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# Optimization of energy efficiency for residential buildings by using artificial intelligence

Andrei Liviu Negrea

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# Optimization of energy efficiency for residential buildings by using artificial intelligence

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*“Success is not final; failure is not fatal:  
It is the courage to continue that counts.”*

*Winston S. Churchill*

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*“If you really look closely, most overnight successes took a long time.” – Steve Jobs*

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*"Thanks, Dad!"*

# Abstract

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Consumption, in general, represents the process of using a type of resource where savings needs to be done. Energy consumption has become one the main issue of urbanization and energy crisis as the fossil depletion and global warming put under threat the planet energy utilization.

In this thesis, an automatic control of energy was developed to reduce energy consumption in residential area and passive house buildings. A mathematical model founded on empirical measurements was developed to emphasize the behavior of a testing laboratory from UPB. The experimental protocol was carried out following actions such as: building parameters database, collecting weather data, intake of auxiliary flows while considering the controlling factors. The control algorithm is controlling the system which can maintain a comfortable temperature within the building with minimum energy consumption.

Measurements and data acquisition have been setup on two different levels: weather and buildings data. The data collection is gathered on a server which was implemented into the testing facility running a complex algorithm which can control energy consumption. The thesis reports several numerical methods for estimating the energy consumption that is further used with the control algorithm.

An experimental showcase based on dynamic calculation methods for building energy performance assessments was made in Granada, Spain, information which was later used in this thesis. Estimation of model parameters (resistances and capacities) with prediction of heat flow was made using nodal method, based on physical elements, input data and weather information. Prediction of energy consumption using state-space modeling show improved results while IoT data collection was uploaded on a Raspberry Pi system.

All these results were stable showing impressive progress in the prediction of energy consumption and their application in energy field.

Keywords: energy prediction, energy consumption, IoT, control algorithm, human behavior

# Résumé

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La consommation, en général, représente le processus d'utilisation d'un type de ressource où des économies doivent être réalisées. La consommation d'énergie est devenue l'un des principaux problèmes d'urbanisation et de crise énergétique, car l'épuisement des combustibles fossiles et le réchauffement climatique mettent en péril l'utilisation de l'énergie des plantes. Cette thèse présente une méthode d'économie d'énergie a été adoptée pour la réduction de consommation d'énergie prévu le secteur résidentiel et les maisons passives. Un modèle mathématique basé sur des mesures expérimentales a été développé pour simuler le comportement d'un laboratoire d'essai de l'UPB. Le protocole expérimental a été réalisé à la suite d'actions telles que : la construction de bases de données sur les paramètres, la collecte de données météorologiques, l'apport de flux auxiliaires tout en considérant le comportement humain.

L'algorithme de contrôle-commande du système est capable de maintenir une température constante à l'intérieur du bâtiment avec une consommation minimale d'énergie. Les mesures et l'acquisition de données ont été configurées à deux niveaux différents : les données météorologiques et les données sur les bâtiments. La collection de données est faite sur un serveur qui a été mis en œuvre dans l'installation de test en cours d'exécution d'un algorithme complexe qui peut fournir le contrôle de consommation d'énergie.

La thèse rapporte plusieurs méthodes numériques pour envisage la consommation d'énergie, utilisée avec l'algorithme de contrôle. Un cas expérimental basé sur des méthodes de calcul dynamiques pour les évaluations de performance énergétique de construction a été faite à Grenade, en Espagne, l'information qui a été plus tard utilisée dans cette thèse. L'estimation des paramètres R-C avec la prévision du flux de chaleur a été faite en utilisant la méthode nodal, basée sur des éléments physiques, des données d'entrée et des informations météorologiques. La prévision d'énergie de consommation présent des résultats améliorés tandis que la collecte de données IoT a été téléchargée sur une carte à base de système de tarte aux framboises. Tous ces résultats ont été stables montrant des progrès impressionnants dans la prévision de la consommation d'énergie et leur application en énergie.

Mots-clés : prévision énergétique, consommation d'énergie, IoT, algorithme de contrôle, comportement humain

# Nomenclature

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## Notational conventions

$x, y, z$	Scalars
$\mathbf{x}, \mathbf{y}, \mathbf{z}$	Vectors
$\mathbf{A}, \mathbf{B}, \mathbf{C}$	Matrices or fuzzy inputs, set of rules
$\mathbb{R}$	Fuzzy output, by composing fuzzy inputs and set of rules
$\mathbb{R}^q$	Space of dimension $q$

## Notations

$\mathbf{A}^T$	Matrix transpose
$\mathbf{A}^{-1}$	Matrix inverse
$\mathbf{A}^{-1/2}$	$(\mathbf{A}^{1/2})^{-1}$
$\mathbf{A}^{-T/2}$	$(\mathbf{A}^{-1/2})^T$
$\det(\mathbf{A})$	Determinant of the matrix $\mathbf{A}$
$\text{tr}(\mathbf{A})$	Trace of the matrix $\mathbf{A}$
$\dot{\mathbf{x}}$	Time derivative of the vector $\mathbf{x}$
$\partial \mathbf{x} / \partial \theta_i$	Partial derivative of $\mathbf{x}$ with respect to $\theta_i$
$\text{diag}(a_1, a_2, \dots, a_N)$	Diagonal matrix with diagonal values $a_1, a_2, \dots, a_N$
$\mathbb{E}(\mathbf{x})$	Expected value of a random variable $\mathbf{x}$
$\mathbb{V}(\mathbf{x})$	Variance of a random variable $\mathbf{x}$
$\mathbb{V}(\mathbf{x}, \mathbf{y})$	Covariance between the random variables $\mathbf{x}$ and $\mathbf{y}$
$p(\mathbf{x})$	Probability density function (pdf) of a random variable $\mathbf{x}$
$p(\mathbf{x} \mathbf{y})$	Conditional pdf of the vector $\mathbf{x}$ given the vector $\mathbf{y}$
$\mathbf{x} \sim p(\mathbf{x})$	Random variable $\mathbf{x}$ with probability distribution $p(\mathbf{x})$
$\mathcal{N}(\mathbf{m}, \mathbf{P})$	Gaussian pdf with mean vector $\mathbf{m}$ and covariance matrix $\mathbf{P}$
$\mathcal{G}(a, b)$	Gamma distribution with shape $a$ and expected value $b$
$\beta(a, b, \theta^{\min}, \theta^{\max})$	Beta distribution with shape parameters $a$ and $b$ , lower bound $\theta^{\min}$ and upper bound $\theta^{\max}$
$\mathcal{U}(\theta^{\min}, \theta^{\max})$	Uniform distribution between the lower bound $\theta^{\min}$ and upper bound $\theta^{\max}$
$\propto$	Proportional
$\approx$	Approximately equal
$\mathbf{x}_{1:N}$	Set of values $\mathbf{x} = [\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_N]$
$\mathbf{F}(\mathbf{x})$	Function of the states $\mathbf{x}$
$\mathbf{u}$	Inputs
$\mathbf{P}$	Active power

Q	Reactive power
V	Voltage
I	Current
F	Frequency
$k$	Boltzmann constant
$\Omega$	Quantum-mechanically
$h$	Convection coefficient
S	Surface
$\sigma_0$	black body radiation coefficient
T	Temperature
$\lambda$	Thermal conductivity
$Q, q_s$	Heