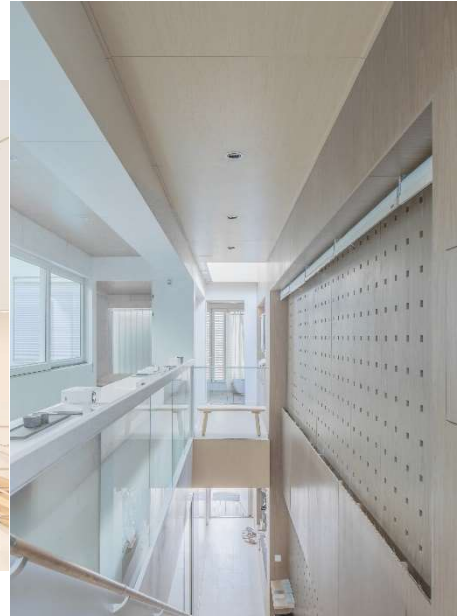
*Figure 12: Team SCUT-POLITO, patio*

The prototype is based on the concept of the **narrow house** and **bamboo house (Lingnan dwelling)**, with two floors, 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. Due 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.



*Figure 13: Living belt and Service belt*



*Figure 14: Staircase, integrated wall*

The house is divided into three main volumes:

**- Integrated wall**

The west wall which is the technical volume of the house, where all the pipes of HVAC system, water system, air distribution, and electrical wires are placed, for an easy maintenance and check, but also, to enclose them in a unique space, and reduce the pipes junctions.

**- Service belt**

the connecting space between different ambient, composed by all the services and systems: the three bathrooms, the mechanical room, the aquaponic system.

**- Served belt**

that is the main used space, containing the four conditioned zones, where the comfort is the main goal. The rooms are connected in pair by two corridors.

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, PM2.5, CO<sub>2</sub>, operating through the HVAC system. In this way, people don't necessarily need to be expert to use the most technological solution adopted, because an expert can easily understand how to operate or set a system, but in this way the system is user-friendly to everyone.

At the end of the competition, the team SCUT-POLITO won the competition with a final score of 959.73 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 rewarded with 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)



*Figure 15: Team SCUT-POLITO, opening ceremony*





*Figure 16: LONG PLAN, day and evening*



*Figure 17: Final award ceremony, first place*



*Figure 18: Leaders of the Chinese team*



*Figure 19: First Prize for both Engineering and Innovation*

	2016												2017												2018													
	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug							
START																																						
Final participating teams																																						
Italian students joining																																						
Design phase																																						
Workshops																																						
Thesis																																						
Building site opening ceremony																																						
Final submit																																						
Construction in Guangzhou																																						
Test																																						
Shipment to Dezhou																																						
Construction in Dezhou																																						
Contest - END																																						

Figure 20: SDC Chronology

## 2. Team SCUT-POLITO prototype: LONG PLAN

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.

### 2.1 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.

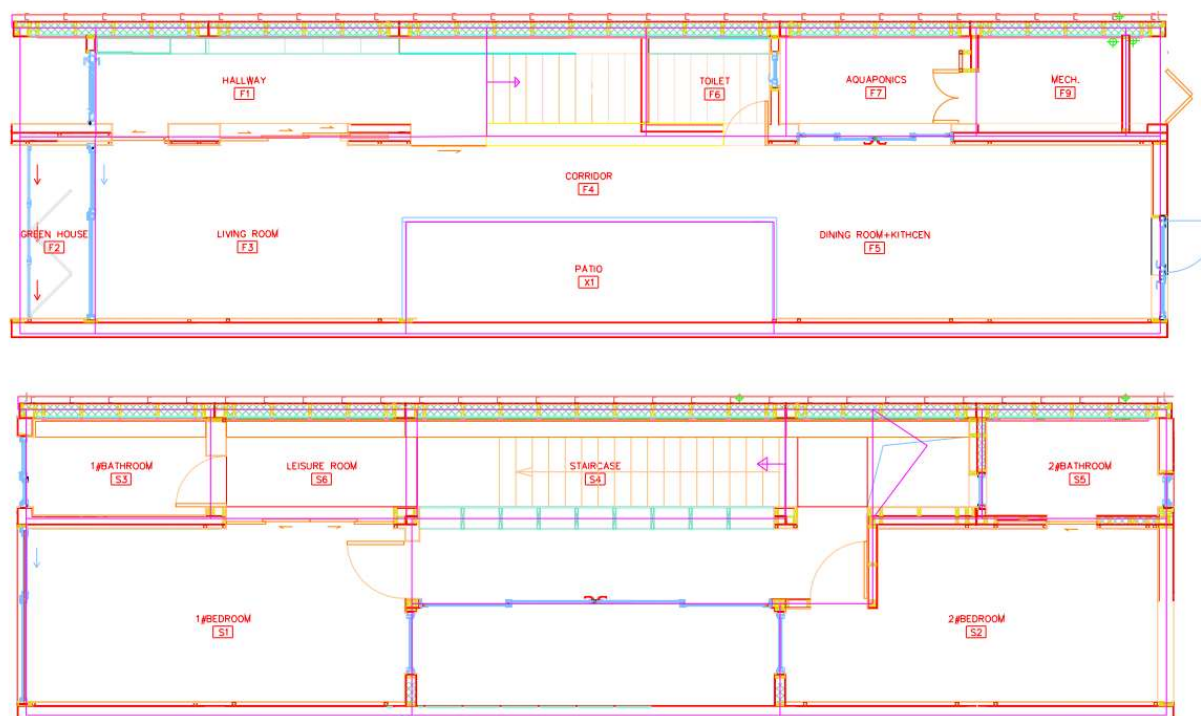
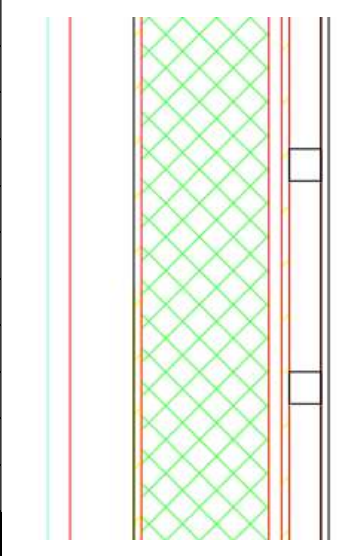


Figure 21: House CAD scheme

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 wall 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 from the roof surfaces with an air gap in the middle. 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 section*

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

*Table 2: Ground floor section*

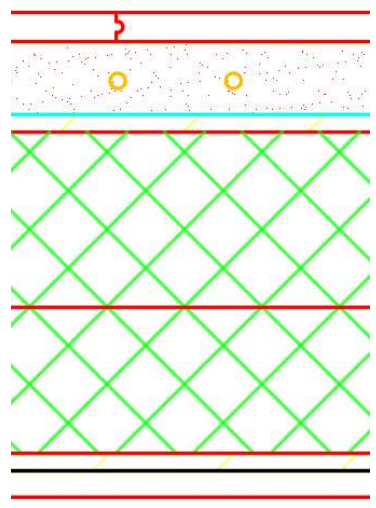
<b>Ground Floor</b>		
Layer	Thickness [mm]	
Laminate floor	15	
Capillary Heating System + Concrete	50	
Waterproof film	1	
OSB	12	
Phenolic insulation	220	
OSB	12	
Vapor barrier	1	
Concrete fibre board	12	



Table 3: Roof section

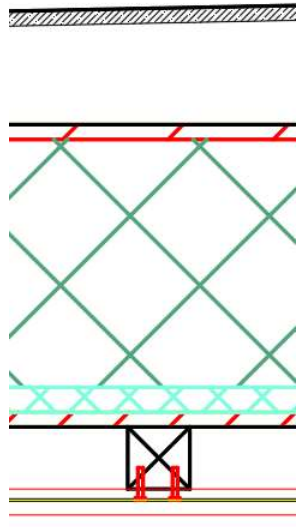
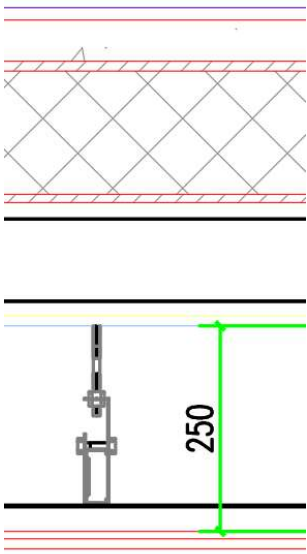
Roof Structure		
Layer	Thickness [mm]	
Self-adhesive waterproofing membrane	15	
OSB	50	
Waterproof film	1	
OSB	12	
Phenolic insulation	220	
OSB	12	
Vapor barrier	1	
Cavity	12	
Wooden finishing	5	

Table 4: Mid ceiling-floor section

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	

## 2.2 HVAC system

The HVAC system of the prototype was developed focussing 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 dimensioned through standards and technical booklet, and a second one, in which further modifications have been carried out after the first dynamic simulations performed on the model. The riser diagram and the technical scheme of the system are shown in the following table:

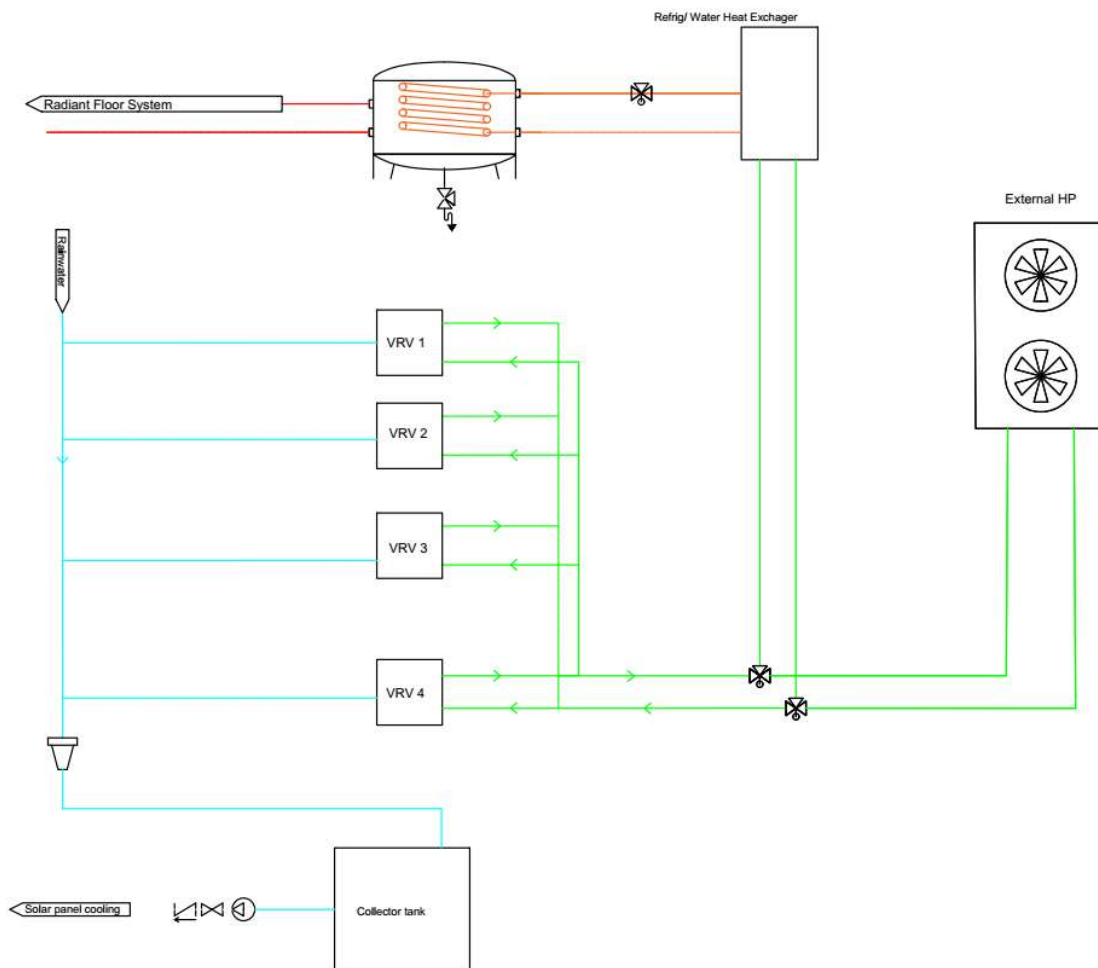


Figure 22: HVAC system

Regarding the ventilation the average request for ventilation has been evaluated in  $350 \text{ m}^3/\text{h}$  of fresh air, an averaged value of 1 ach in order to clean the amount of  $\text{CO}_2$  and  $\text{PM}_{2.5}$  that maybe will be accumulated during the contest's tasks period.

### Cooling system

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

Table 5: Daikin outdoor unit data

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: Daikin indoor VRV data

		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
Rated power	W	36/32	33/29	55/51	52/48
Cooling mode	m <sup>3</sup> /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 of 115% with a maximum deliverable cooling power of 14 kW on all the 4 conditioned zones.

### *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:

*Table 7: Capillary radiant floor module*

Module size	m	2.5 x 1
# of modules	-	18
Diameter	mm	4.3
Total surface	m <sup>2</sup>	45
Water temperature	°C	35
Water capacity	l/m <sup>2</sup>	0.29
Water tank	l	40
Heat dissipation	W/m <sup>2</sup>	~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.

### *Ventilation system*

The ventilation system has been designed in order to reduce the CO<sub>2</sub> and PM2.5 concentration in the inside air. The selected method was the use of an **Energy Recovery Ventilator** with a fresh air flow of 350 m<sup>3</sup>/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 tables:

Table 8: ERV

Panasonic FY-35ZDP1C					Exchange efficiency	
Power supply	Mode	Input Power[w]	Current[I]	Air flow[m <sup>3</sup> /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 9: Second floor bathrooms ventilator

Manufacturer	Panasonic
Model	FV-30BUS3C
Power [W]	1650
Airflow [m <sup>3</sup> /h]	170
Airflow [kg/h]	208.25
Heating Power [W]	1650
Ventilation Power [W]	26

Table 10: First floor bathroom ventilator

Manufacturer	Panasonic
Model	FV-24CU8C
Room	Bathroom 1
Power [W]	11
Airflow [m <sup>3</sup> /h]	140
Airflow [kg/h]	171.5

## 2.3 Domestic Hot Water

The **DHW** system is composed by a hot water storage of 300 l divided in two 150 l tanks. The first tank has the function of pre-heating water while the second one ensures to provide the right amount of water at the design temperature. The pre-heating is obtained through 6 m<sup>2</sup> 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:

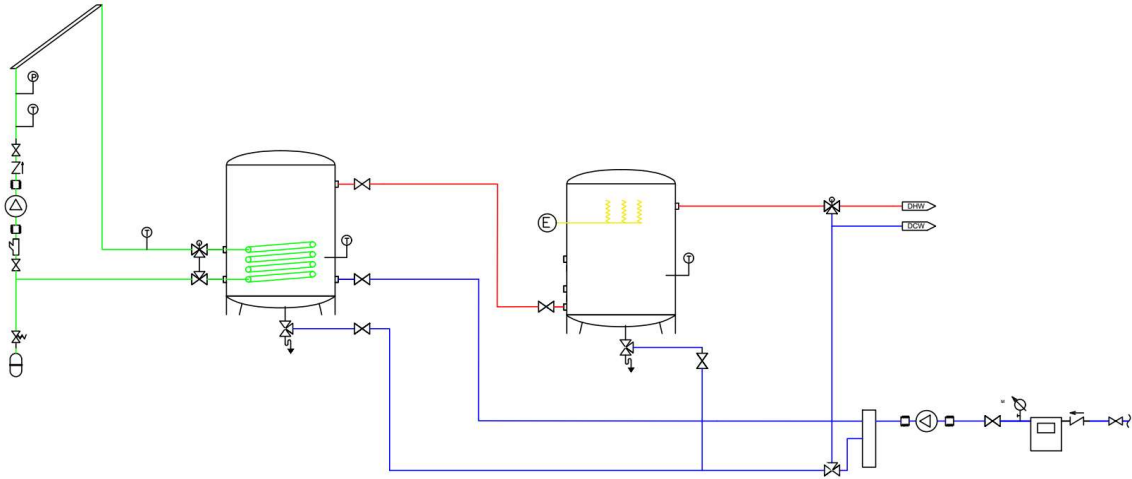


Figure 23: DHW loop scheme

## 2.4 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 kW<sub>p</sub>. 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 11: PV panels data, STC

		TwinMAX 60 cell	TwinMAX 72 cell
Max Power	W	285	330
Efficiency	%	17.3	16.9
Voltage <sub>mpp</sub>	V	32	37.7
Current <sub>mpp</sub>	A	8.91	8.76
Voltage <sub>oc</sub>	V	39	46.6
Current <sub>sc</sub>	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.

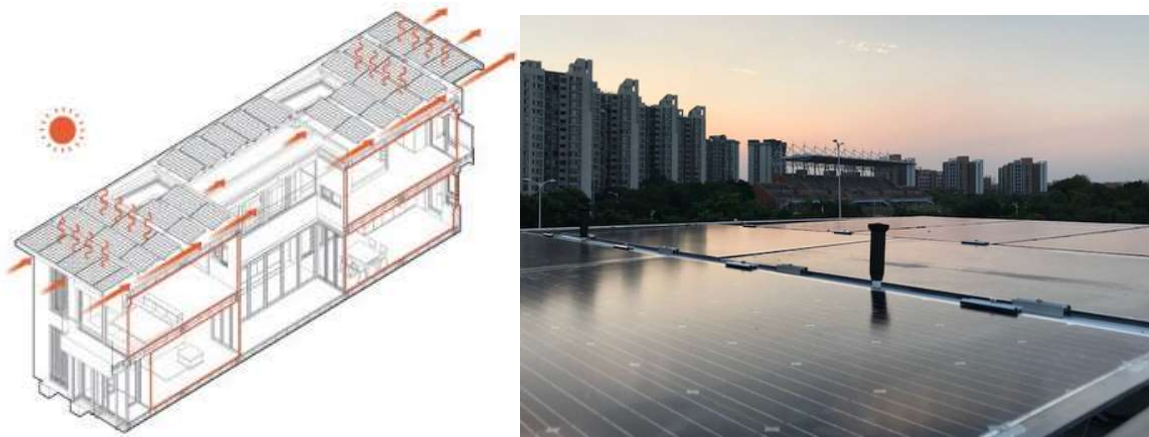


Figure 24: Cooling solutions for the PV panels

Considering all the intervention the PV panels data have been corrected accordingly:

Table 12: PV panels data and coefficients

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

The annual expected production is ~17000 kWh with an expected consumption with contest-type schedule for appliances of ~4500 kWh divided as:

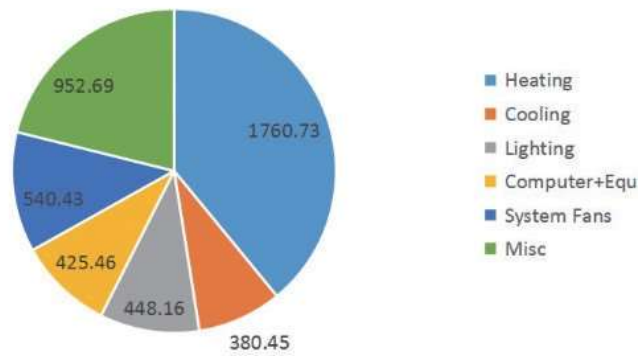


Figure 25: Energy consumption

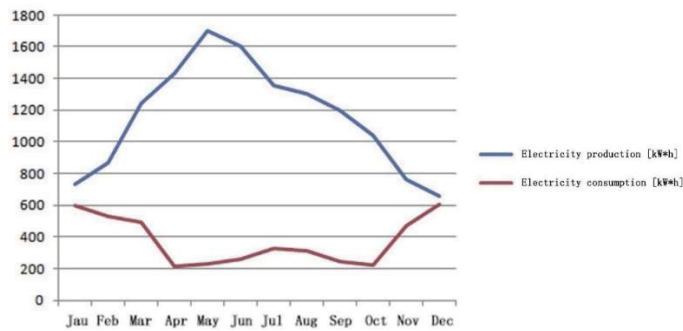


Figure 26: Energy production and consumption



### 3. Energy Model

Below an overview of the **energy model** is shown, including the main features of the system, the envelope, all the components, and the working conditions. The domestic hot water system is simulated to check the parameters and consumption, but it is not included inside the optimization process, due to some fixed working conditions, little variability on the possible score, and different simulation parameters, that could compromise the study on the overall project, like the higher time-step to avoid errors in the water tanks.

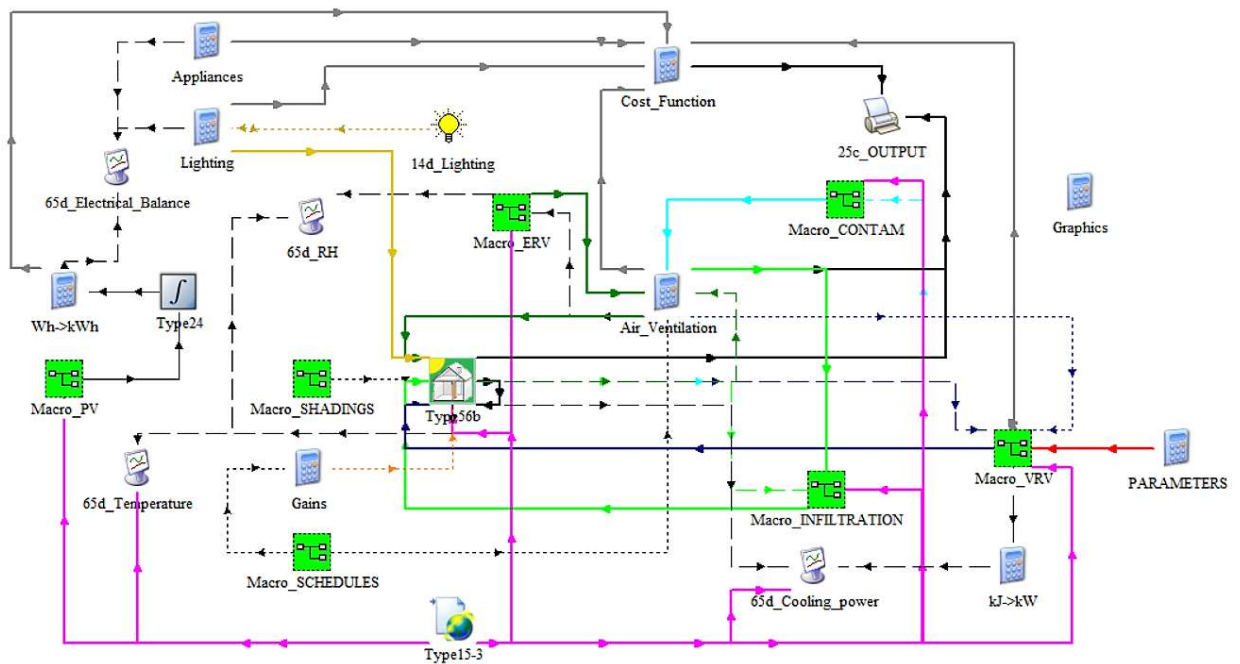


Figure 27: TRNSYS Energy Model

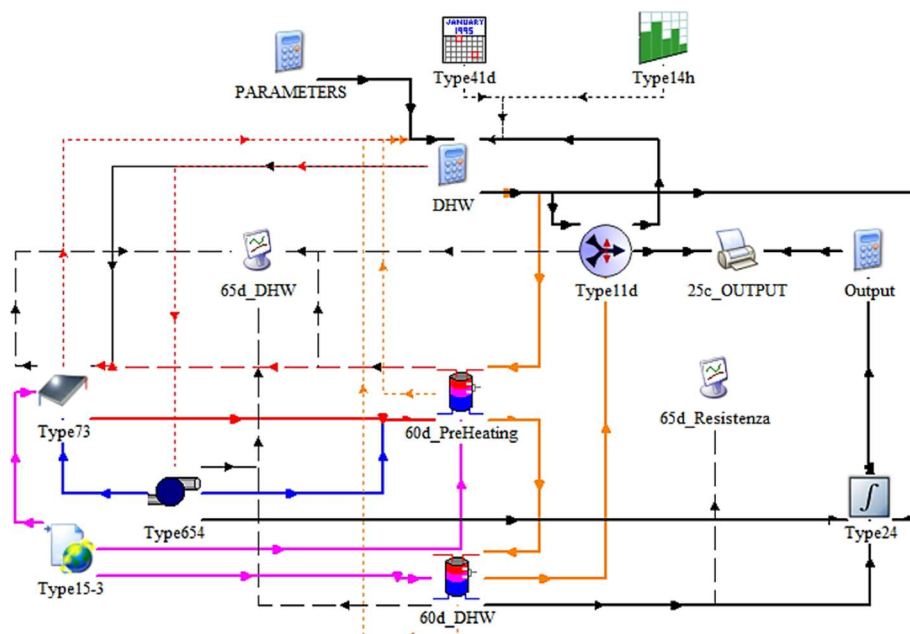


Figure 28: Domestic Hot Water System

## 3.1 Prototype Description and main characteristics

### 3.1.1 Requirements and simulation specifications

As it is shown in the rules, the parameters have a strict range to get the full score [1], with the possibility to have reduce points in some of the tasks, to achieve the overall optimum score. About the simulation, since the contest period goes from August 2, to August 16, there is no need to simulate the heating system, the capillary radiant floor; it is very important, instead, to clearly define all the operational schedules, for every single sub-contest, to analyse the real-time behaviour of the house, with respect to the contest. Every day, different tasks are required, assigning a portion of the total score. As said before, the points are earned in three different ways: **jury's review**, **task performing**, and **measured parameters**. The latter is the critical one, whom this work wants to focus on. The systems are put together in some macro, inside the program to manage them properly, having a clear path for the connections. They most important system to be simulated are: the **VRV System**, **ERV**, air flows and **infiltrations**, **PV system**, and **plumbing**.

The simulation runs within the contest period, starting from the hour 5112 and ending with the hour 5472 of the year. The **time step** selected is 1 minute, for the main simulation, and 10 minutes for the DHW ones, because it allows a more precise calculation, specifically to use the thermostat, coupled with the cooling system, otherwise the behaviour of the HVAC system will be totally different from the real one.

At the end of the process, two files will be created, deck file (.dck), and the building file (.bui), where the variables of the optimization will replace the fixed parameters respectively, for the system on the deck file, and for the envelope on the building one [11].

### 3.1.2 Envelope and Architecture

To model the envelope of the prototype, an inside tool of TRNSYS is used, **TRNBuild** [4]. This tool is useful for the construction of the multizone building. There are libraries to select the proper materials for walls and windows, and a lot of data, such as the area, or the exposition to the sunlight for the zones. The main conditioned zones are the living room, the kitchen and the two bedrooms, where all the HVAC system works together to maintain the comfort conditions.

The house is divided into sixteen **zones**:

- 1) Hallway
- 2) Green house
- 3) Living Room
- 4) Patio
- 5) Corridor 1
- 6) Kitchen
- 7) Bathroom 1
- 8) Aquaponics
- 9) Mechanical Room
- 10) Staircase
- 11) Bedroom 1
- 12) Bedroom 2
- 13) Bathroom 3
- 14) Leisure Room
- 15) Bathroom 3
- 16) Corridor 2

### 3.1.3 Systems and Engineering

- VRV

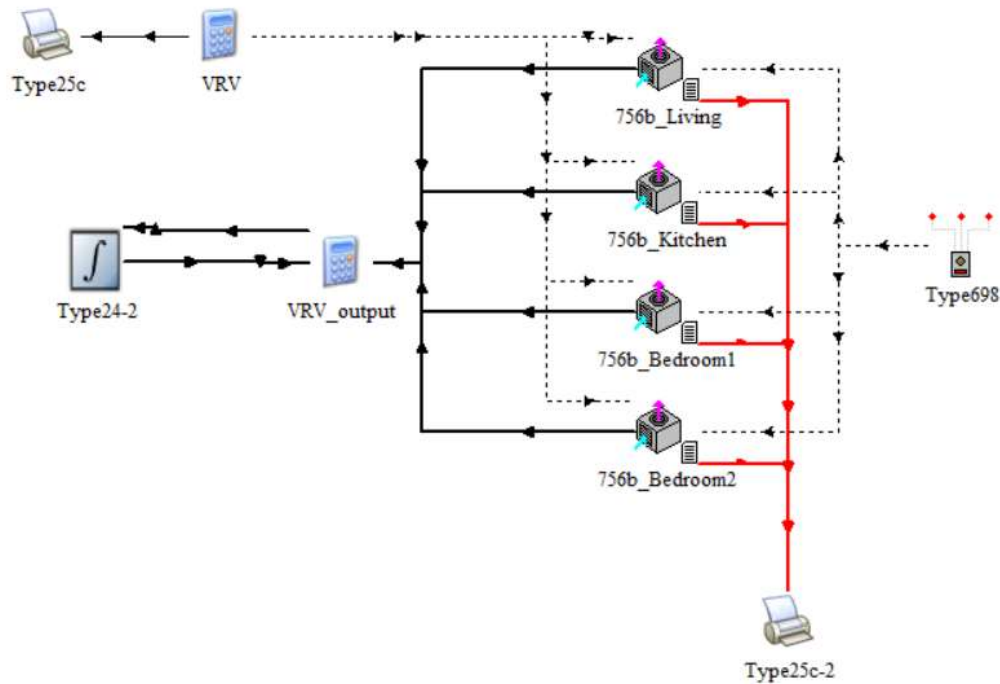


Figure 29: VRV Macro

The VRV system is not present in the version of TRNSYS used (TRNSYS 16) therefore, it was necessary to build it, assembling different type together, making them work with the same principle of the real component. Four different internal machines were used, using the data provided from the manufacturer of the VRV, each component worked following the real behaviour of the outdoor unit, varying the load accordingly to the internal setpoint, and the power available, thanks to a system of equations that regulate the partial load. The leading parameter set was the temperature, coupling the machines to a multizone thermostat.

- **ERV**

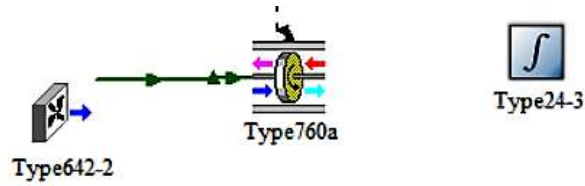


Figure 30: ERV Macro

The Energy Recovery Ventilator (ERV), has the goal of maintain the **ACH** needed, while treating the air, to reach a safe level of contaminants, indeed it has a filter for the **PM2.5**, that means the level of **CO<sub>2</sub>** and PM 2.5 for the measured tasks of the comfort zone are followed by this component. Moreover, it has a heat exchanger, to recover part of the sensible energy from the exhaust air, which has the positive effect of pre-cooling the fresh air and save energy.

- **CONTAM**

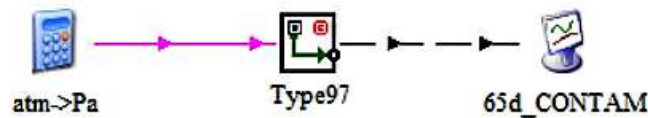
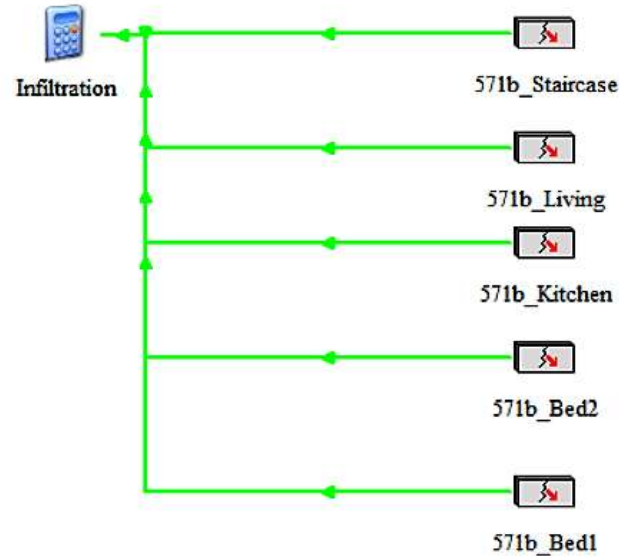


Figure 31: CONTAM Macro

TRNSYS 16 does not perform airflow mass balance, just the heat exchange between the nodes of the zones, therefore, there is the need of a calculation about the airflow between the rooms, for all the possible configurations, in which the house can be open, like during the exhibition time, or closed, like the testing time, or during the night. **CONTAM** is a program that can solve this problem, furthermore, it has a special channel for TRNSYS, because there is a special type on the simulation tool, that can use a sub-routine of CONTAM, using the model created, and calculating the air flowrate through the openings. For the purpose of the project, only the artificial ventilation, in the configuration with all the doors and windows closed, is calculate, because, due to the large flowrate in the configuration of natural ventilation, with all the doors open, TRNSYS is not able to handle such a big flow during a calculation, giving back an error. Therefore, for this particular configuration, an arbitrary airflow, high enough to reach the thermal balance between the zones, is set.

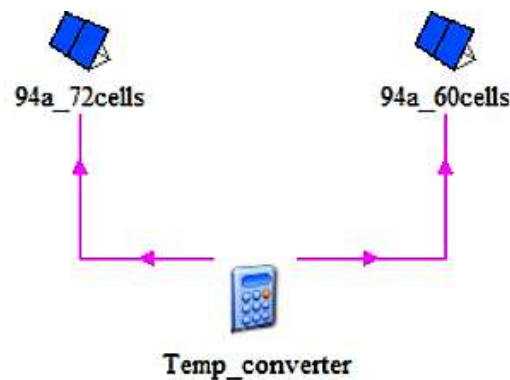
- **INFILTRATION**



*Figure 32: Infiltration Macro*

The infiltrations are taken into account just for the main conditioned rooms, because of different reasons: they have the bigger openings, the effect of the infiltration is more important in these rooms, since the sensors for the scoring system are located there.

- **PV**



*Figure 33: PV Macro*

The two rows of PV panels are modelled with two types, one for the model with 72 cells, and the other for the model with 60 cells. They are used to calculate the presumed energy production.

- **SHADINGS**



Figure 34: Shadings Macro

The shadings opening, and closing are independent, so it has been decided to insert them in three different categories for a further investigation in their usage, analysing the impact of the solar radiation to the envelope, added to all the contributes of the envelope.

- **SCHEDULES**

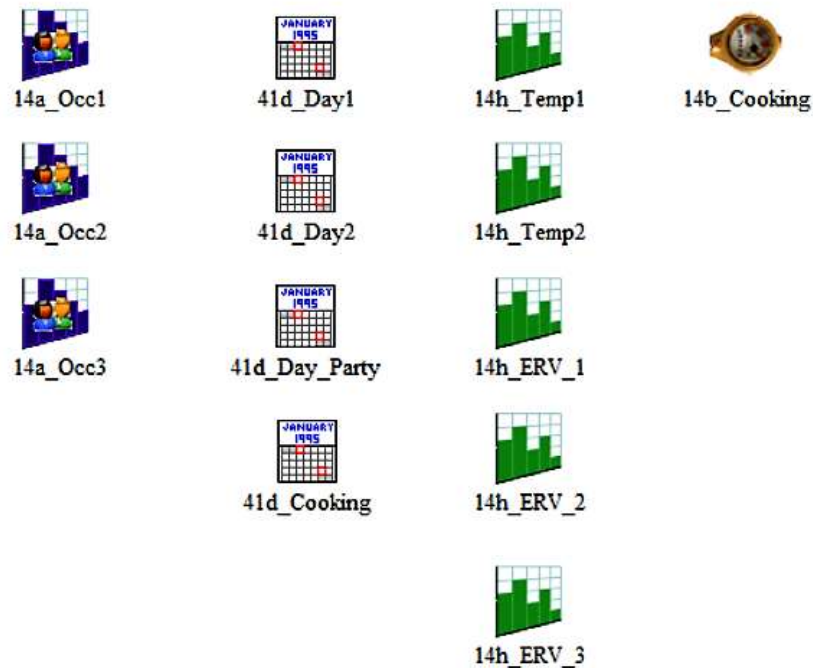


Figure 35: Schedules Macro

The most critical part of the project is related to the complex schedule's system. Every task, or measure, is taken with a specific pattern, in a specific day. Often, they are not regular, and do not have the same number of tasks, or score, every day [1]. It is mandatory to make a scheme about the operational schedules, specifying all the necessary details, therefore, different types are used to control the days, the time about the HVAC system, the occupancy, and the tasks. They are not used just about the time arrange during the simulation, but also to manage the change of the heat loads, or the internal gains.

- **APPLIANCES**

For all the appliances used during the contest, a list is made, to check the consumptions when operated, and so they are treated as a boundary condition to the simulation, because there is no degree of freedom both in time and specification about them.

- **LIGHTING**

The lighting contest is a regular contest, which occurs every day, at the same time. Its contribute is both an electrical and heat load. That is why it is separate from the calculation of the appliances, that are a simple electrical load.



## 3.2 TRNSYS Type for the energy model

The whole project is developed in TRNSYS software, linking the energy system and the envelope of the prototype house. To build the energy model, different Types, that are components written in TRNSYS to simulate the systems, are used, setting for each of them the correct input/output parameters. For each type, there are different boards, used to set the variable parameters [4][12]. The most important are:

- Parameter
- Input
- Output
- External Files

### 3.2.1 Type 756b – VRV



This type belongs to the **TESS** library of TRNSYS, it is used to model the internal unit of the VRV. It works like a single split; therefore, it is important to carefully control this component, making it works like the real one. Four types are used, since there are four internal units, and they are linked together, as a unique system. The key point is included in the external file, which contains all the performance curves, provided from the DAIKIN manufacturer. In this way the real-time consumption and power delivered are suitably calculated, in particular for the **partial load** working condition. To assess the correct load, through a system of equations, the cooling power needed, with respect to the environmental parameters, is calculated for each room, therefore, the flowrate is corrected varying the operation of the units. Below, the sheets about the parameters, and their values are presented.

1		Humidity mode	2	-
2		Logical unit for performance data	91	-
3		Number of condenser temperatures	16	-
4		Number of evaporator flows	2	-
5		Number of indoor wet bulbs	7	-
6		Number of indoor dry bulb temps.	1	-
7		Blower power draw	258.119982	kJ/hr

Figure 36: Type 756 - Parameter









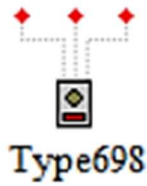
1		Ambient temperature	30	C
2		Indoor temperature	20	C
3		Not used (w)	0.008	-
4		Indoor percent RH	50	% (base 100)
5		Evaporator flow rate	992	kg/hr
6		Indoor air pressure	1	atm
7		Air-side pressure drop	0	atm
8		Control signal	1	-

Figure 37: Type 756 - Input

<b>Type 756b VRV Living</b>	Number of Condenser Temperature	Number of Evaporator Flows	Number of Indor Wet Bulbs	Number of Indor Dry Bulbs Temperature	Blower Power Draw
	-	-	-	-	W
	16	2	7	1	72
	Ambient Temperature	Indoor Temperature	Not Used	Indoor Percent RH	Evaporator Flow Rate
	°C	°C	-	%	kg/h
	T_amb	T_living		RH_Living	992
<b>Type 756b VRV Kitchen</b>	Number of Condenser Temperature	Number of Evaporator Flows	Number of Indor Wet Bulbs	Number of Indor Dry Bulbs Temperature	Blower Power Draw
	-	-	-	-	W
	16	2	7	1	61.4
	Ambient Temperature	Indoor Temperature	Not Used	Indoor Percent RH	Evaporator Flow Rate
	°C	°C	-	%	kg/h
	T_amb	T_kitchen		RH_Kitchen	720
<b>Type 756b VRV Bedroom 1</b>	Number of Condenser Temperature	Number of Evaporator Flows	Number of Indor Wet Bulbs	Number of Indor Dry Bulbs Temperature	Blower Power Draw
	-	-	-	-	W
	16	2	7	1	46
	Ambient Temperature	Indoor Temperature	Not Used	Indoor Percent RH	Evaporator Flow Rate
	°C	°C	-	%	kg/h
	T_amb	T_bed1		RH_bed1	610
<b>Type 756b VRV Bedroom 2</b>	Number of Condenser Temperature	Number of Evaporator Flows	Number of Indor Wet Bulbs	Number of Indor Dry Bulbs Temperature	Blower Power Draw
	-	-	-	-	W
	16	2	7	1	41.3
	Ambient Temperature	Indoor Temperature	Not Used	Indoor Percent RH	Evaporator Flow Rate
	°C	°C	-	%	kg/h
	T_amb	T_bed2		T_bed2	529

Table 13: VRV Parameters and Inputs

### 3.2.2 Type 698 – Thermostat



This type is used to control the room temperatures of the conditioned zones, and through them, to control the HVAC system to maintain the required levels. To work properly, the simulation time step should be little, otherwise the operation of the thermostat has no meaning. This confirms the choice to use 1 minute as time step, both for accuracy of the results and accurate working mode. This component presents the control of one possible parameter of optimization, the temperature.

1		Number of zones to monitor	4	-
2		# of oscillations permitted	2	-
3		1st stage heating in 2nd stage?	1	-
4		2nd stage heating in 3rd stage?	1	-
5		1st stage heating in 3rd stage?	1	-
6		1st stage cooling in 2nd stage?	1	-
7		Temperature dead band	2	deltaC

Figure 38: Type 698 - Parameter

1		1st stage heating setpoint temperature	20.0	C
2		2nd stage heating setpoint temperature	18.0	C
3		3rd stage heating setpoint temperature	16.0	C
4		1st stage cooling setpoint temperature	T_setpoint_cooling	string
5		2nd stage cooling setpoint temperature	26.0	C
6		Temperature of zone-1	20.0	C
7		Temperature of zone-2	20.0	C
8		Temperature of zone-3	20.0	C
9		Temperature of zone-4	20.0	C

Figure 39: Type 698 - Input

### 3.2.3 Type 24 – Integrator



The type 24 has been used many times, to calculate the various consumptions of the system. It is set to calculate the energy consumed during all the contest period.

### 3.2.4 Type 25 – Printer & Type 65d – plot



Type25



Type65d

These types have been used to obtain the output of the simulation and checking the behaviour through some specific plot. The printer's outputs are used for the post-processing of the simulation, to make the objective function to be minimized. They are connected to different outputs, that can be changed according to the section to analyse. The types 65d, online plotter, can be shut down during the simulation, to make the process faster, quite a useful feature to speed up the optimization.

### 3.2.5 Type 571b – Infiltration



Type571b

An important part regards the infiltrations, they are calculated just for the main zones, such as the four conditioned zones, and the staircase, so the effect is immediate, in the controlled rooms. The house is built with very high-quality materials, but the manufacture is a little bit poor, therefore, even if the prototype is a NZEB, it is better to consider the envelope with a standard air tightness. The type 571b, uses an empirical method from the ASHRAE Handbook of Fundamentals [12], based on the equation:

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

Where:

$K_1$  = Constant coefficient (ACH)

$K_2$  = Temperature dependent infiltration coefficient (ACH/°C)

$K_3$  = Windspeed dependent infiltration coefficient (ACH.s/m)

$T_{zone}$  = Zone temperature (°C)

$T_{ambient}$  = Ambient temperature (°C)

WinSpeed = Wind velocity (m/s)

Tight Construction –  $K_1 = 0.1$ ,  $K_2 = 0.011$ ,  $K_3 = 0.034$

Medium Construction –  $K_1 = 0.1$ ,  $K_2 = 0.017$ ,  $K_3 = 0.049$

Loose Construction –  $K_1 = 0.1$ ,  $K_2 = 0.023$ ,  $K_3 = 0.070$

The medium construction is adopted.

The mass flow rate infiltrated is calculated as:

$$\dot{m} = ACH * \rho_{air} * Vol$$

And then, the associated energy is:

$$Q_{inf} = \dot{m} * C_p * (T_{ambient} - T_{zone})$$

### 3.2.6 Type 41d – Day

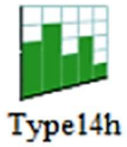


The type 41d is the first type needed to build the schedules architecture for the contest. Its main function is to give an output for some days of the year. Using two of them, lead to split the contest days into two categories: a day with full-tasks, and a simpler one. Here an example of how to manage the non-standard day of the year. After the filter is applied, and the day is selected, the time is organized through daily schedules.

1		Number of profiles for each day	1	-
2		Input set for day 1	1	-
3		Input set for day 2	2	-
4		Input set for day 3	3	-
5		Input set for day 4	4	-
6		Input set for day 5	5	-
7		Input set for day 6	6	-
8		Input set for day 7	7	-
9		Number of nonstandard days	4	-
10		Input set for nonstandard days	8	-
11		Day of year for nonstandard day-1	216	-
12		Day of year for nonstandard day-2	217	-
13		Day of year for nonstandard day-3	223	-
14		Day of year for nonstandard day-4	224	-

Figure 40: Type 41d - Input

### 3.2.7 Type 14h – Schedules and shadings



This type is the generic hourly schedule generator, useful for many possibilities. It has been used to arrange the time operation about the comfort zone, about the temperature and relative humidity check for the VRV, and for the pollutant levels, CO<sub>2</sub> and PM<sub>2.5</sub>, for the ERV time; it has been used also in the DHW simulation. Besides the regular schedules about the HVAC, also some sporadic event is calculated, for example, there are the dinner parties and movie night to be considered. Time and the corresponding values assumed by the function can be inserted, but there is also a function editor, to have a graphical management of the function. The function is considered like a cycle, therefore is repeated during all the simulation.

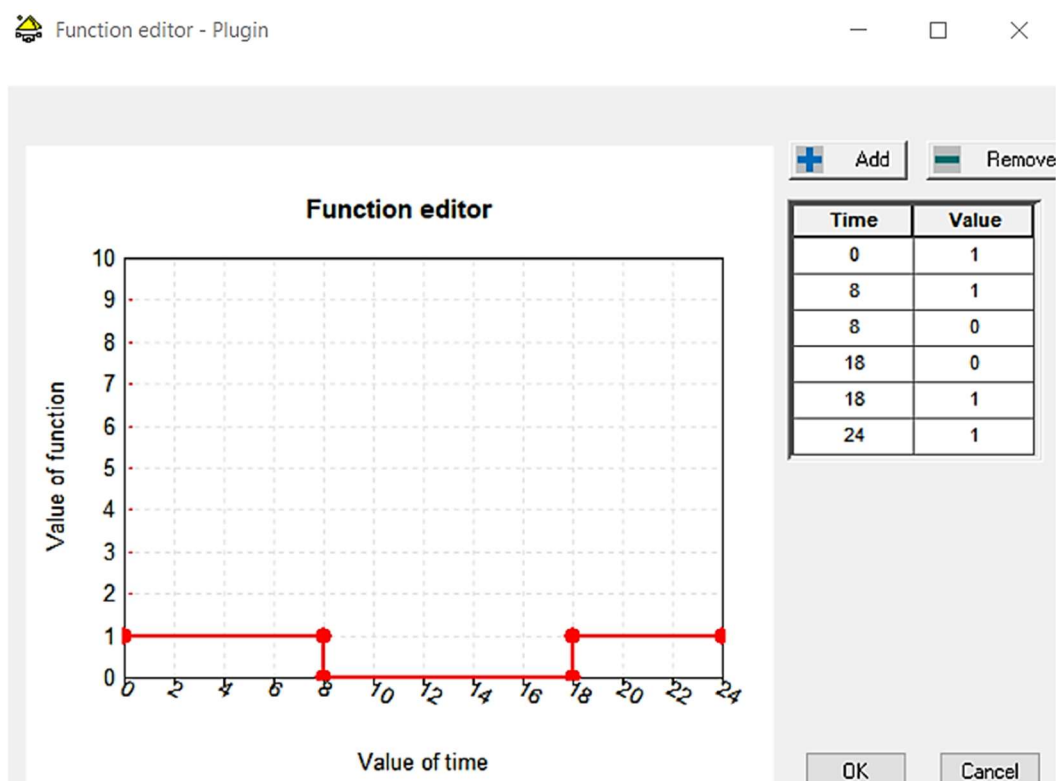


Figure 41: Type 14h - Function editor













1		Initial value of time	0	hr
2		Initial value of function	1	any
3		Time at point-1	8	hr
4		Value at point -1	1	any
5		Time at point-2	8	hr
6		Value at point -2	0	any
7		Time at point-3	18	hr
8		Value at point -3	0	any
9		Time at point-4	18	hr
10		Value at point -4	1	any
11		Time at point-5	24	hr
12		Value at point -5	1	any

Figure 42: Type 14h - Parameter

### 3.2.8 Type 14a – Occupancy



Type14a

As the generic type 14h, the type 14a is a schedule generator, in this case, it is used for the occupancy, giving as output the number of people. They are used to manage the occupancy during the exhibition time, the impound period, and the task performing time.

### 3.2.9 Type 14b – Cooking



Type14b

For the cooking sub-contest, the type with the output unit in kg/h is used to calculate the contribute about the water evaporation as an extra humidity gain.

### 3.2.10 Type 14d – Lighting



Type14d

As for the Type 14b, this one has the only difference in terms of units, the output is kJ/h. The function editing is the same of all the other type 14.



### 3.2.11 Type 94a – PV



Two types are used for the PV panels, since there are two kinds of module: one with 72 cells, and the other with 60 cells. They have been arranged in this way to maximize the area covered in the roof, dealing with the limited space.

1		Module short-circuit current at reference conditions	9.25	amperes
2		Module open-circuit voltage at reference conditions	46.6	V
3		Reference temperature	298.15	K
4		Reference insolation	1000	W/m <sup>2</sup>
5		Module voltage at max power point and reference conditions	37.7	V
6		Module current at max power point and reference conditions	8.76	amperes
7		Temperature coefficient of Isc at (ref. cond)	0.04	any
8		Temperature coefficient of Voc (ref. cond.)	-0.3	any
9		Number of cells wired in series	72	-
10		Number of modules in series	18	-
11		Number of modules in parallel	1	-
12		Module temperature at NOCT	319.15	K
13		Ambient temperature at NOCT	293.15	K
14		Insolation at NOCT	800	W/m <sup>2</sup>
15		Module area	1.95	m <sup>2</sup>
16		tau-alpha product for normal incidence	0.95	-
17		Semiconductor bandgap	1.12	any
18		Slope of IV curve at Isc	0	any
19		Module series resistance	-1	any

Figure 43: Type 94a - Parameter

1		Total incident radiation	0	kJ/hr.m <sup>2</sup>
2		Ambient temperature	298	K
3		Load voltage	0	V
4		Flag for convergence promotion	0	-
5		Array slope	PV_slope	string
6		Beam radiation	0	kJ/hr.m <sup>2</sup>
7		Diffuse radiation	0	kJ/hr.m <sup>2</sup>
8		Incidence angle of beam radiation	0	degrees

Figure 44: Type 94a - Input



Table 14: PV panels Parameters and Inputs

Type 94a PV Panel (60 cells)	Module Short- circuit Current at Reference Conditions	Module Short- circuit Voltage at Reference Conditions	Module Voltage at Max Power Point and Reference Conditions	Module Current at Max Power Point and Reference Conditions	Number of Cells Wired in Series	Number of Modules in Series	Module Area
	A	V	V	A	-	-	m <sup>2</sup>
	9.3	39	32	8.91	60	16	1.64
Type 94a PV Panel (72 cells)	Module Short- circuit Current at Reference Conditions	Module Short- circuit Voltage at Reference Conditions	Module Voltage at Max Power Point and Reference Conditions	Module Current at Max Power Point and Reference Conditions	Number of Cells Wired in Series	Number of Modules in Series	Module Area
	A	V	V	A	-	-	m <sup>2</sup>
	9.25	46.6	37.7	8.76	72	18	1.95

### 3.2.12 Type 97 – CONTAM



TRNSYS has a special feature to read some external file from external programs, and CONTAM is one of them. The sketch of the house is done, inserting windows and doors, to calculate the airflow between the zones, because TRNSYS does not perform mass balance, just energy balances. Therefore, to simulate the real thermal behaviour is mandatory to take care about the air path. As previously anticipated, the type 97 uses a sub-routine from CONTAM, working on an external file, which is the model created on CONTAM. The software can perform the analysis about the contaminants' diffusion, but this cannot be implemented on TRNSYS, therefore, the level of CO<sub>2</sub> and PM<sub>2.5</sub> are not calculated by CONTAM. Below there is the model of the house done in CONTAM, and then applied in TRNSYS.

□Ambt

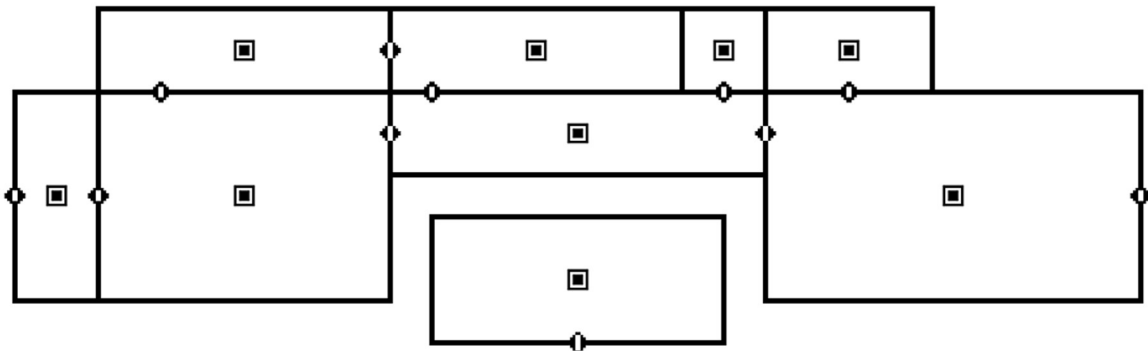


Figure 45: CONTAM first floor

□Ambt

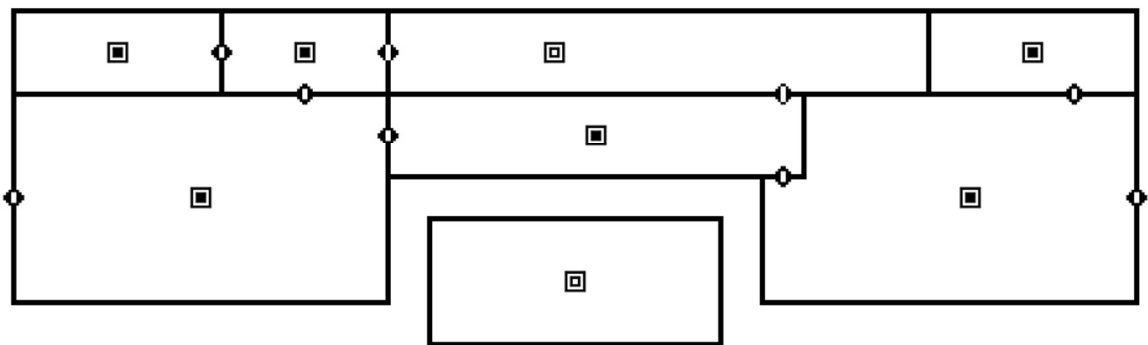


Figure 46: CONTAM second floor

### 3.2.13 Type 760a – ERV



The type 760a from the TESS library, simulates the heat exchange between the two fluxes of air, the exhaust air from the house, and the fresh air taken from the ambient. The flux should be controlled from another type to follow the time schedule. The consumption is taken only from one component to avoid errors. The data of the air are given in input, respectively from the outdoor conditions for the fresh air, and from the mixing of the two flows extracted from the air system.

1		Humidity mode	2	-
2		Rated power	608.399954	kJ/hr
3		Control mode	0	-

Figure 47: Type 760a - Parameter

1		Exhaust air temperature	20	C
2		Not used	0.005	-
3		Exhaust air %RH	60	-
4		Exhaust air flow rate	0	kg/hr
5		Exhaust air pressure	1	atm
6		Exhaust air pressure drop	0	atm
7		Fresh air temperature	20	C
8		Not used	0.005	-
9		Fresh air %RH	50	-
10		Fresh air flow rate	428.75	kg/hr
11		Fresh air pressure	1	atm
12		Fresh air pressure drop	0	atm
13		Sensible effectiveness	0.61	Fraction
14		On/Off Control Signal	1	-
15		Control temperature	20	C

Figure 48: Type 760a - Input

### 3.2.14 Type 642 – ERV flow



Type642

The type 642, is a fan to set the airflow of the ERV, directed to the heat exchanger of the ERV when requested. Its power has been set to zero, to avoid wrong consumptions.

1		Humidity mode	2	-
2		Rated flow rate	428.75	kg/hr
3		Rated power	0	kJ/hr
4		Motor efficiency	1	-
5		Motor heat loss fraction	0	-

Figure 49: Type 642 - Parameter

1		Inlet air temperature	20	C
2		Not used (w)	0	-
3		Inlet air %RH	50	% (base 100)
4		Air flow rate	2000	kg/hr
5		Inlet air pressure	1	atm
6		Control signal	1	-
7		Air-side pressure increase	0	atm

Figure 50: Type 642 - Input

### 3.2.15 Type 15 – Weather file



Type15-3

The weather file is extremely useful, the one selected was the EnergyPlus format. Since no official weather file about Dezhou exists, as suggested by the committee of the Solar Decathlon China, the one of a nearby city was used, from Raoyang. The weather file is linked to a lot of component, it has information about the outdoor parameters, useful for temperature, humidity, windspeed, and solar radiation with all the components, to check the energy production and the heat gains.

1		File Type	3	-
2		Logical unit	89	-
3		Tilted Surface Radiation Mode	3	-
4		Ground reflectance - no snow	0.2	-
5		Ground reflectance - snow cover	0.7	-
6		Number of surfaces	4	-
7		Tracking mode-1	1	-
8		Slope of surface-1	90	degrees
9		Azimuth of surface-1	180	degrees










10		Tracking mode-2	1	-
11		Slope of surface-2	90	degrees
12		Azimuth of surface-2	0	degrees
13		Tracking mode-3	1	-
14		Slope of surface-3	90	degrees
15		Azimuth of surface-3	-90	degrees
16		Tracking mode-4	1	-
17		Slope of surface-4	90	degrees
18		Azimuth of surface-4	90	degrees

Figure 51: Type 15-3 - Parameter

### 3.2.16 Equation



Equa

To create a consistent link between all the types, to pass the correct information, with the right units, to every system, and to proceed calculating the suitable quantities, there is a powerful tool in TRNSYS: the equation tool. Many of them have been widely used; some of them are dedicated to the unit's converter between input and output of different types, others, the biggest of the simulation, are used for the main calculation of the HVAC: for the air coupling between the zones, and for the VRV partial load calculation and power delivering. The schedule's operational signals are used inside these equations. Last, but not least, the equation tool is used to prepare the output needed from the simulation, to be sent to the post-processing.

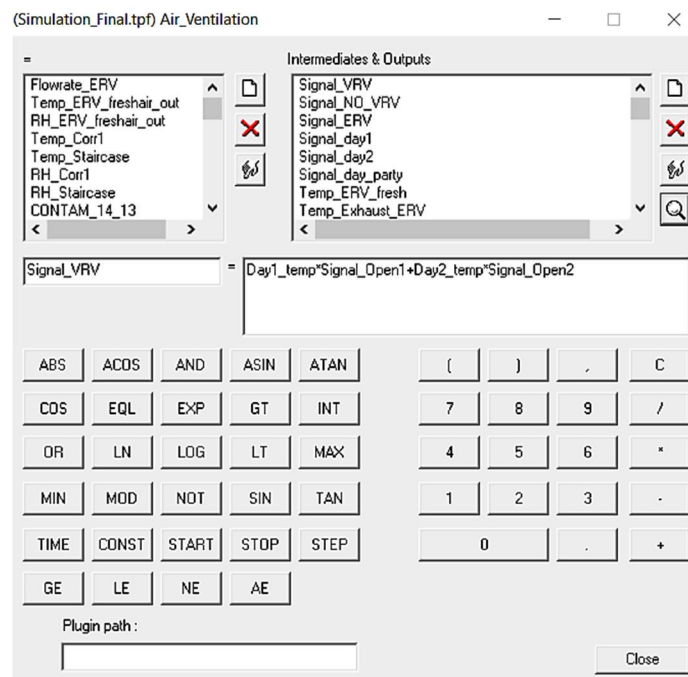


Figure 52: Equation tool

### 3.2.17 Type 60d – Water Tank



The two tanks of the domestic hot water loop are modelled with the type 60, the vertical cylinder, with one input – one output. For the first one, the pre-heating tank, a heat exchanger is present to be integrated with the solar thermal, while the other has the electrical heater, with 1.5 kW power. The liquid inside the heat exchanger of the solar loop, is a mixture of water and glycol, in a percentage of 30%.

1	User-specified inlet positions	2	-
2	Tank volume	150	l
3	Tank height	1.186	m
4	Tank perimeter	-1	m
5	Height of flow inlet 1	0.112	m
6	Height of flow outlet 1	1.019	m
7	Not used (inlet 2)	-1	-
8	Not used (outlet 2)	-1	-
9	Fluid specific heat	4.187	kJ/kg.K
10	Fluid density	983	kg/m³
11	Tank loss coefficient	3.0	kJ/hr.m².K
12	Fluid thermal conductivity	1.40	kJ/hr.m.K
13	Destratification conductivity	0.0	kJ/hr.m.K
14	Boiling temperature	100.0	C
15	Auxiliary heater mode	2	-
16	Height of 1st aux. heater	0.698	m
17	Height of 1st thermostat	0.85	m
18	Set point temperature for element 1	55.0	C
19	Deadband for heating element 1	5.0	deltaC
20	Maximum heating rate of element 1	0	kJ/hr
21	Height of heating element 2	1	m
22	Height of thermostat 2	1	m
23	Set point temperature for element 2	55.0	C
24	Deadband for heating element 2	5.0	deltaC
25	Maximum heating rate of element 2	0	kJ/hr
26	Overall loss coefficient for gas flue	0.0	kJ/hr.K
27	Flue temperature	20.0	C
28	Fraction of critical timestep	6	-
29	Gas heater?	0	-
30	Number of internal heat exchangers	1	-
31	Equal sized nodes	0	-
32	Uniform tank losses	0	-
33	HX Fluid Indicator	2	-
34	Fraction of glycol	0.3	-
35	Heat exchanger inside diameter	0.01	m
36	Heat exchanger outside diameter	0.015	m
37	Heat exchanger fin diameter	0.015	m
38	Total surface area of heat exchanger	0.95	m²
39	Fins per meter for heat exchanger	0	-
40	Heat exchanger length	12	m
41	Heat exchanger wall conductivity	1.40	kJ/hr.m.K
42	Heat exchanger material conductivity	1.40	kJ/hr.m.K
43	Height of heat exchanger inlet	0.702	m
44	Height of heat exchanger outlet	0.212	m

Figure 53: Parameter - Type 60d, tank 1

1	User-specified inlet positions	2	-
2	Tank volume	150	l
3	Tank height	1.186	m
4	Tank perimeter	-1	m
5	Height of flow inlet 1	0.112	m
6	Height of flow outlet 1	1.019	m
7	Not used (inlet 2)	-1	-
8	Not used (outlet 2)	-1	-
9	Fluid specific heat	4.187	kJ/kg.K
10	Fluid density	983	kg/m³
11	Tank loss coefficient	3.0	kJ/hr.m².K
12	Fluid thermal conductivity	1.40	kJ/hr.m.K
13	Destratification conductivity	0.0	kJ/hr.m.K
14	Boiling temperature	100.0	C
15	Auxiliary heater mode	2	-
16	Height of 1st aux. heater	0.562	m
17	Height of 1st thermostat	0.882	m
18	Set point temperature for element 1	Tank2_temp	string
19	Deadband for heating element 1	Deadband_resistance	string
20	Maximum heating rate of element 1	1.5	kW
21	Height of heating element 2	1	m
22	Height of thermostat 2	1	m
23	Set point temperature for element 2	55.0	C
24	Deadband for heating element 2	5.0	deltaC
25	Maximum heating rate of element 2	0	kJ/hr
26	Overall loss coefficient for gas flue	0.0	kJ/hr.K
27	Flue temperature	20.0	C
28	Fraction of critical timestep	6	-
29	Gas heater?	0	-
30	Number of internal heat exchangers	0	-
31	Equal sized nodes	0	-
32	Uniform tank losses	0	-

Figure 54: Parameter - Type 60d, tank 2
















1		Flow rate at inlet 1	0.0	kg/hr
2		Flow rate at outlet 1	-2	kg/hr
3		Not used (flow inlet 2)	-1	-
4		Not used (flow outlet 2)	-1	-
5		Temperature at inlet 1	20.0	C
6		Not used (temp inlet 2)	20.0	C
7		Environment temperature	22.0	C
8		Control signal for element 1	1.0	-
9		Control signal for element 2	1.0	-
10		Flow rate for heat exchanger	0.0	kg/hr
11		Inlet temperature for heat exchanger	20.0	C
12		Nusselt constant for heat exchanger	0.50	-
13		Nusselt exponent for heat exchanger	0.25	-

Figure 55: Input - Type 60d

### 3.2.18 Type 73 – Solar Thermal Panel



Type73

There are four flat plate solar panels, of 6 m<sup>2</sup> area, to preheat the hot water. They are connected to the first tank. With respect the PV panels, which have a tilt angle of 2°, they have a slope of 5°.










1		Number in series	1	-
2		Collector area	6	m <sup>2</sup>
3		Fluid specific heat	3.388	kJ/kg.K
4		Collector fin efficiency factor	0.7	-
5		Bottom, edge loss coefficient	3	kJ/hr.m <sup>2</sup> .K
6		Absorber plate emittance	6	% (base 100)
7		Absorptance of absorber plate	0.92	-
8		Number of covers	1	-
9		Index of refraction of cover	1.526	-

Figure 56: Parameter - Type 73










1		Inlet temperature	20	C
2		Inlet flowrate	0	kg/hr
3		Ambient temperature	10	C
4		Incident radiation	0	kJ/hr.m <sup>2</sup>
5		Windspeed	0	m/s
6		Horizontal radiation	0	kJ/hr.m <sup>2</sup>
7		Horizontal diffuse	0	kJ/hr.m <sup>2</sup>
8		Ground reflectance	0.2	-
9		Incidence angle	20	degrees

Figure 57: Input - Type 73

### 3.2.19 Type 654 – Water Pump



Type654

The water pump is used to give the signal about the operation of the solar pump, both to the type 73 and 60. And efficiency of about 90% is considered.

1		Rated flow rate	443	kg/hr
2		Fluid specific heat	3.388	kJ/kg.K
3		Rated power	745.555575	W
4		Motor heat loss fraction	0	-

Figure 58: Parameter - Type 654

1		Inlet fluid temperature	20	C
2		Inlet fluid flow rate	0	kg/hr
3		Control signal	1	-
4		Overall pump efficiency	0.6	-
5		Motor efficiency	0.9	-

Figure 59: Input - Type 654

### 3.2.20 Type 11d – Flow Mixer



Type11d

For the final part of the water delivering, a flow mixer is introduced to take into account the cold tap water, in a city like Dezhou, during summer, 15 to 20 °C can be considered. Two equal fluxes are set; therefore, the mixing coefficient is selected according to the output temperature.



### 3.2.21 Type 56b – Building



The last one is the **Type 56b**. This type represents the building file, allowing the connection with all the engineering system. The editing of the file is done in another tool, called **TRNBuild** [4], the file about the building is separated from the simulation file, but they can work together. Inside the tool, it is possible to create the envelope of the prototype, defining the initial conditions, defining the walls, the windows, and all the properties of the materials composing them. Therefore, after all the base elements are defined, the zones can be described, assigning the areas of walls and windows, volume, capacitance, orientation, and the coupling between the zones. The internal gains, heating, cooling, coupling, and ventilation can be specified defining an input in the building file, and then, linking the input with the external parameter from the simulation file.

There are 16 zones, 7 materials, 8 walls, 7 windows, 6 infiltrations, 6 ventilations, 4 cooling, 27 gains, 34 couplings defined, for a total of 104 inputs required.

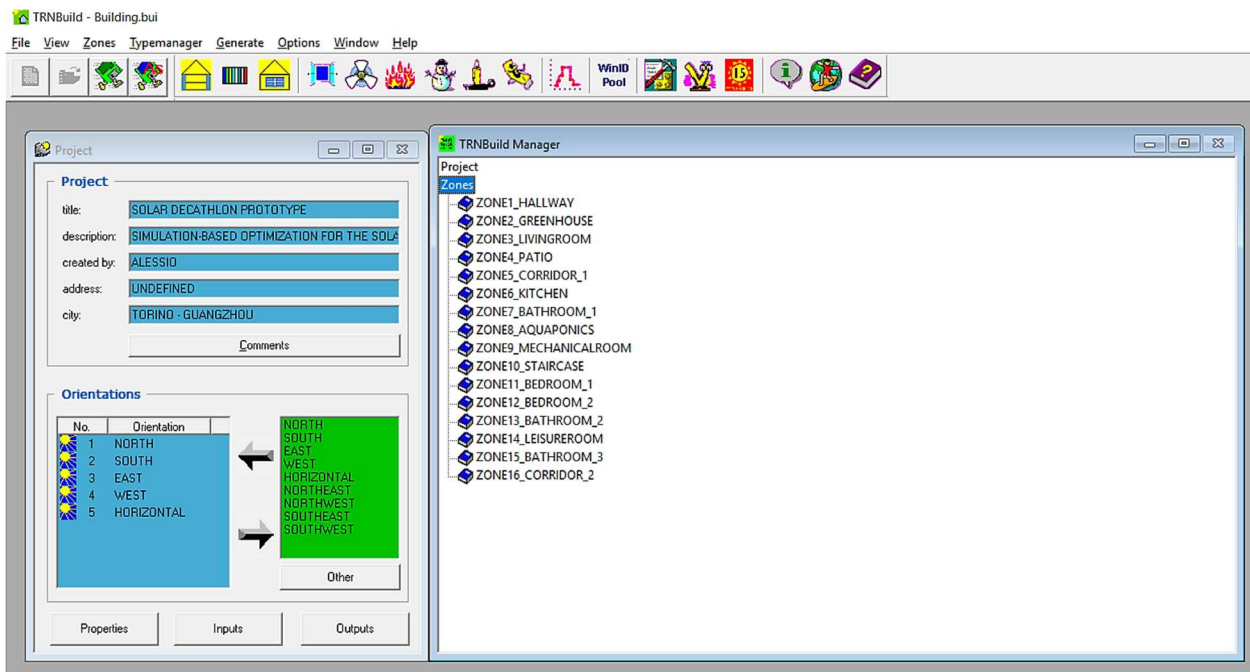


Figure 60: File Building Homepage

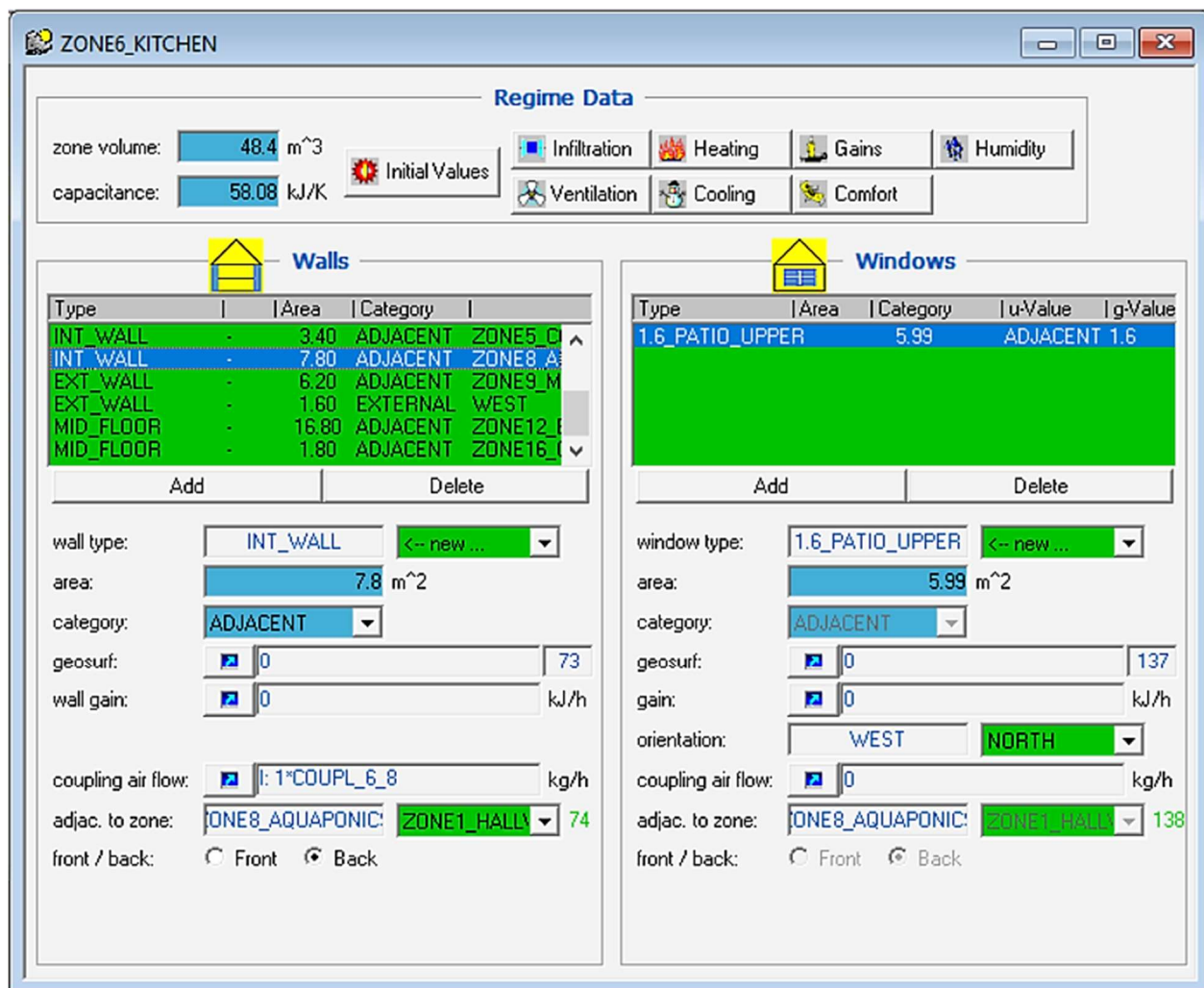



Figure 61: File Building Zone example

Wall Type Manager

 wall type: **EXT\_WALL**

**front / inside**

No.	Layer	Thickness	Type
1	OSB_BOARD	0.012	massive
2	PHENOLIC_INS	0.180	massive
3	POLYURETHANE		massless
4	VACUUM_LAYER		massless
5	POLYURETHANE		massless
6	OSB_BOARD	0.024	massive

**back**

total thickness:  m

u - value:  W/m<sup>2</sup> K for reference only  
(incl.  $\alpha_{i}=7.7$  W/m<sup>2</sup> K and  $\alpha_{o}=25$  W/m<sup>2</sup> K !)

**Solar Absorptance of Wall**

front:  -

back:  -

**Convective Heat Transfer Coefficient of Wall**

**Front**

☒ userdefined ☐ internal calculation

kJ/h m<sup>2</sup> K

**Back**

☒ userdefined ☐ internal calculation

kJ/h m<sup>2</sup> K



OK Cancel Save to user library 

Figure 62: File Building Wall type manager

Window Type Manager

 window type: **0.8\_EXTERNAL**

**Glazing**

ID number:  WinID

slope of window:  degree

For 1 glazing module width:  m height:  m

u - value:  W/m<sup>2</sup> K values acc. to glazing library (for reference only)

g - value:  %/100

ID spacer:  Aluminum - ASHREA Metallic

**Frame**

area frame/window:  % / 100

solar absorptance:  -

u - value (1/ R):  kJ/h m<sup>2</sup> K (without conv. + rad. heat transfer coefficients!)

**Optional Properties of Shading Devices**

**Additional Thermal Resistance**

internal device:  h m<sup>2</sup> K/kJ

external device:  h m<sup>2</sup> K/kJ

**Reflection Coefficient of Internal Device**

towards window:  % / 100

towards zone:  % / 100

**Fraction of abs. Solar Radiation to Zone Air Node (CCISHADE)**

% / 100

**Convective Heat Transfer Coefficient of Window (glazing + frame)**

**Front (inside)**

☒ userdefined ☐ internal calculation

kJ/h m<sup>2</sup> K

**Back (outside)**

☒ userdefined ☐ internal calculation

kJ/h m<sup>2</sup> K




OK Cancel Save to user library 

Figure 63: File Building Windows Type Manager

Cooling Type Manager


 cooling type: **COOLING\_LIVING**

**Room Temperature Control**

set temp.:  **I: 1\*T\_SETPOINT\_COOLING** °C


**Cooling Power**

☐ unlimited

☒ limited  **I: 1\*VRV\_LIVING\_POWER** kW / h

**Dehumidification**


☐ off      desired rel. humidity:

☒ on  **I: 1\*RH\_SETPOINT\_COOLING** %


OK Cancel **RDCN**

Figure 64: File Building Cooling Type Manager

Ventilation Type Manager


 ventilation type: **VENT\_BED1**

**Airchange of Ventilation**

 **I: 0.01683\*INF\_BED1\_ERV** 1/h


**Temperature of Air Flow**

☐ outside

☒ other  **I: 1\*TEMP\_ERV** °C

**Rel. Humidity of Air Flow**

☐ outside

☒ other  **I: 1\*RH\_ERV** %

OK Cancel **RDCN**

Figure 65: File Building Ventilation Type Manager

**Infiltration Type Manager**

infiltration type: **INF\_BED1**

**Airchange of Infiltration**

**I: 1\*INF\_BED1** 1/h

OK Cancel **R D C N**

Figure 66: File Building Infiltration Type Manager

**Gains [ Zone: ZONE6\_KITCHEN ]**

**Persons**

☐ off ☒ on

☒ ISO 7730 ☐ VDI 2078

Table degree of activity  
Standing, light work or working slowly

scale: **I: 1\*OCC\_KITCHEN**

**Computer**

☒ off ☐ on

**Artificial Lighting**

☒ off ☐ on

**Other Gains**

Type	Scale	Geo Position
LIGHT_06	1	
COOKING_ABS_HUMIDITY	1	
COOLING_06	1	
RH_06	1	

Add Delete

gain type: **LIGHT\_06** <-- new ...

scale: **1**

OK Cancel

Figure 67: File Building Gains

### 3.3 Model for the CO<sub>2</sub> and PM 2.5

TRNSYS 16 has no possibility to be linked with the CONTAM ability to simulate the contaminants flow, so an analytical model has been implemented. A **decay method** is suitable to monitor the levels of CO<sub>2</sub> and PM2.5 [13].

The model is based on the equations:

#### Build-up phase

$$\left( \langle C \rangle - C_b - \frac{q_i}{\varepsilon_v n V} \right) = \left( \langle C_0 \rangle - C_b - \frac{q_i}{\varepsilon_v n V} \right) e^{-(\varepsilon_v n t)}$$

#### Decay phase

$$(\langle C \rangle - C_b) = (\langle C_0 \rangle - C_b) e^{-(\varepsilon_v n t)}$$

#### Ventilation efficiency

$$\varepsilon_v = \frac{C_{exh} - C_b}{\langle C \rangle - C_b}$$

Where:

$\langle C \rangle$  is the average concentration;

$C_b$  is the background concentration;

$\langle C_0 \rangle$  is the initial concentration;

$C_{exh}$  is the outdoor concentration;

$q_i$  is the pollutant source;

$\varepsilon_v$  is the ventilation efficiency;

$n$  is the air change per hour;

$V$  is the volume of the zone;

$t$  is the time in [h].

The terms are arranged with respect to the conditions in which the house is set in different periods, varying the operation of the systems, or the occupancy.

Some values adopted are:

- CO<sub>2</sub> outdoor concentration equal to 400 ppm;
- Average number of people during visiting time in the main rooms equal to 5;
- Production of CO<sub>2</sub> per person equal to 0.02 m<sup>3</sup>/h.person;
- Ventilation efficiency equal to 0.8;
- PM2.5 filtration efficiency equal to 98%;
- PM2.5 outdoor concentration equal to 200 µg/m<sup>3</sup>;

\*During some period of the contest – e.g. dinner party – some values change.

Some measurements have been performed about the air quality, to check the performance of the systems.

Two instruments were used:



Figure 68: PM2.5 Meter



Figure 69: Zero-filter

### **METONE 831 Mass monitor**

It measures PM1, PM2.5, PM4, PM10. A filter for the zero check is provided, so the instrument has been tested before the test.



Figure 70: CO2 Meter

### **TES 1370 NDIR CO<sub>2</sub> Meter**

Less accurate than the previous one, it measures CO<sub>2</sub> level, Temperature, and Relative Humidity.

Both the instruments scored values during the tests suitable with the expectations, therefore, the decay model, along with the data provided from the technical datasheets of the ERV, can be considered reliable.



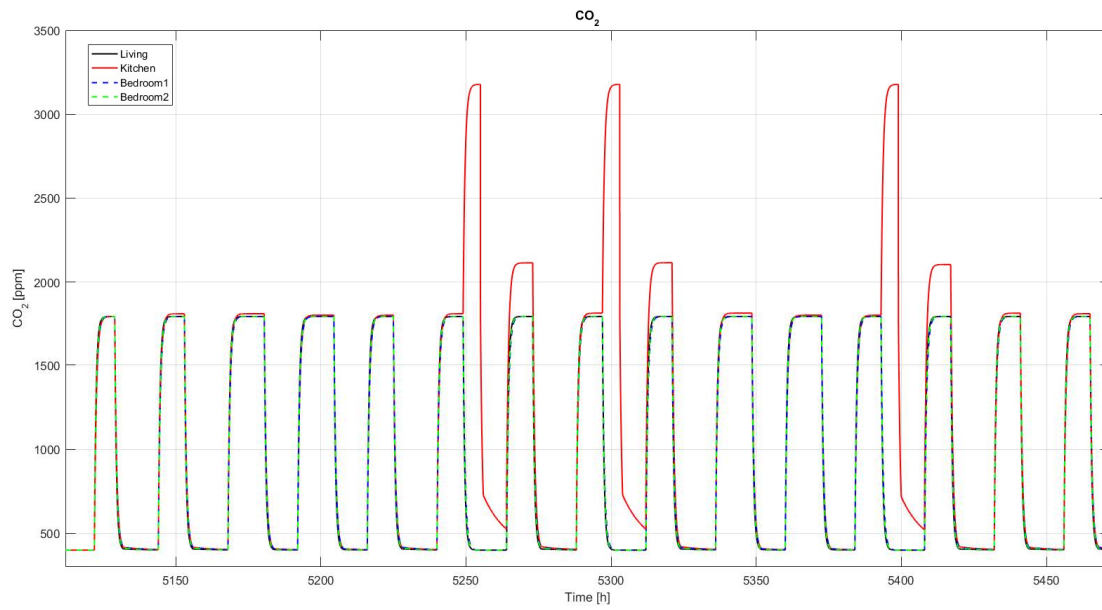


Figure 71: Contest CO<sub>2</sub>

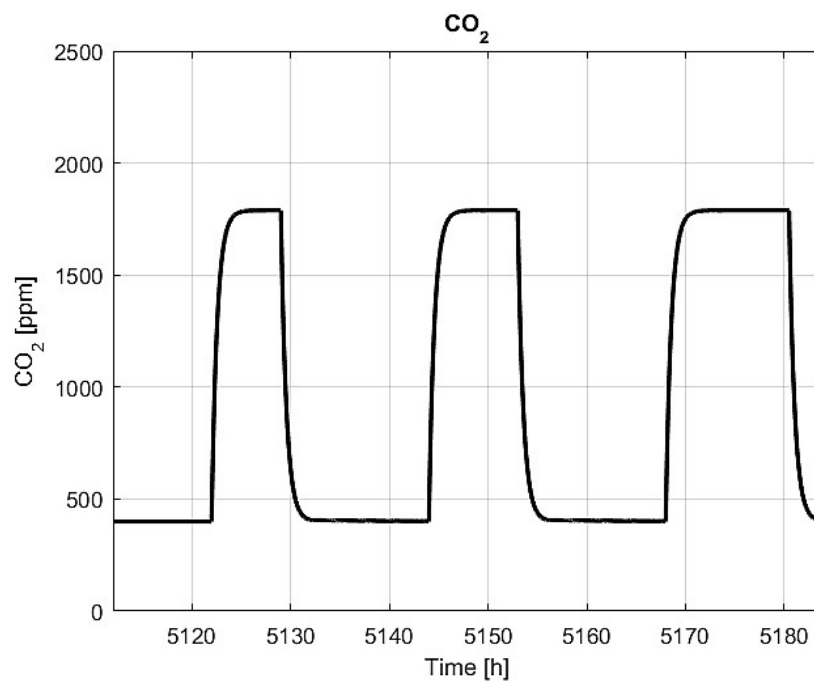


Figure 72: Contest CO<sub>2</sub> detail



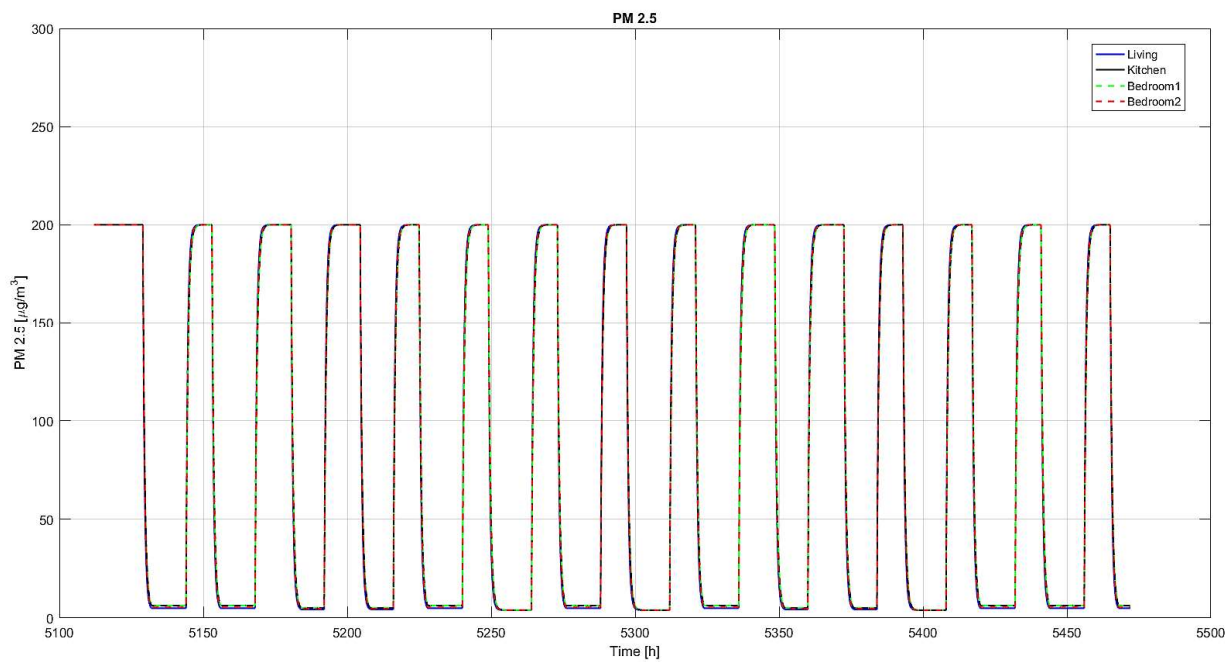


Figure 73: Contest PM2.5

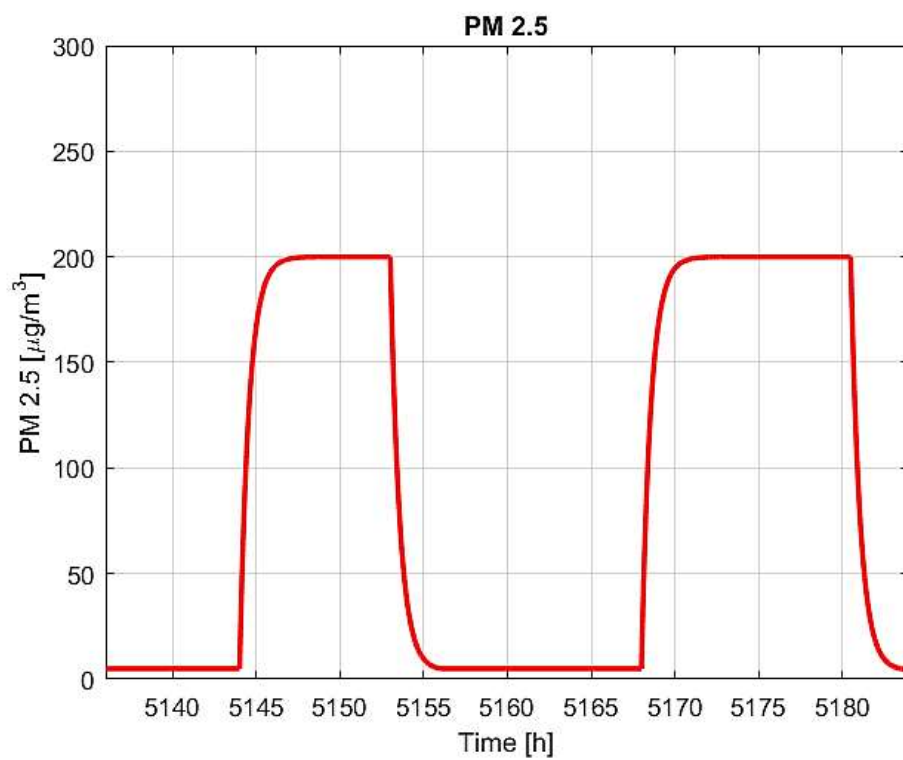


Figure 74: Contest PM2.5 detail

## 4. Problem statement and implementation of the method

### 4.1 Simulation-based Optimization

Once the energy model is completed, it is possible to test the behaviour of the prototype and make the appropriate considerations on the design. Many decisions were based on the designers' experience and on the theory, sometimes they can be successful, sometimes they are wrong, if combined to different environment, or other applications. Therefore, the need of an instrument able to control effectively all the possibilities, whom the prototype can be changed. Usually, the user adopts a **parametric approach** [14], based on the most important parameter, varying the range with respect to a fixed simulation, but again, it is related to the experience, and cannot be best way to operate. Furthermore, jumping from one parameter to another, the time requested increases, as increases also the possibility of a wrong choice about the previous parameters.

The optimization should follow a method carried by a simulation, taking advantage from the calculation power of a computer, therefore the **Simulation-based optimization** [15].

#### 4.1.1 General Description of the Problem and Mathematical Reference

The optimization consists on an automated model where a **simulation program** is coupled with an optimization engine; the problem, therefore, is solved through **iterative methods** guided by **optimization algorithms** [16]. Usually the optimization has been applied to a lot of sort of problems, like energy consumption reduction, efficiency of systems, indoor comfort, and mostly on the costs, as the life cycle cost [2]. In this work, the goal is the optimization of the score gained during the Solar Decathlon contest. The problem is based on a mathematical lower-bounded function, called “**Objective function**”, or “**Cost function**”, imposed by the user [15]. The optimization is usually carried out by minimizing the function set in the form:

$$\min_{x \in X} f(x)$$

Where X is all the possible combination of the variables.

Since in this case the problem consists on a **maximization** of the function, it can be easily reversed, putting a minus in front of the solution, and considering the negative value. To choose the best algorithm, that suits the problem, there are a lot of parameters to consider; three can be considered [17]:

- nature of the variables (continuous, discrete, mixed);
- the presence of constraints on the objective function;
- nature of the objective function (continuous, discontinuous, linear, non-linear, convex, number of local minima...).

There are different kind of algorithm for the simulation-based optimization method (**SBOM**): genetic algorithms, hybrid algorithms, particle swarm optimization, Hooke-Jeeves, generalized pattern search, discrete Armijo gradient, and so on... [16]

These algorithms are solved by iterative methods, with progressively better approximation to a solution. Due to the characteristics of the objective function, it is no so obvious to find a minimum, there could be local minima, wrong for the solution, therefore, the algorithm can fail [17].

The problem about a building design is characterized by **discrete variables**, considering the components need available commercial sizes and cannot vary on very little variations, and the operational plan must have feasible ranges - i.e. temperature setpoint cannot changes about 0.1 °C, or turning ON/OFF the systems cannot change about 1 minutes – therefore, the algorithm has to be able to deal with discrete variables [18]. **Twenty-five variables** are chosen for the optimization. Combining all these variables, leads to a hypercube of possible solutions, that would require a huge amount of time to be investigated without an optimization algorithm. A meta-heuristic method was selected, belonging to the stochastic population-based family algorithms: **The Particle Swarm Optimization (PSO)**. [8][9]

#### 4.1.2 PSO - Particle Swarm Optimization

The Particle Swarm Optimization has the main characteristics of the **stochastic population**-based, in common with the Genetic Algorithms [19]:

- Need few or no assumptions about the objective function and can search very large search-spaces
- Not to “get stuck” in local optima
- Large number of cost function evaluations
- Global minimum cannot be guaranteed

The peculiarity of this method is the **swarm intelligence**.

The algorithm was created by Russell Eberhart and James Kennedy. It is inspired by social behaviour of **bird flock** or **fish school** [8]. It was originally designed for continuous variables, with possibly discontinuous cost function, but it can solve also problems with discrete variables. The PSO explores a set of potential solutions to the problem: the solution is called “**particle**”, while the set of potential solutions in each iteration step is called “**population**”. The first population is randomly generated. The initial version of the PSO, is presented below. Each particle  $j = 1, \dots, n$  has a position  $x_j$  and a velocity vector  $v_j$ . The “ $i$ ” represents the generation number. The update equations for both velocity and position are [6][10][20][21]:

$$v_j^{(i+1)} = v_j^{(i)} + c_1 \rho_1^{(i+1)} (P_j^{(i)} - x_j^{(j)}) + c_2 \rho_2^{(i+1)} (G^{(i)} - x_j^{(j)})$$

$$x_j^{(i+1)} = x_j^{(i)} + v_j^{(i+1)}$$

Where:

$P_j^{(i)}$  is the best position ever attained by the particle itself (cognitive memory);

$G^{(i)}$  is the best position ever attained by the swarm as a whole (global, social);

$c_1$  is the cognitive acceleration constant;

$c_2$  is the social acceleration constant;

$\rho_1, \rho_2$  are random numbers uniformly distributed in the range (0,1).

The set of points where the global minimum is taken is defined by the neighbourhood topology. For the purpose of this work, the **Von Neumann topology** has been used, with a size of 5. In the picture there is an example of the topology with size 1 [16].

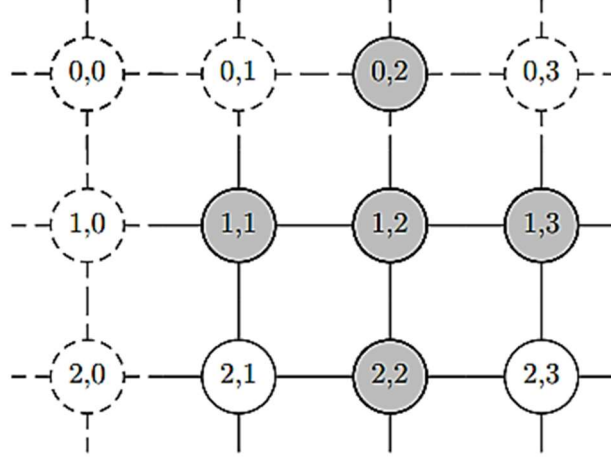


Figure 75: Von Neumann topology, size 1

In the case of discrete variable, the algorithm encodes them in a string of binary numbers, using Grey encoding with “ $m$ ” bits [6][20].

$\hat{x}_j^{(i)} \in \{0,1\}^m$  is the binary representation of the variable  $\hat{x}_j^{(i)}$ .

Each  $k$ -th bit is considered as a separated particle and updated with the equations:

$$\hat{v}_j^{(i+1)} = \hat{v}_j^{(i)} + c_1 \rho_1^{(i+1)} (\hat{P}_j^{(i)} - \hat{x}_j^{(j)}) + c_2 \rho_2^{(i+1)} (\hat{G}^{(i)} - \hat{x}_j^{(j)})$$

$$w_{j,k}^{(i+1)} = \text{sigm}(\text{sat}(\hat{v}_{j,k}^{(i+1)}))$$

$$\hat{x}_j^{(i+1)} = \begin{cases} 0, & \text{if } w_{j,k}^{(i+1)} \leq \alpha_{j,k}^{(i)} \\ 1, & \text{otherwise} \end{cases}$$

$$\text{sigm}(v) \triangleq \frac{1}{1 + e^{-v}}$$

$\alpha_{j,k}^{(i)}$  is a uniform random number between 0 and 1.

The sigmoid function and the saturation function put the velocity at  $v_{max}$ .

$\hat{P}_j^{(i)}$  and  $\hat{G}^{(i)}$  are the binary representation of  $P_j^{(i)}$  and  $G^{(i)}$ .

In the binary PSO a small  $v_{max}$  allows a large exploration, while in the continuous PSO causes a small exploration of the solution space. Often,  $v_{max}$  is set to 4, to prevent saturation of the sigmoid function, and the parameters  $c_1$ ,  $c_2$  are chosen, such that  $c_1 + c_2 = 4$ . [8][22]

### PSO with Inertia Weight

In this version of the algorithm, a coefficient called **inertia weight** is introduced, multiplying the term  $\hat{v}_j^{(i)}$ . This trick improves the performance of the original PSO. [9][16][20]

$$v_{max}^{(k)} \triangleq \lambda(u^k - l^k)$$

Where  $u, l$  are the upper and lower bound of the independent variable.

A common value is  $\lambda = 0.5$ . If  $\lambda \leq 0$ , no velocity clamping is used.

The inertia weight is computed as:

$$\omega^{(i)} = \omega_0 - \frac{i}{n_G}(\omega_0 - \omega_1)$$
$$0 \leq \omega_1 \leq \omega_0$$

$\omega_0$  is the initial inertia weight;

$\omega_1$  is the final inertia weight (for the last generation);

$n_G$  is the maximum number of generations.

A good choice is to set  $\omega_1 = 1.2$  and  $\omega_0 = 0$ . [16]

#### 4.1.3 Implementation on GenOpt

The **PSO** with Inertia weight has been implemented. **GenOpt** has a library of optimization algorithms; to recall the correct one, defining the parameters the correct syntax is:

```
Algorithm{
  Main = PSOIW;
  NeighborhoodTopology = gbest | lbest | vonNeumann;
  NeighborhoodSize = Integer; // 0 < NeighborhoodSize
  NumberOfParticle = Integer;
  NumberOfGeneration = Integer;
  Seed = Integer;
  CognitiveAcceleration = Double; // 0 < CognitiveAcceleration
  SocialAcceleration = Double; // 0 < SocialAcceleration
  MaxVelocityGainContinuous = Double;
  MaxVelocityDiscrete = Double; // 0 < MaxVelocityDiscrete
  InitialInertiaWeight = Double; // 0 < InitialInertiaWeight
  FinalInertiaWeight = Double; // 0 < FinalInertiaWeight
}
```

Figure 76: PSO with Inertia weight in GenOpt

**‘Main’** is the key word for the algorithm;  
**‘NeighborhoodTopology’** defines the kind of topology used;  
**‘NeighborhoodSize’** is the size of the topology;  
**‘NumberOfParticle’** is the variable  $n_p \in \mathbb{N}$ ;  
**‘NumberOfGneration’** is the variable  $n_g \in \mathbb{N}$ ;  
**‘Seed’** is the value to initialize the random number generator;  
**‘CognitiveAcceleration’** is the variable  $c_1 \in \mathbb{R}^+$ ;  
**‘SocialAcceleration’** is the variable  $c_2 \in \mathbb{R}^+$ ;  
**‘MaxVelocityGainContinuous’** is the variable  $\lambda \in \mathbb{R}^+$ ;  
**‘MaxVelocityDiscrete’** is the variable  $v_{max} \in \mathbb{R}^+$ ;  
**‘InitialInertiaWeight’** is  $\omega_0 \in \mathbb{R}^+$ ;  
**‘FinalInertiaWeight’** is  $\omega_1 \in \mathbb{R}^+$ .

To set up an optimization problem, first, a **cost function** must be defined, paying attention to potential constraints to the variables. It is very important the simulation program writes the cost function without truncating any digits. The files in GenOpt are organized in **sections**, filled with all the information. Several files are required: **initialization** file, **configuration** file, **command** file, **log** file, **output** files. [10][16]

#### ➤ Initialization file (.ini)

This is the **file** where all the **positions** of the files are specified. In particular, where the optimization files are located, the simulation files to be saved, what number is the cost function in the simulation file and how to locate it, if the cost function value has to be processed, and what simulation program is used. It is divided into two section: “*Simulation*” and “*Optimization*”. For the *Simulation* the sections are “*Files*”, “*CallParameter*” (optional), and “*ObjectiveFunctionLocation*”.

The sub-section *Files* contains the path for:

- *Templates* – copies of the simulation files, in which the parameters that are selected for the optimization are changed with variables;
- *Input* – same files of the template, and must be the same number of files, but these files will change during the process;

- *Log* – the file to check the presence of errors from the simulation program;
- *Output* – files to search the cost function.
- *Configuration* – configuration file of TRNSYS 16.

The *ObjectiveFunctionLocation* defines the name of the objective function, and where to find its value after each simulation; GenOpt will read the file starting from the last line, proceeding to the first. It will find the value of the cost function as soon as it finds the **delimiter** imposed, which is the string in front of the value.

About the *Optimization*, it just points where the file (command) with the specification is located.

```
Simulation {
  Files {
    Template {
      File1 = String | StringReference;
      [ Path1 = String | StringReference; ]
      [ File2 = String | StringReference; ]
      [ Path2 = String | StringReference; ]
      [ ... ] ]
    }
    Input { // the number of input file must be equal to
           // the number of template files
      File1 = String | StringReference;
      [ Path1 = String | StringReference; ]
      [ SavePath1 = String | StringReference; ]
      [ File2 = String | StringReference; ]
      [ Path2 = String | StringReference; ]
      [ SavePath2 = String | StringReference; ]
      [ ... ] ]
    }
    Log {
      // The "Log" section has the same syntax as the "Input" section.
    }
    Output {
      // The "Output" section has the same syntax as the "Input" section.
    }
    Configuration {
      File1 = String | StringReference;
      [ Path1 = String | StringReference; ]
    }
  } // end of section Simulation.Files
  [CallParameter {
    [Prefix = String | StringReference;]
    [Suffix = String | StringReference;]
  }]
  [ObjectiveFunctionLocation {
    Name1 = String;
    Delimiter1 = String | StringReference; | Function1 = String;
    [FirstCharacterAt1 = Integer;]

    [ Name2 = String;
      Delimiter2 = String | StringReference; | Function2 = String;
```



```

        [FirstCharacterAt2 = Integer;]
        [ ... ] ]

    }}
} // end of section Simulation
Optimization {
    Files {
        Command {
            File1 = String | StringReference;
            [ Path1 = String | StringReference; ]
        }
    }
} // end of section Optimization

```

Figure 77: GenOpt Initialization file syntax

### ➤ Configuration file (.cfg)

The configuration file is common for all the simulations regarding the same software, it contains information about the **simulation errors** syntax, the simulation start's command line, and again the objective function location, which will be ignored if it has been specified in the initialization file.

```

// Error messages of the simulation program.
SimulationError{
    ErrorMessage = String;
    [ErrorMessage = String;
    [ ... ] ]
}

// Number format for writing simulation input files.
IO{
    NumberFormat = Float | Double;
}

// Specifying how to start the simulation program.
SimulationStart{
    Command = String;
    WriteInputFileExtension = Boolean;
}

// Specifying the location of the
// cost function value in the simulation output file
ObjectiveFunctionLocation{
    Name1      = String;
    Delimiter1 = String | StringReference; | Function1 = String;

    [ Name2      = String;
      Delimiter2 = String | StringReference; | Function2 = String;
    [ ... ] ]
}

```

Figure 78: GenOpt Configuration file syntax

### ➤ Command file (.txt)

Command file is divided into three main sections: “*Vary*”, “*OptimizationSettings*”, “*Algorithm*”.

The *Vary* section is the one where all the **variables**, with their own range, should be defined. There are two main kind of variable, continuous, or discrete. Since this project considers just the discrete ones, only the syntax of that kind will be explained.

```
// Settings for a discrete parameter
Parameter{
    Name    = String;
    Ini     = Integer;
    Values  = String;
    [ Type  = SET; ]
}
```

Figure 79: GenOpt discrete variables syntax

*Name* – string concerning the variable **name** used in the optimization;

*Ini* – integer regarding the **initial value** of the variable;

*Value* – vector containing all the **discrete values** that the variable can assume;

*Type* – SET states the variable is **discrete**.

The section *OptimizationSettings* is about only few data about the optimization: the **maximum number of iterations**, the **maximum equal results**, and the two optional strings: the first about the **units of execution**, the parallel computing cores, and the second about the specification of writing the **number of steps** inside the simulation file.

The last section, *Algorithm*, is the most important, because it contains the **parameters** of the Particle Swarm Optimization implemented. The syntax has been explained in the chapter “Implementation of the PSO”. The following values have been used for the first attempts of the optimization. Afterwards some of them can be changed to check the behaviour of the optimization, and how well the algorithm responds.

```

Algorithm {
  Main = PSOIW;
  NeighborhoodTopology = vonNeumann;
  NeighborhoodSize = 5;
  NumberOfParticle = 10;
  NumberOfGeneration = 10;
  Seed = 1;
  CognitiveAcceleration = 2.0;
  SocialAcceleration = 2.0;
  MaxVelocityGainContinuous = 0.5;
  MaxVelocityDiscrete = 4;
  InitialInertiaWeight = 1.2;
  FinalInertiaWeight = 0.0;
}

```

#### ➤ Log file

The log file, named GenOpt.log, contains information about the optimization, as the time spent during the process, in addition it has information about **warnings** and **errors** occurred during the optimization.

#### ➤ Output file (.txt)

GenOpt writes two **output** files, one containing all the **iterations**, the other just the main iteration steps. They save the value of the objective function, and the corresponding variables' values for each iteration.

## 4.2 Application to the Prototype

### 4.2.1 Objective Function

Among the sub-contests to compose the total score, only the measured parts are useful for this work, therefore, the juried contests and the ones regarding the tasks are not considered [1]. The remaining elements that can be monitored and simulate through an energy simulation program are:

- **Temperature** – 40 points;
- **Humidity** – 20 points;
- **CO<sub>2</sub>** – 20 points;
- **PM2.5** – 20 points;
- **Energy balance** – 80 points;

The total maximum possible score is 180.

The objective function is implemented and calculated on MATLAB.

### 4.2.2 Variables

**Twenty-five variables** for the start have been chosen between the envelope and the system, named as follow:

Table 15: Variables names

Parameters	Type	GenOpt name
Setpoint Temperature	VRV	T_VRV
Deadband		Deadband_VRV
ERV turn on time day 1	ERV	ERV_on1
ERV turn on time day 2		ERV_on2
ERV turn off time day 1		ERV_off1
ERV turn off time day 2		ERV_off2
Array Slope	PV Panel	PV_angle
Shading North	Building	Sh_N
Shading South		Sh_S
Shading Horizontal		Sh_H
Shading Time ON North		Sh_N_on
Shading Time ON South		Sh_S_on
Shading Time ON Horizontal		Sh_H_on
Shading Time OFF North		Sh_N_off
Shading Time OFF South		Sh_S_off
Shading Time OFF Horizontal		Sh_H_off
OSB North		OSB_N
OSB South		OSB_S
OSB Roof		OSB_Roof
OSB Other		OSB
Phenolic Insulant North		INS_N
Phenolic Insulant South		INS_S
Phenolic Insulant Horizontal		INS_H
Phenolic Insulant Other		INS
Phenolic Insulant Internal Walls		INS_int

The chosen variables rely on the main categories of **cooling setpoint**, operation of the **ventilation system**, tilt angle of the **PV panel**, **shading** fraction and time schedule, **thickness** of the two main component of the walls: massive components, such as the **Oriented Strain Board (OSB)**, and the **phenolic insulation**. Checking the **Vacuum Insulated Panel** thickness is pointless, because they are high-performance prefabricated modules, and it is not possible to change their thickness. Some of them are split for different orientations, to see what the influence for the performance and the score is, and how they change between themselves.

For the first simulations, the variables' ranges of the table below were chosen, trying to spread them as much as possible, to see the possibilities of design options [23].

Table 16: First values of the variables

GenOpt name	Values	Initial value	Unit
T_VRV	[21, 22, 23, 24, 25, 26]	4	°C
Deadband_VRV	[2.0, 3.0, 4.0]	1	°C
ERV_on1	[16.00, 17.00, 18.00]	2	hour
ERV_on2	[19.50, 20.50, 21.50]	2	hour
ERV_off1	[19.50, 20.50, 21.50]	2	hour
ERV_off2	[22.00, 23.00, 24.00]	2	hour
PV_angle	[2.0, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0, 18.0, 20.0]	1	°
Sh_N	[0.00, 0.25, 0.50, 0.75 1.00]	1	Fraction
Sh_S	[0.00, 0.25, 0.50, 0.75 1.00]	1	Fraction
Sh_H	[0.00, 0.25, 0.50, 0.75 1.00]	1	Fraction
Sh_N_on	[7.00, 7.50, 8.00, 8.50, 9.00, 9.50, 10.00, 10.50, 11.00]	3	hour
Sh_S_on	[7.00, 7.50, 8.00, 8.50, 9.00, 9.50, 10.00, 10.50, 11.00]	3	hour
Sh_H_on	[7.00, 7.50, 8.00, 8.50, 9.00, 9.50, 10.00, 10.50, 11.00]	3	hour
Sh_N_off	[17.0, 17.5, 18.0, 18.5, 19.0, 19.5, 20.0, 20.5, 21.0, 21.5, 22.0]	3	hour
Sh_S_off	[17.0, 17.5, 18.0, 18.5, 19.0, 19.5, 20.0, 20.5, 21.0, 21.5, 22.0]	3	hour
Sh_H_off	[17.0, 17.5, 18.0, 18.5, 19.0, 19.5, 20.0, 20.5, 21.0, 21.5, 22.0]	3	hour
OSB_N	[0.012, 0.024, 0.036]	1	mm
OSB_S	[0.012, 0.024, 0.036]	1	mm
OSB_Roof	[0.012, 0.024, 0.036]	1	mm
OSB	[0.012, 0.024, 0.036]	1	mm
INS_N	[0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24]	6	mm
INS_S	[0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24]	6	mm
INS_H	[0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24]	6	mm
INS	[0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24]	6	mm
INS_int	[0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24]	6	mm

After some preliminary optimization, the ranges of the variables have been refined, cutting some worthless parameters, like the operational time of the shadings and the fraction, adding new parameters in the variation, or modifying others. The setpoint temperature of the cooling system has been changed, cutting the upper bound, and adding a new lower bound, because every simulation was stuck on the lower value, therefore, it was possible to have a better exploration, and the deadband has been removed.

Moreover, the project is part of a bigger study, in which the energy model has been calibrated [25], through a measurements campaign on the prototype, coupled with different computational tools, like simulation programs, sensitivity analysis, and optimization process, to obtain some adjustments to the model, to simulate the house behaviour closest to the real one. Thus, the results from the calibration has been implemented on the optimization of this work, to achieve the highest reliable result.

*Table 17: Second values of the variables*

GenOpt name	Values	Initial Value	Unit
<b>T_VRV</b>	[20, 21, 22, 23, 24, 25]	5	°C
<b>ERV_on1</b>	[16.00, 16.50, 17.00, 17.50, 18.00]	3	hour
<b>ERV_on2</b>	[19.50, 20.00, 20.50, 21.00, 21.50]	3	hour
<b>ERV_off1</b>	[19.50, 20.00, 20.50, 21.00, 21.50]	3	hour
<b>ERV_off2</b>	[22.00, 22.50, 23.00, 23.50, 24.00]	3	hour
<b>PV_angle</b>	[2.0, 5.0, 10.0, 15.0, 20.00, 25.00]	1	°
<b>Sh_N</b>	[0.00, 0.50, 1.00]	1	Fraction
<b>Sh_S</b>	[0.00, 0.50, 1.00]	1	Fraction
<b>Sh_H</b>	[0.00, 0.50, 1.00]	1	Fraction
<b>Sh_N_on</b>	[7.00, 8.00, 9.00, 10.00, 11.00, 12.00]	5	hour
<b>Sh_S_on</b>	[7.00, 8.00, 9.00, 10.00, 11.00, 12.00]	5	hour
<b>Sh_H_on</b>	[7.00, 8.00, 9.00, 10.00, 11.00, 12.00]	5	hour
<b>Sh_N_off</b>	[17.00, 18.00, 19.00, 20.00, 21.00, 22.00]	3	hour
<b>Sh_S_off</b>	[17.00, 18.00, 19.00, 20.00, 21.00, 22.00]	3	hour
<b>Sh_H_off</b>	[17.00, 18.00, 19.00, 20.00, 21.00, 22.00]	3	hour
<b>OSB_N</b>	[0.012, 0.024, 0.036]	1	mm
<b>OSB_S</b>	[0.012, 0.024, 0.036]	1	mm
<b>OSB_Roof</b>	[0.012, 0.024, 0.036]	1	mm
<b>OSB</b>	[0.012, 0.024, 0.036]	1	mm
<b>INS_N</b>	[0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24]	6	mm
<b>INS_S</b>	[0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24]	6	mm
<b>INS_H</b>	[0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24]	6	mm
<b>INS</b>	[0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24]	6	mm
<b>INS_int</b>	[0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24]	6	mm

### 4.2.3 Process

The common application of a simulation-based optimization imposes a direct connection between the optimization algorithm and the simulation program, in this case GenOpt and TRNSYS. Considering the peculiarity of the outputs needed to constitute the cost function, due to the variety of the points to be taken from different types, it is quite tricky to have them in a simple way, consequently, a coupling with MATLAB, between the two programs was necessary. At this point, another problem must be faced, GenOpt cannot handle two programs as a single simulation software, so an expedient has been created: GenOpt runs a **batch file** on the command line of Windows, calling TRNSYS and MATLAB, with the appropriate precautions, instead of calling the simulation software itself.

The overall process, after running GenOpt initialization file, follows precise **steps**, that must be well-synchronized to avoid errors, wasting time:

- A. Run the **batch file** (.bat);
- B. The batch file calls **TRNSYS**, which uses also a sub-routine from **CONTAM** to evaluate the air flows, from the command line and wait the execution on the simulation, and the creation of the **output file**;
- C. When the simulation has ended, the batch file calls the **MATLAB** script, to manage the outputs, and evaluate the **cost function**, waiting the production of a text file with the value of the function, to be read by GenOpt, otherwise it will give an error, or the simulation program will start again, before having the results;
- D. **GenOpt** reads the value of the cost function, and then, apply the PSO continuing the optimization, until the minimum is reached.

The batch file is organized in this manner:

```
"C:\Program Files (x86)\Trnsys16\Exe\TRNExe.exe" "D:\POLITO\+TESI\TRNSYS\Simulation_final\Model\Simulation_Final.dck" /n
matlab -wait -nodisplay -nosplash -nodesktop -minimize -r "run('D:\POLITO\+TESI\TRNSYS\Simulation_final\Model\Data_processing.m');quit;" -logfile
:ciclo
timeout /t 2
    if not exist "D:\POLITO\+TESI\TRNSYS\Simulation_final\Model\Contest_Points.txt" (
        goto :ciclo
    )
:ending
:exit;
```

*Figure 80: Batch file*

The MATLAB code is available in the “Appendix” section.

## 5. Results and Discussion

### 5.1 Results of the optimization

Many optimizations have been performed, checking the efficiency of the algorithm, and the effectiveness of the tool. Different numbers of **iterations** were tested, varying the number of particles  $n_p$  and the number of generations  $n_g$  [6][14][20]. The **time** required for a step of a simulation is around two minutes, in a computer equipped with a processor Intel Core I7-6700HQ (2.6 GHz) and 8 GB RAM. The time for the optimization, obviously, grows as the number of generations and particles grows, therefore, it is very important to see how many iterations are required to reach the maximum, and how much it varies according to the iterations. Once the maximum is reached and there is no failure of the process, even the parameters of the algorithm can be changed. Some combinations are used for acceleration coefficients  $c_1$  and  $c_2$ , and for the inertia weight [8][9][16][19][20][22][23]. The starting score with the project data is 162.42789. Each optimization shows an improvement of the solution, the **maximum** roams around the value of **175 points**, for the early runs of the optimization.

The **highest score** achieved is equal to **176.93825**.

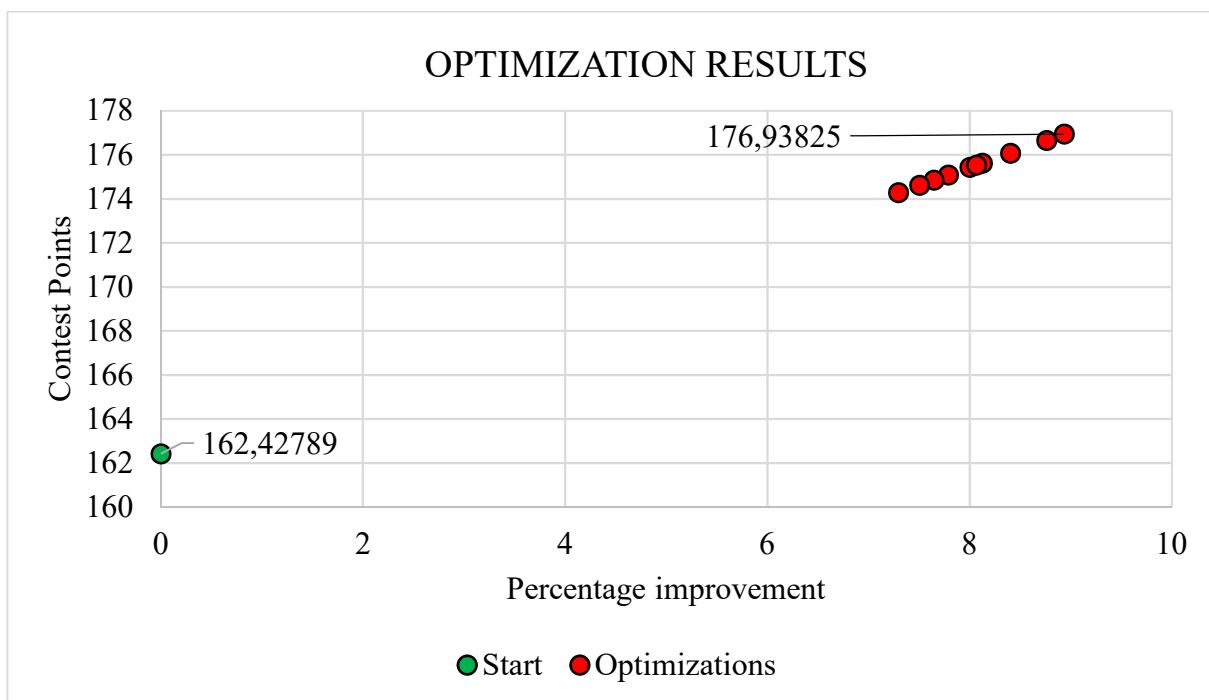


Figure 81: Optimization Results



Table 18: Results of the simulations 1 - 6

Variable	Opt 1	Opt 2	Opt 3	Opt 4	Opt 5	Opt 6
<b>Contest Points</b>	175.08032	175.42584	174.8459	174.61665	175.62231	175.53278
<b>T VRV</b>	21	21	21	21	21	21
<b>Deadband VRV</b>	3	5	2	1	3	4
<b>ERV on 1</b>	16	16	16	17	17	16
<b>ERV on 2</b>	20.5	19.5	20.5	19.5	20.5	19.5
<b>ERV off 1</b>	19	19	19	19	19	20
<b>ERV off 2</b>	22	22	22	22	22	22
<b>PV angle</b>	16	2	16	6	20	20
<b>Sh N</b>	0.4	0.2	0.4	1	0.25	0.25
<b>Sh S</b>	1	0.4	1	1	0.25	0
<b>Sh H</b>	0	1	0	0	0.25	0.25
<b>Sh N on</b>	9	11	9	10.5	11	10.5
<b>Sh S on</b>	7.5	8.5	7.5	10	8.5	11
<b>Sh H on</b>	8	11	8	9.5	11	11
<b>Sh N off</b>	18.5	22	18.5	17	21	22
<b>Sh S off</b>	21	22	21	17.5	22	20.5
<b>Sh H off</b>	22	18.5	22	22	17.5	21.5
<b>OSB N</b>	0.036	0.048	0.036	0.048	0.024	0.012
<b>OSB S</b>	0.036	0.012	0.024	0.036	0.048	0.024
<b>OSB Roof</b>	0.024	0.012	0.024	0.048	0.024	0.024
<b>OSB</b>	0.024	0.036	0.012	0.036	0.048	0.048
<b>INS N</b>	0.16	0.16	0.16	0.22	0.22	0.14
<b>INS S</b>	0.12	0.1	0.12	0.24	0.12	0.2
<b>INS H</b>	0.14	0.2	0.14	0.16	0.16	0.16
<b>INS</b>	0.18	0.14	0.18	0.1	0.14	0.18
<b>INS int</b>	0.2	0.24	0.2	0.14	0.22	0.14
<b>NeighborhoodSize</b>	5	5	5	5	5	5
<b>N° of Particle</b>	10	20	5	15	20	20
<b>N° of Generation</b>	10	10	5	10	15	15
<b>Seed</b>	1	1	1	1	1	1
<b>CognitiveAcceleration</b>	2	2	2	2	2	2.5
<b>SocialAcceleration</b>	2	2	2	2	2	1.5
<b>MaxVelocityGainContinuous</b>	0.5	0.5	0.5	0.5	0.5	0.5
<b>MaxVelocityDiscrete</b>	4	4	4	4	4	4
<b>InitialInertiaWeight</b>	1.2	1.2	1.2	1.2	1.2	1.2
<b>FinalInertiaWeight</b>	0	0	0	0	0	0
<b>MaxIteration</b>	100	100	100	100	100	100
<b>MaxEqualResults</b>	5	5	5	5	5	5
<b>Time [h]</b>	5	8.08	01:38	05:23	12:45	12:20
<b>Iterations</b>	160	-	-		375	375
<b>Iteration of minimum</b>	6	-	-	-	298	348

On the **third simulation** the **calibrated parameters** have been implemented. While from the **seventh** the **deadband** of the VRV has been fixed to 2, like the real operation, and an extra humidity control of the VRV added, modifying the consumption. The parameters of the algorithm are modified too, trying other combination. Some progress of the cost function is presented in the following graphs, for some optimization.

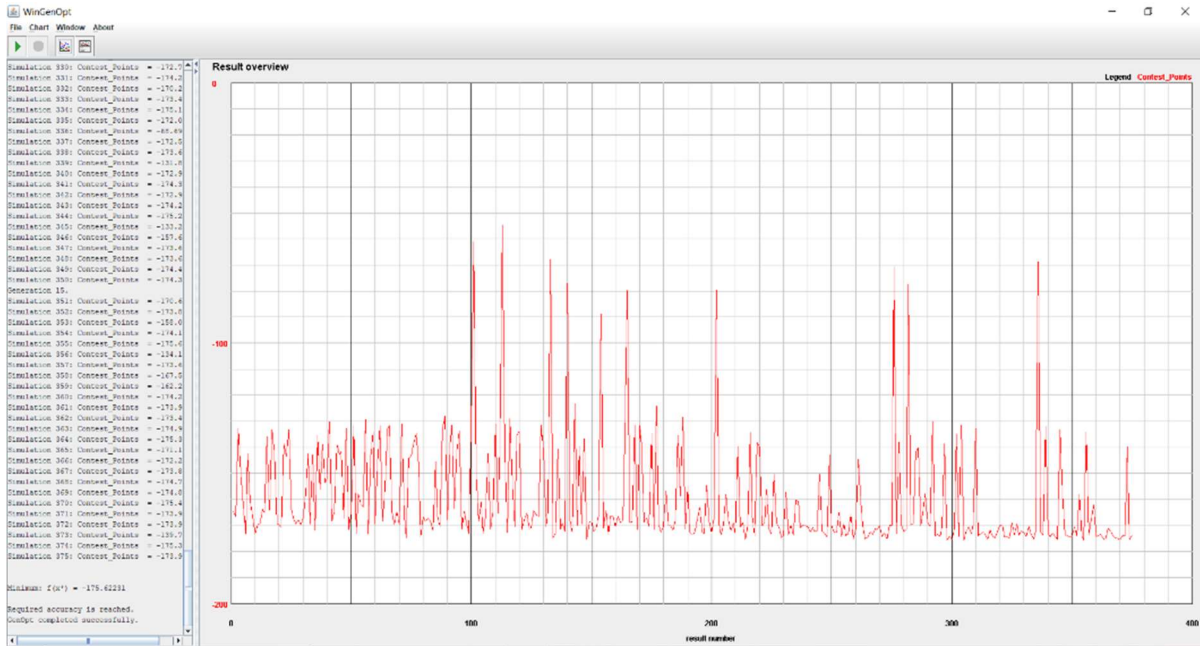


Figure 82: Optimization 5

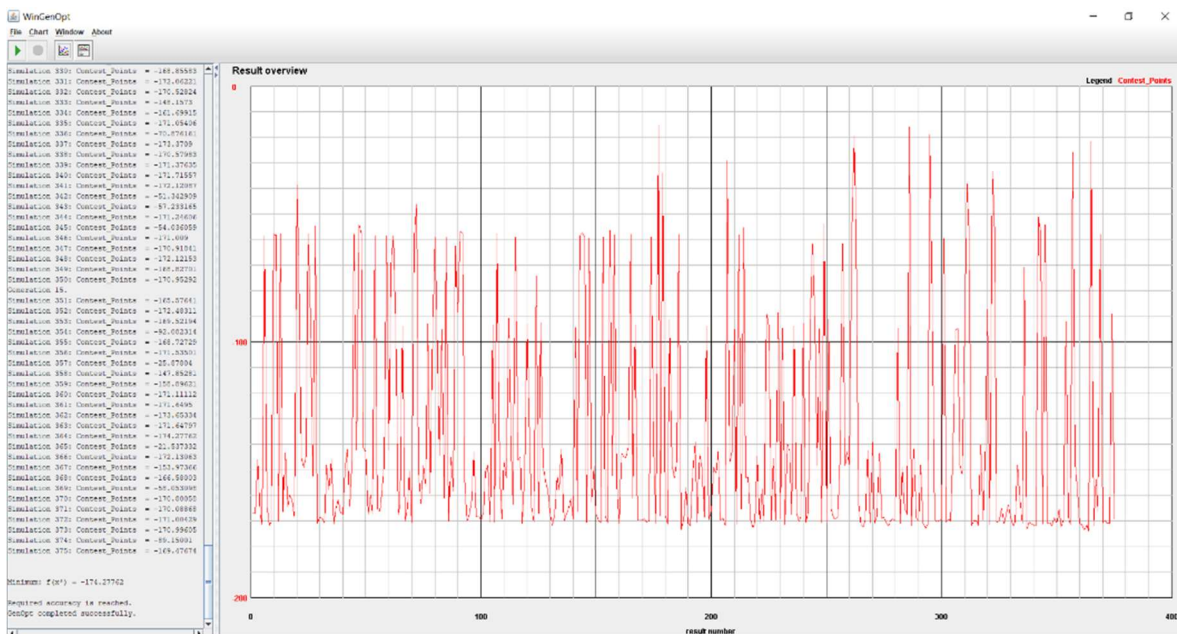


Figure 83: Optimization 7

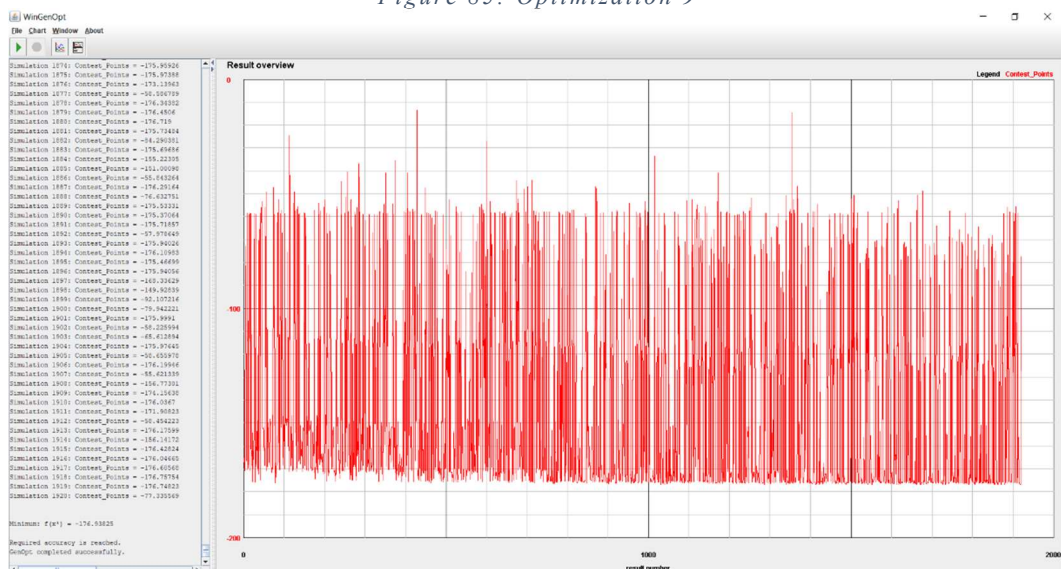
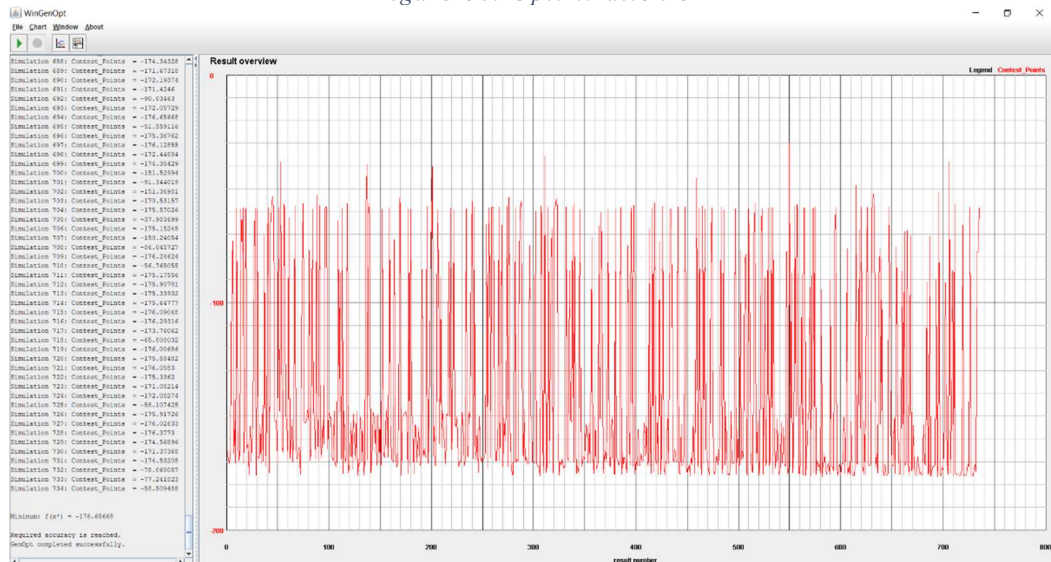
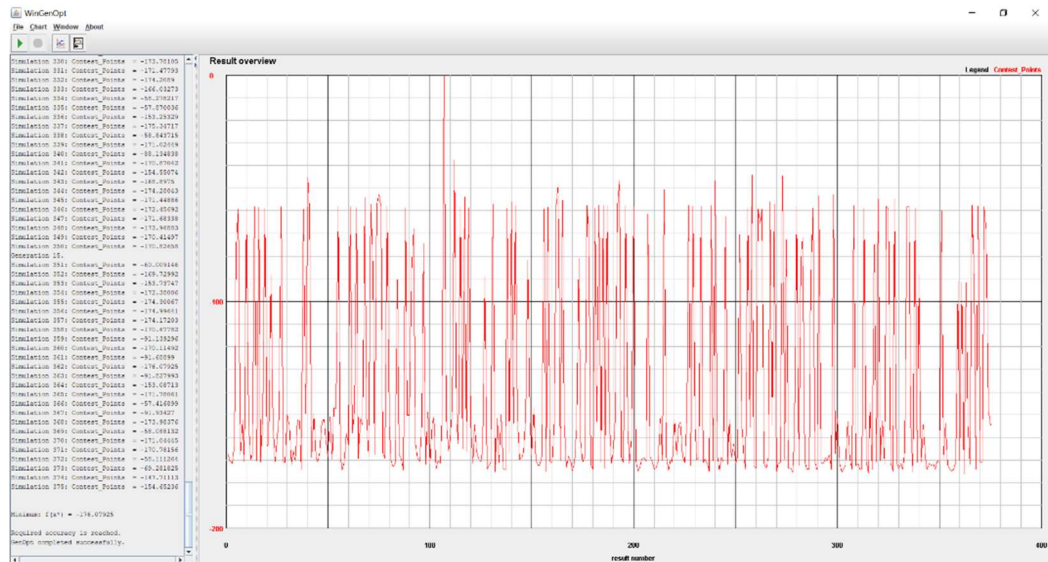


Table 19: Results of the simulations 7 - 10

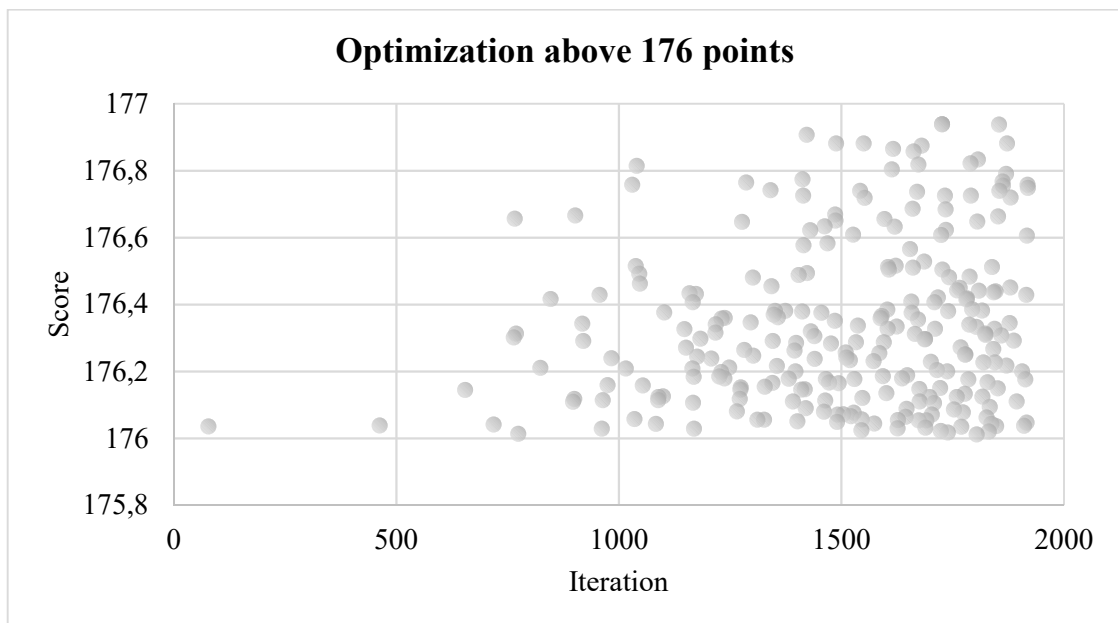
Variable	Opt 7	Opt 8	Opt 9	Opt 10
<b>Contest Points</b>	174.2776	176.07925	176.65668	176.93825
<b>T VRV</b>	21	21	21	21
<b>Deadband VRV</b>	4	-	-	-
<b>ERV on 1</b>	18	18	17.5	16
<b>ERV on 2</b>	21	20	20	19.5
<b>ERV off 1</b>	19.5	19.5	19	19.5
<b>ERV off 2</b>	23.5	22	22	22
<b>PV angle</b>	25	25	2	25
<b>Sh N</b>	1	0	0	0
<b>Sh S</b>	1	1	0.5	0.5
<b>Sh H</b>	1	0	0.5	0
<b>Sh N on</b>	10	9	12	12
<b>Sh S on</b>	12	11	9	12
<b>Sh H on</b>	8	12	12	7
<b>Sh N off</b>	21	17	20	22
<b>Sh S off</b>	21	19	22	19
<b>Sh H off</b>	22	22	22	22
<b>OSB N</b>	0.012	0.048	0.012	0.036
<b>OSB S</b>	0.012	0.036	0.036	0.036
<b>OSB Roof</b>	0.048	0.024	0.012	0.036
<b>OSB</b>	0.048	0.036	0.036	0.024
<b>INS N</b>	0.1	0.1	0.1	0.12
<b>INS S</b>	0.12	0.14	0.22	0.12
<b>INS H</b>	0.24	0.18	0.1	0.14
<b>INS</b>	0.16	0.1	0.14	0.1
<b>INS int</b>	0.2	0.18	0.22	0.18
<b>NeighborhoodSize</b>	5	5	5	5
<b>N° of Particle</b>	20	20	40	60
<b>N° of Generation</b>	15	15	15	30
<b>Seed</b>	1	1	1	1
<b>CognitiveAcceleration</b>	2.5	2.5	2	1.49618
<b>SocialAcceleration</b>	1.5	1.5	2	1.49618
<b>MaxVelocityGainContinuous</b>	0.5	0.5	0.5	0.5
<b>MaxVelocityDiscrete</b>	4	4	4	4
<b>InitialInertiaWeight</b>	1.2	1.2	0.9	0.7298
<b>FinalInertiaWeight</b>	0	0	0	0
<b>MaxIteration</b>	100	100	100	100
<b>MaxEqualResults</b>	5	5	5	5
<b>Time [h]</b>	11:35	13:05	25:48	65:22
<b>Iterations</b>	375	375	734	1920
<b>Iteration of minimum</b>	364	362	695	1726

The **results** show that the maximum value is higher with the adjustments, and with a bigger swarm, around **176.5**. There are a lot of combinations which lead to a better configuration, near the minimum; such a big number of minima requires a big exploration of the solution space; therefore, a higher number of particles could be beneficial.

After few trials the upper limit of the **OSB** has been reduced to 0.036, otherwise the final wall will be too big, because the purpose of this work is to achieve the highest possible score, maintaining the features of practical feasibility and construction.

**Last simulations** have been carried with a growing number of iterations, increasing the number of particles up to 60, and the number of generations up to 30, allowing 1920 iterations [24]; it has also a test on velocity coefficients, both equal to 1.49618, and the inertial weight equal to 0.7298, as suggested from a study about the particle swarm optimization [23]. On the long-term run, the values are refined, from the figure 85, it is clear that the last generations are catching more effective scores, near maximum, pushing it a little bit further, demonstrating the good choice about the higher number of iterations.

Last, but not least, there is a visible positive effect of the optimization with respect to the result, which is another evidence to the possibility behind this tool.



*Figure 87: Best points of last optimization*

## 5.2 Design Variation

The tool provides a method, not applicable just for this prototype, to make some decisions. One of the problems encountered during the contest, was the mismatch between the data of the **weather file**, of the city Raoyang, recommended by the committee, because there was no file for Dezhou, and the real weather conditions. The weather was hottest, more humid, and more covered, therefore the power needed for the cooling was higher, with higher consumption too, and the electricity production less than expected, in fact it has rained for 2 days. With a **safety range** on the design for the cooling power, and an accurate energy management, the team has been able to face all the problems in a brilliant way, without losing valuable scores, and confirming the strength of the optimization.

Since the time required for the development is high, there was no time to prepare changes on the structure of the project, because it involves a lot of test, check on different practical feasibilities of the modifications, and new arrangements with sponsors. Therefore, some of the suggestions given by the optimizations, mainly on the envelope, are just **theoretical**; they cannot be implemented, but they are not worthless, actually they are useful for the research, to learn new information about the correct design for the future studies. On the other hand, there are some **practical** parameters, belonging to the side of the **management** of the engineering system.

The outputs from the optimizations are very interesting, some of them are predictable, other outcomes are unexpected.

- An earlier operation of the ERV, seems a constant feature to ensure the air quality score, but to keep the consumption low, it is not acceptable, therefore the time is reduced to a littler range;
- The temperature setpoint of the VRV, in the maximum configuration, is always set to 21, because the solar radiation, and the heat stored during the day, are enough to rise the temperature fast, without exceeding with the consumption, while a lower temperature is totally out of the reasonable range.



- PV panels' tilt angle usually is set to higher value, because the production is better. The angle was 2° because the higher one can cause shading on the other panel, making necessary a space between the panels, reducing the area available. This factor should be implemented on the choice, higher angles do not mean obligatory higher production (because there is a smaller number of panel).
- The shadings on the north façade are not important, while the others (south and horizontal), must be used at half of their capability, to avoid the solar radiation, that is a quite challenging heat gain for this contest; the insulation is not so problematic in the north and south façades, because the areas of the opaque walls is little, while it becomes important for the roof, again for the solar radiation, which is connected to the shadings outcomes. They have been convenient for the energy management during the contest phases, having an objective feedback for the last-minute decisions.

Checking the last results and considering all the simulations in which the final score is higher than 176, the mean values of the variables are:

*Table 20: Design variation*

<b>Variable</b>	<b>Mean Value</b>	<b>Variable</b>	<b>Mean Value</b>
<b>T VRV</b>	21	<b>Sh N off</b>	20
<b>ERV on 1</b>	16.5	<b>Sh S off</b>	19
<b>ERV on 2</b>	19.5 - 20	<b>Sh H off</b>	21
<b>ERV off 1</b>	19.5	<b>OSB N</b>	0.036
<b>ERV off 2</b>	22	<b>OSB S</b>	0.036
<b>PV angle</b>	20 - 25	<b>OSB Roof</b>	0.036
<b>Sh N</b>	0	<b>OSB</b>	0.024
<b>Sh S</b>	0.5	<b>INS N</b>	0.14 - 0.16
<b>Sh H</b>	0.5	<b>INS S</b>	0.12 - 0.14
<b>Sh N on</b>	11 - 12	<b>INS H</b>	0.14 - 0.16
<b>Sh S on</b>	11 - 12	<b>INS</b>	0.10 - 0.12
<b>Sh H on</b>	7 - 8	<b>INS int</b>	0.18 - 0.20

For the next constructions of the house, the new parameters' values can be updated to improve the envelope, achieving the top-performing prototype.

## 6. Conclusion

Summing up all the aspects and features from this work, the advantages demonstrated are important, in a specific context, like an international competition, or a research on a certain design, every improvement adds more value to the work itself, especially in this case, where a single point can change the outcome of the competition, since our team has won with a deviation less than 12 points (11.31) out of 1000.

The more the model is accurate, the more the results will be effective. The coupling between the two works, the **calibration** [25], and this one, the **optimization**, is fundamental to high level of design. There are many experiences about some mistakes between the simulations and the real behaviour. This work is very useful, it uses an upgrade to the traditional simulation approach, showing an appreciable improvement to the reachable score. The combination of design and operational variables has been demonstrated very successful for the goal of the project. Many other simulations can be performed, exploring more and more the possible coefficients of the algorithm, and the parameters of the swarm, trying with some computational expensive try, to see the best configurations. It could seem a time expensive method, but the time saving with respect to the combination of the variable is huge, taking into account the optimized result obtained.

A **sensitivity analysis** can also help to choose the correct parameters, and which one should have a bigger range, or a refined mesh of variation.

Since the effectiveness of the tool has been proven quite well, there are some possible further implementations. First, the tool can be applied to other **prototype**, fine-testing building, and, of course, should be used for other **competitions**. Another kind of test could be the test of the prototype, in different **scenarios** and **environments**, along with the optimization, to have a comparison on the differences to the results, but also to test and make some preliminary analysis for the possible introduction to the **market** in other countries for a renovation of the urban context.



## Appendix

### MATLAB Code

```
clear all
close all
clc

%load inputs
open Cost_Function.out
Input = importdata('Cost_Function.out');
Matrix = Input.data;
Time = Matrix(:,1);
T_Living = Matrix(:,2);
T_Kitchen = Matrix(:,3);
T_Bed1 = Matrix(:,4);
T_Bed2 = Matrix(:,5);
Signal_VRV1 = Matrix(:,6);
Signal_VRV2 = Matrix(:,7);
RH_Living = Matrix(:,8);
RH_Kitchen = Matrix(:,9);
RH_Bed1 = Matrix(:,10);
RH_Bed2 = Matrix(:,11);
Energy_Balance = Matrix(end,12);
Signal_ERV = Matrix(:,13);
Signal_party = Matrix(:,14);
Energy_Consumption = Matrix(end,15);
Signal_party(8581:8640) = 0;
Signal_party(11461:11520) = 0;
Signal_party(17220:17280) = 0;

%Initialize
aa = 40*24/744; %point Temp
day = 1;
time_end = Time(1)+24;
T1 = 0; %°C
T2 = 0; %°C
T3 = 0; %°C
T4 = 0; %°C
bb = 20*24/744; %20*24/744 point RH/CO2/PM2.5
RH1 = 0;
RH2 = 0;
RH3 = 0;
RH4 = 0;
CO2_1 = 0;
CO2_2 = 0;
CO2_3 = 0;
CO2_4 = 0;
PM_1 = 0;
PM_2 = 0;
PM_3 = 0;
PM_4 = 0;
nStep = 0;
Points_Temp = 0;
Points_RH = 0;
Points_CO2 = 0;
Points_PM = 0;
```

```

% Points_water = 0;
% cc = 0.5*6.250; %point DHW
C_b = 400; %ppm
Flow_ERV = 360 ; %m3/h
Flow_room = Flow_ERV/4; %m3/h
Flow_open_house = 90; %m3/h
V_03 = 40.3; %m3
V_06 = 48.4; %m3
V_11 = 48.5; %m3
V_12 = 43.8; %m3
Signal_VRV = Signal_VRV1+Signal_VRV2;
EPS_Vent = 0.8;
num_pp1 = 5;
qi_CO2 = 0.02; %m3/h/person
tt = 0;
tt_star = 0;
timestep = Time(2)-Time(1); %h
counter_0 = 0;
CO2_06_build = C_b;
CO2_03_0 = C_b;
CO2_03 = CO2_03_0*ones(1,600);
CO2_06_0 = C_b;
CO2_06 = CO2_06_0*ones(1,600);
CO2_11_0 = C_b;
CO2_11 = CO2_11_0*ones(1,600);
CO2_12_0 = C_b;
CO2_12 = CO2_12_0*ones(1,600);
PP = 0.02;
PM_out = 200;
PM_ERV = PM_out*PP;
PM_03 = PM_out*ones(1,600);
PM_06 = PM_out*ones(1,600);
PM_11 = PM_out*ones(1,600);
PM_12 = PM_out*ones(1,600);
PM_0 = PM_out*ones(4,3); %fasi: Build-up > ERV > VRV_noERV

for ii = 600:length(Time)

    % CO2 + PM2.5
    n_03_open = (Flow_open_house/V_03);
    n_03 = (Flow_room/V_03)*(Signal_ERV(ii)==1)+... %ERV ON
        n_03_open*(Signal_VRV(ii)<1 && Signal_ERV(ii)<1)... %Build-up
        +0.15*(Signal_VRV(ii)==1 && Signal_ERV(ii)<1); %ERV OFF/VRV ON %ACH

    n_06_open = (Flow_open_house/V_06); %ACH
    n_06 = (Flow_room/V_06)*(Signal_ERV(ii)==1)+... %ERV ON
        n_06_open*(Signal_VRV(ii)<1 && Signal_ERV(ii)<1)... %Build-up
        +0.15*(Signal_VRV(ii)==1 && Signal_ERV(ii)<1); %ERV OFF/VRV ON %ACH

    n_11_open = (Flow_open_house/V_11); %ACH
    n_11 = (Flow_room/V_11)*(Signal_ERV(ii)==1)+... %ERV ON
        n_11_open*(Signal_VRV(ii)<1 && Signal_ERV(ii)<1)... %Build-up
        +0.15*(Signal_VRV(ii)==1 && Signal_ERV(ii)<1); %ERV OFF/VRV ON %ACH

    n_12_open = (Flow_open_house/V_12); %ACH
    n_12 = (Flow_room/V_12)*(Signal_ERV(ii)==1)+... %ERV ON
        n_12_open*(Signal_VRV(ii)<1 && Signal_ERV(ii)<1)... %Build-up

```

```

+0.15*(Signal_VRV(ii)==1 && Signal_ERV(ii)<1); %ERV OFF/VRV ON %ACH

counter = 1*(Signal_ERV(ii)==1)...
+2*(Signal_VRV(ii)<1 && Signal_ERV(ii)<1)...
+3*(Signal_VRV(ii)==1 && Signal_ERV(ii)<1);
if counter ~= counter_0
    tt = 0;
    tt_star = 0;
end
counter_0 = counter;

if counter == 1 %ERV ON

    CO2_03(ii) = C_b...
        +(CO2_03_build - C_b)*exp(-EPS_Vent*n_03*tt); %ppm
    if Signal_party(ii)~=Signal_party(ii-1)
        tt_star = 0;
    end
    CO2_06(ii) = C_b + (1000000*qi_CO2*10/EPS_Vent/V_06/n_06_open)*Signal_party(ii)...
        +(CO2_06_build - C_b...
            -(1000000*qi_CO2*10/EPS_Vent/V_06/n_06_open)*Signal_party(ii))...
            *exp(-EPS_Vent*n_06*tt_star); %ppm
    CO2_11(ii) = C_b...
        +(CO2_11_build - C_b)*exp(-EPS_Vent*n_11*tt); %ppm
    CO2_12(ii) = C_b...
        +(CO2_12_build - C_b)*exp(-EPS_Vent*n_12*tt); %ppm
    PM_03(ii) = PM_ERV + (PM_0(1,1)-PM_ERV)*exp(-EPS_Vent*n_03*tt); %ug/m3
    PM_06(ii) = PM_ERV + (PM_0(2,1)-PM_ERV)*exp(-EPS_Vent*n_06*tt); %ug/m3
    PM_11(ii) = PM_ERV + (PM_0(3,1)-PM_ERV)*exp(-EPS_Vent*n_11*tt); %ug/m3
    PM_12(ii) = PM_ERV + (PM_0(4,1)-PM_ERV)*exp(-EPS_Vent*n_12*tt); %ug/m3
    tt = tt+timestep;
    tt_star = tt_star+timestep;
    CO2_03_0 = CO2_03(ii);
    CO2_06_0 = CO2_06(ii);
    CO2_11_0 = CO2_11(ii);
    CO2_12_0 = CO2_12(ii);
    PM_0(:,2) = [PM_03(ii); PM_06(ii); PM_11(ii); PM_12(ii)];

elseif counter == 2 %Build-up
    CO2_03(ii) = C_b + 1000000*qi_CO2*num_pp1/EPS_Vent/V_03/n_03...
        +(-1000000*qi_CO2*num_pp1/EPS_Vent/V_03/n_03)*exp(-EPS_Vent*n_03*tt); %ppm
    CO2_06(ii) = CO2_06_0 + 1000000*qi_CO2*num_pp1/EPS_Vent/V_06/n_06...
        +(-1000000*qi_CO2*num_pp1/EPS_Vent/V_06/n_06)*exp(-EPS_Vent*n_06*tt); %ppm
    CO2_11(ii) = C_b + 1000000*qi_CO2*num_pp1/EPS_Vent/V_11/n_11...
        +(-1000000*qi_CO2*num_pp1/EPS_Vent/V_11/n_11)*exp(-EPS_Vent*n_11*tt); %ppm
    CO2_12(ii) = C_b + 1000000*qi_CO2*num_pp1/EPS_Vent/V_12/n_12...
        +(-1000000*qi_CO2*num_pp1/EPS_Vent/V_12/n_12)*exp(-EPS_Vent*n_12*tt); %ppm
    PM_03(ii) = PM_out + (PM_0(1,3)-PM_out)*exp(-EPS_Vent*n_03*tt); %ug/m3
    PM_06(ii) = PM_out + (PM_0(2,3)-PM_out)*exp(-EPS_Vent*n_06*tt); %ug/m3
    PM_11(ii) = PM_out + (PM_0(3,3)-PM_out)*exp(-EPS_Vent*n_11*tt); %ug/m3
    PM_12(ii) = PM_out + (PM_0(4,3)-PM_out)*exp(-EPS_Vent*n_12*tt); %ug/m3
    tt = tt+timestep;
    PM_0(:,1) = [PM_03(ii); PM_06(ii); PM_11(ii); PM_12(ii)];
    CO2_03_build = CO2_03(ii);
    CO2_06_build = CO2_06(ii);
    CO2_11_build = CO2_11(ii);
    CO2_12_build = CO2_12(ii);

```

```

elseif counter == 3 %ERV OFF/VRV ON
    CO2_03(ii) = C_b + (CO2_03_0-C_b)*exp(-EPS_Vent*n_03*tt); %ppm
    CO2_06(ii) = C_b + (CO2_06_0-C_b)*exp(-EPS_Vent*n_06*tt); %ppm
    CO2_11(ii) = C_b + (CO2_11_0-C_b)*exp(-EPS_Vent*n_11*tt); %ppm
    CO2_12(ii) = C_b + (CO2_12_0-C_b)*exp(-EPS_Vent*n_12*tt); %ppm
    tt = tt+timestep;
    PM_03(ii) = PM_0(1,2); %ug/m3
    PM_06(ii) = PM_0(2,2); %ug/m3
    PM_11(ii) = PM_0(3,2); %ug/m3
    PM_12(ii) = PM_0(4,2); %ug/m3
    PM_0(:,3) = [PM_03(ii); PM_06(ii); PM_11(ii); PM_12(ii)];

end

% TEMPERATURE & RELATIVE HUMIDITY
%Collecting the Temperatures, Relative Humidities, CO2 concentrations
if Signal_VRV(ii) == 1
    nStep = nStep+1;
    T1 = T1 + T_Living(ii);
    T2 = T2 + T_Kitchen(ii);
    T3 = T3 + T_Bed1(ii);
    T4 = T4 + T_Bed2(ii);
    RH1 = RH1 + RH_Living(ii);
    RH2 = RH2 + RH_Kitchen(ii);
    RH3 = RH3 + RH_Bed1(ii);
    RH4 = RH4 + RH_Bed2(ii);
    CO2_1 = CO2_1 + CO2_03(ii);
    CO2_2 = CO2_2 + CO2_06(ii);
    CO2_3 = CO2_3 + CO2_11(ii);
    CO2_4 = CO2_4 + CO2_12(ii);
    PM_1 = PM_1 + PM_03(ii);
    PM_2 = PM_2 + PM_06(ii);
    PM_3 = PM_3 + PM_11(ii);
    PM_4 = PM_4 + PM_12(ii);
end

if Time(ii) >= time_end
    if day > 1
        aa = 40*56/744*Signal_VRV1(ii)+40*40/744*Signal_VRV2(ii);
        bb = 20*56/744*Signal_VRV1(ii)+20*40/744*Signal_VRV2(ii);
    end
    day = day + 1;
    time_end = time_end+24;
    T1 = sum(T1)/nStep;
    T2 = sum(T2)/nStep;
    T3 = sum(T3)/nStep;
    T4 = sum(T4)/nStep;
    RH1 = sum(RH1)/nStep;
    RH2 = sum(RH2)/nStep;
    RH3 = sum(RH3)/nStep;
    RH4 = sum(RH4)/nStep;
    CO2_1 = sum(CO2_1)/nStep;
    CO2_2 = sum(CO2_2)/nStep;
    CO2_3 = sum(CO2_3)/nStep;
    CO2_4 = sum(CO2_4)/nStep;
    PM_1 = sum(PM_1)/nStep;
    PM_2 = sum(PM_2)/nStep;
    PM_3 = sum(PM_3)/nStep;

```

```

PM_4 = sum(PM_4)/nStep;
T_max = max([T1, T2, T3, T4]);
RH_max = max([RH1, RH2, RH3, RH4]);
CO2_max = max([CO2_1, CO2_2, CO2_3, CO2_4]);
PM_max = max([PM_1, PM_2, PM_3, PM_4]);

%Calculate points
Points_Temp = Points_Temp + aa*((T_max >= 22) && (T_max <= 25))+...
    aa*(T_max-19)/(22-19)*((T_max >= 19) && (T_max < 22))+...
    aa*(T_max-28)/(25-28)*((T_max >= 25) && (T_max < 28));
Points_RH = Points_RH + bb*(RH_max <= 60)+...
    bb*(RH_max-70)/(60-70)*((RH_max > 60) && (RH_max < 70));
Points_CO2 = Points_CO2 + bb*(CO2_max <= 1000)+...
    bb*(CO2_max-2000)/(1000-2000)*((CO2_max > 1000) && (CO2_max < 2000));
Points_PM = Points_PM + bb*(PM_max <= 35)+...
    bb*(PM_max-75)/(35-75)*((PM_max > 35) && (PM_max < 75));
T1 = 0;
T2 = 0;
T3 = 0;
T4 = 0;
RH1 = 0;
RH2 = 0;
RH3 = 0;
RH4 = 0;
CO2_1 = 0;
CO2_2 = 0;
CO2_3 = 0;
CO2_4 = 0;
PM_1 = 0;
PM_2 = 0;
PM_3 = 0;
PM_4 = 0;
nStep = 0;
end
end

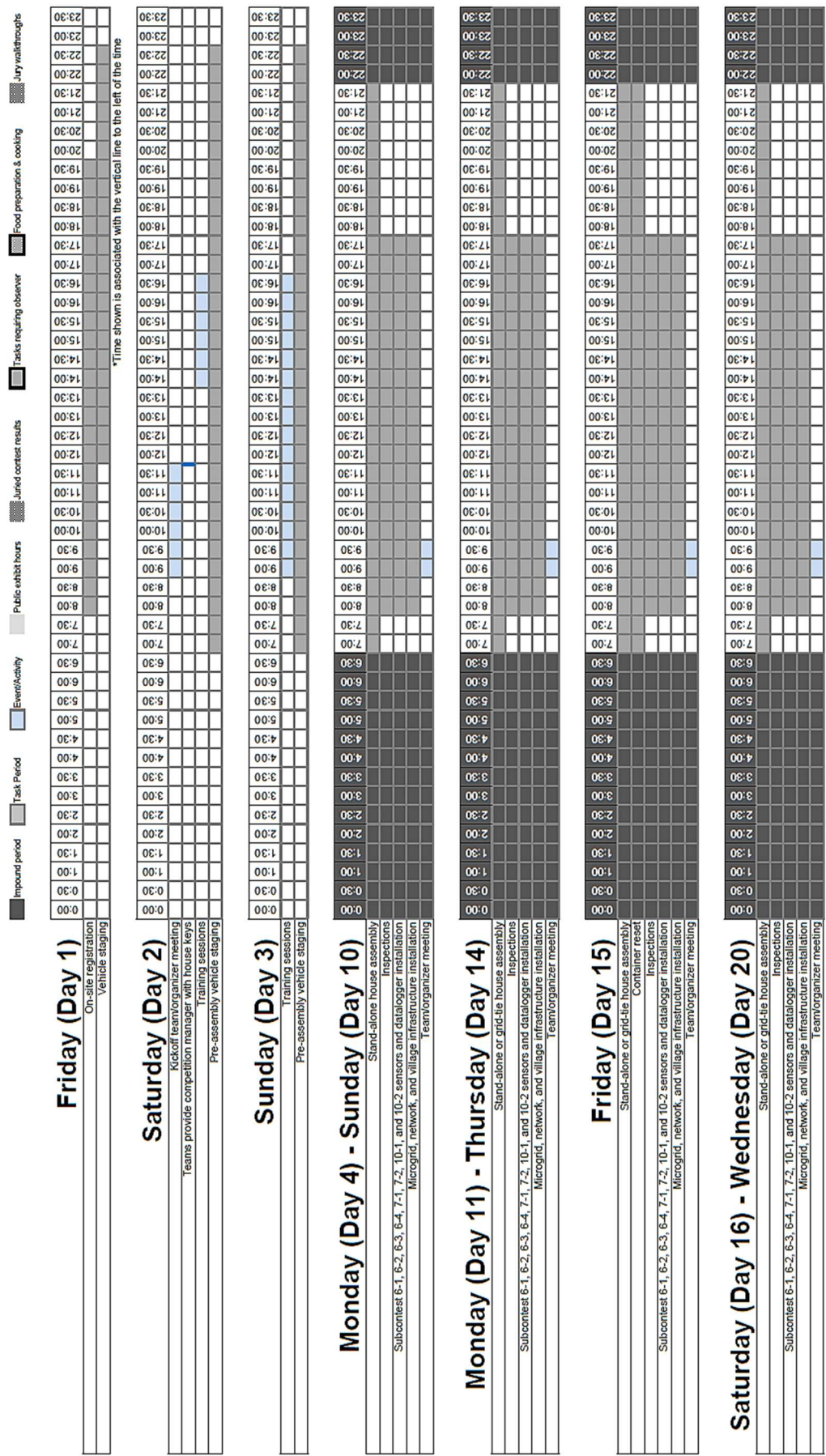
Points_Energy = 0 + 80*(Energy_Balance>0)...
+80*(Energy_Balance/50)*(Energy_Balance>-50 && Energy_Balance<0);
Max_points = 40+20+20+20+80;
Total = Points_Temp + Points_RH + Points_CO2 + Points_PM + Points_Energy;
Points = [100, -(Total)];
save('Contest_Points.txt','Points','-ascii')

mFileErrorCode = 0; % Tell TRNSYS that we reached the end of the m-file without errors
return

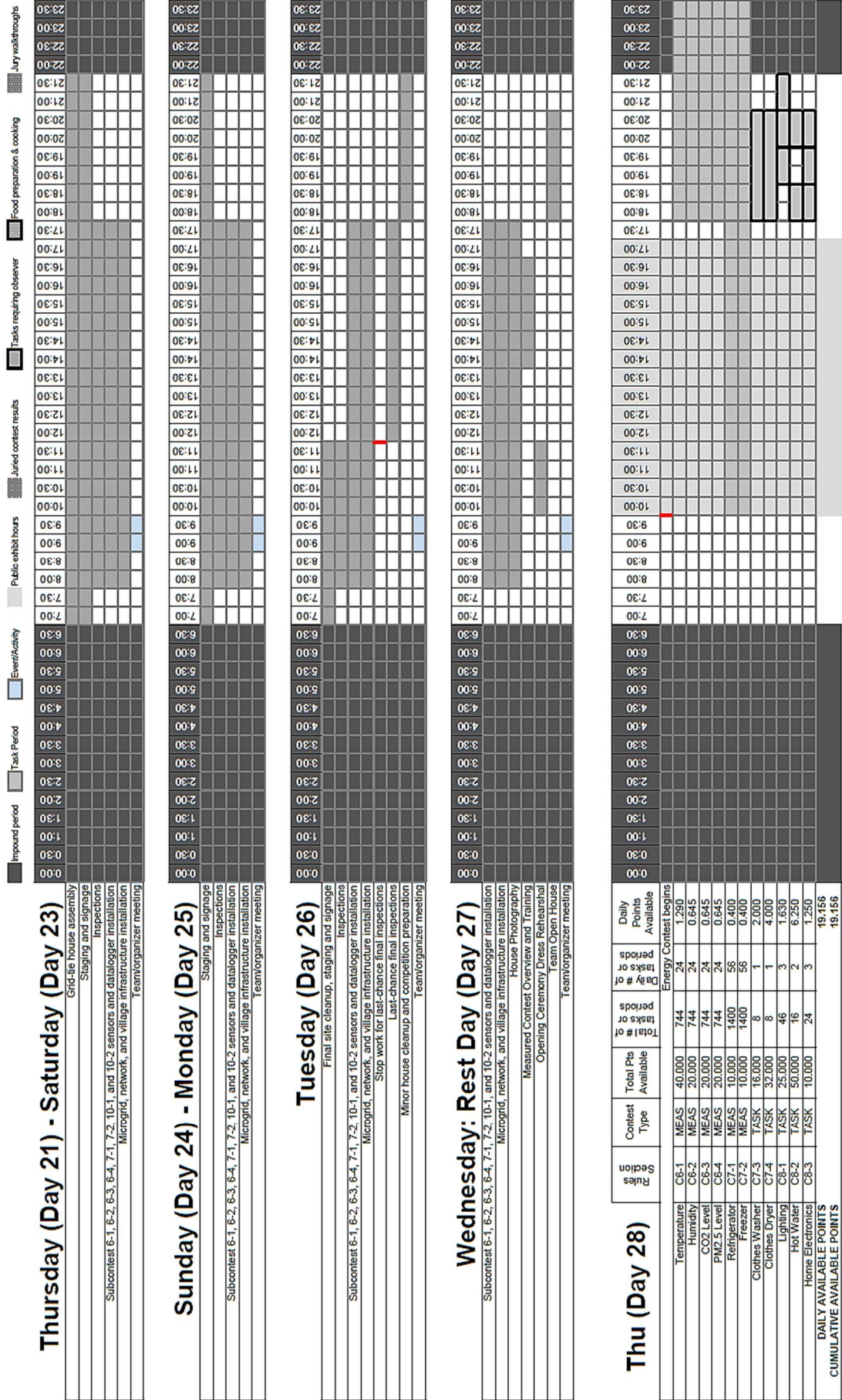
```

*Published with MATLAB® R2016a*

# Contest detailed schedule







Opening Ceremony/ VIP Tours									
Impound period	Task Period	Event/Activity	Public exhibit hours	Juned contest results	Tasks requiring observer	Food preparation & cooking	Jury walkthroughs		
Sunrise: 05:20      Sunset: 19:23									

## Fri (Day 29)

Fri (Day 29)					
Contest Type	Section Rules	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available
Temperature Humidity CO2 Level PM2.5 Level Refrigerator Freezer Clothes Washer Clothes Dryer Dishwasher Cooking Lighting Hot Water Home Electronics Commuting	C6-1	MEAS	40,000	744	3,011
	C6-2	MEAS	20,000	744	56
	C6-3	MEAS	20,000	744	56
	C6-4	MEAS	20,000	744	56
	C7-1	MEAS	10,000	1400	96
	C7-2	MEAS	10,000	1400	96
	C7-3	TASK	16,000	8	2,000
	C7-4	TASK	32,000	8	1
	C7-5	TASK	17,000	5	1
	C7-6	TASK	15,000	5	1
	C8-1	TASK	25,000	46	3
	C8-2	TASK	50,000	16	2
	C8-3	TASK	10,000	24	3
	C9	TASK	100,000	8	1
	DAILY AVAILABLE POINTS				
CUMULATIVE AVAILABLE POINTS					62,085
Team/organizer meeting					62,085
Sunrise: 05:21 Sunset: 19:22					

## Sat (Day 30)

Sat (Day 30)																														
Rules	Section	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available																								
Temperature Humidity CO2 Level PM2.5 Level Refrigerator Freezer Lighting	C6-1	MEAS	40,000	744	40	2,151																								
	C6-2	MEAS	20,000	744	40	1,075																								
	C6-3	MEAS	20,000	744	40	1,075																								
	C6-4	MEAS	20,000	744	40	1,075																								
	C7-1	MEAS	10,000	1400	96	0,696																								
	C7-2	MEAS	10,000	1400	96	0,696																								
	C8-1	TASK	25,000	46	3	1,630																								
DAILY AVAILABLE POINTS						8,378																								
CUMULATIVE AVAILABLE POINTS						70,463																								
						Team/organizer meeting																								
						Sunrise: 05:21      Sunset: 19:21																								

## Sun (Day 31)

Sun (Day 31)																														
Rules Section	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available																									
Temperature Humidity CO2 Level PM2.5 Level Refrigerator Freezer Lighting	C6-1	MEAS	40,000	744	40	2,151																								
	C6-2	MEAS	20,000	744	40	1,075																								
	C6-3	MEAS	20,000	744	40	1,075																								
	C6-4	MEAS	20,000	744	40	1,075																								
	C7-1	MEAS	10,000	1400	96	0,686																								
	C7-2	MEAS	10,000	1400	96	0,686																								
	C8-1	TASK	25,000	46	3	1,630																								
DAILY AVAILABLE POINTS						8,378																								
CUMULATIVE AVAILABLE POINTS						78,841																								
						Team/organizer meeting																								
						Sunrise: 05:20																								
						Sunset: 19:20																								



## Mon (Day 32)

Rules Section	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available
Temperature	C6-1 MEAS	40,000	744	56	3,011
Humidity	C6-2 MEAS	20,000	744	56	1,505
CO2 Level	C6-3 MEAS	20,000	744	56	1,505
PM2.5 Level	C6-4 MEAS	20,000	744	56	1,505
Refrigerator	C7-1 MEAS	10,000	1400	96	0,686
Freezer	C7-2 MEAS	10,000	1400	96	0,686
Clothes Washer	C7-3 TASK	16,000	8	1	2,000
Clothes Dryer	C7-4 TASK	32,000	8	1	4,000
Lighting	C8-1 TASK	25,000	46	3	1,630
Hot Water	C8-2 TASK	50,000	16	2	6,250
Home Electronics	C8-3 TASK	10,000	24	3	1,250
Commuting	C9 TASK	100,000	8	1	12,500
Jury Walkthroughs	C2-4 JURIED	-	-	-	-
DAILY AVAILABLE POINTS		36,529			
CUMULATIVE AVAILABLE POINTS		115,370			
		Team/organizer meeting			

Sunrise: 05:23

Sunset: 19:18

## Tue (Day 33)

Rules Section	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available
Temperature	C6-1 MEAS	40,000	744	56	3,011
Humidity	C6-2 MEAS	20,000	744	56	1,505
CO2 Level	C6-3 MEAS	20,000	744	56	1,505
PM2.5 Level	C6-4 MEAS	20,000	744	56	1,505
Refrigerator	C7-1 MEAS	10,000	1400	96	0,686
Freezer	C7-2 MEAS	10,000	1400	96	0,686
Lighting	C8-1 TASK	25,000	46	3	1,630
Dinner Parties	C8-4 SUBJ	10,000	2	1	5,000
Commuting	C9 TASK	100,000	8	1	12,500
Jury Walkthroughs	C2-4 JURIED	-	-	-	-
DAILY AVAILABLE POINTS		28,029			
CUMULATIVE AVAILABLE POINTS		143,399			
		Team/organizer meeting			

Sunrise: 05:24

Sunset: 19:17

## Wed (Day 34)

Rules Section	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available
Market Appeal	C2 SUBJ	100,000	n/a	n/a	100,000
Communications	C4 SUBJ	100,000	n/a	n/a	100,000
Temperature	C6-1 MEAS	40,000	744	56	3,011
Humidity	C6-2 MEAS	20,000	744	56	1,505
CO2 Level	C6-3 MEAS	20,000	744	56	1,505
PM2.5 Level	C6-4 MEAS	20,000	744	56	1,505
Refrigerator	C7-1 MEAS	10,000	1400	96	0,686
Freezer	C7-2 MEAS	10,000	1400	96	0,686
Clothes Washer	C7-3 TASK	16,000	8	1	2,000
Clothes Dryer	C7-4 TASK	32,000	8	1	4,000
Dishwasher	C7-5 TASK	17,000	5	1	3,400
Cooking	C7-6 TASK	15,000	5	1	3,000
Lighting	C8-1 TASK	25,000	46	3	1,630
Hot Water	C8-2 TASK	50,000	16	2	6,250
Home Electronics	C8-3 TASK	10,000	24	3	1,250
Commuting	C9 TASK	100,000	8	1	12,500

DAILY AVAILABLE POINTS	242,929
CUMULATIVE AVAILABLE POINTS	386,328
Market Appeal contest awards	
Communications contest awards	
Team/organizer meeting	
Sunrise: 05:25 Sunset: 19:16	

Contest Rules & @	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available
C6-1	MEAS	40,000	744	56	3,011
Temperature					
C6-2	MEAS	20,000	744	56	1,505
Humidity					
C6-3	MEAS	20,000	744	56	1,505
CO2 Level					
C6-4	MEAS	20,000	744	56	1,505
PM2.5 Level					
C7-1	MEAS	10,000	1400	96	0,686
Refrigerator					
C7-2	MEAS	10,000	1400	96	0,686
Freezer					
C8-1	TASK	25,000	46	4	2,174
Lighting					
C8-5	SURJ	5,000	1	1	5,000
Movie Night					
C3-5	JURIED	-	-	-	-
Jury Walkthroughs					
DAILY AVAILABLE POINTS		16,072			
CUMULATIVE AVAILABLE POINTS		402,400			
Team/organizer meeting					
Sunrise: 05:26 Sunset: 19:15					

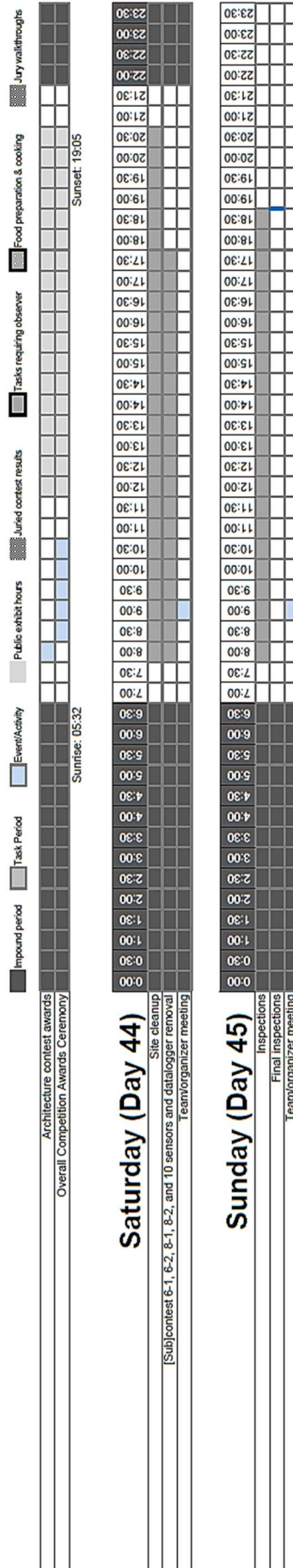
Contest Rules & @	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available
C6-1	MEAS	40,000	744	56	3,011
Temperature					
C6-2	MEAS	20,000	744	56	1,505
Humidity					
C6-3	MEAS	20,000	744	56	1,505
CO2 Level					
C6-4	MEAS	20,000	744	56	1,505
PM2.5 Level					
C7-1	MEAS	10,000	1400	96	0,686
Refrigerator					
C7-2	MEAS	10,000	1400	96	0,686
Freezer					
C7-3	TASK	16,000	8	1	2,000
Clothes Washer					
C7-4	TASK	32,000	8	1	4,000
Clothes Dryer					
C7-5	TASK	17,000	5	1	3,400
Dishwasher					
C7-6	TASK	15,000	5	1	3,000
Cooking					
C8-1	TASK	25,000	46	3	1,630
Lighting					
C8-2	TASK	50,000	16	2	6,250
Hot Water					
C8-3	TASK	10,000	24	3	1,250
Home Electronics					
C9	TASK	100,000	8	1	12,500
Commuting					
C3-5	JURIED	-	-	-	-
Jury Walkthroughs					
DAILY AVAILABLE POINTS		42,929			
CUMULATIVE AVAILABLE POINTS		446,329			
Team/organizer meeting					
Sunrise: 05:27 Sunset: 19:14					

Contest Rules & @	Contest Type	Total Pts Available	Total # of tasks or periods	Daily # of tasks or periods	Daily Points Available
C3	SURJ	100,000	n/a	n/a	100,000
Engineering					
C5	SURJ	100,000	n/a	n/a	100,000
Innovation					
C6-1	MEAS	40,000	744	40	2,151
Temperature					
C6-2	MEAS	20,000	744	40	1,075
Humidity					
C6-3	MEAS	20,000	744	40	1,075
CO2 Level					
C6-4	MEAS	20,000	744	40	1,075
PM2.5 Level					
C7-1	MEAS	10,000	1400	96	0,686
Refrigerator					
Sunrise: 05:28 Sunset: 19:13					









## References

- [1] Solar Decathlon China RULES,
- [2] M. Ferrara, E. Fabrizio, J. Virgone, M. Filippi, A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings,
- [3] W. Wu, J. Guo, J. Li, H. Hou, Q. Meng, W. Wang, A Multi-objective Optimization Design Method in Zero Energy Building Study: A Case Study Concerning Small Mass Buildings in Cold District of China,
- [4] TRNSYS Documentation,
- [5] W. Stuart Dols, B.J. Polidoro, CONTAM User Guide and Program Documentation Version 3.2
- [6] M. Ferrara, F. Dabbene, E. Fabrizio, Optimization Algorithms Supporting The Cost-Optimal Analysis: The behaviour of PSO,
- [7] U. Bau, D. Neitzke, F. Lanzerath, A. Bardow, Multi-objective optimization of dynamic systems combining genetic algorithms and Modelica: Application to adsorption air-conditioning systems
- [8] J. Kennedy, R. Eberhart, Particle Swarm Optimization,
- [9] G. Venter, J. Sobieszczanski-Sobieski, Particle Swarm Optimization,
- [10] M. Wetter, Design Optimization with GenOpt,
- [11] M. Kummert, Using GenOpt with TRNSYS 16 and Type 56,
- [12] TESS Library Documentation,
- [13] P. Tronville, G.V. Fracastoro, Energy savings and comfort in buildings IAQ and ventilation,
- [14] K. Li, L. Pan, W. Xue, H. Jiang, H. Mao, Multi-Objective Optimization for Energy Performance Improvement of Residential Buildings: A Comparative Study,
- [15] M. Ferrara, E. Fabrizio, J. Virgone, M. Filippi, Energy systems in cost-optimized design of nearly zero-energy buildings,
- [16] M. Wetter, Generic Optimization Program User Manual,
- [17] A.T. Nguyen, S. Reiter, P. Rigo, A review on simulation-based optimization methods applied to building performance analysis,
- [18] L. Magnier, F. Haghighat, Multi-objective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network,
- [19] R. Hassan, B. Cohanin, O. de Weck, G. Venter, A comparison of particle swarm optimization and the genetic algorithm,

- [20] A.P. Engelbrecht, Computational Intelligence: An Introduction, Second Edition,
- [21] M.N. Alam, Particle Swarm Optimization: Algorithm and its Codes in MATLAB,
- [22] N. Delgarm, b. Sajadi, F. Kowsary, S, Delgarm, Multi-objective optimization of the building energy performance: A simulation-based approach by means of particle swarm optimization (PSO),
- [23] F. van de Bergh, A.P. Engelbrecht, A study of particle swarm optimization particle trajectories,
- [24] A. Serani, M. Diez, C. Leotardi, D. Peri, G. Fasano, U. Iemma, E.F. Campana, On the use of synchronous and asynchronous single-objective deterministic particle swarm optimization in ship design problems,
- [25] C. Lisciandrello, Calibrated Simulation of a N-ZEB: The Solar Decathlon China 2018 SCUT-PoliTo Prototype House.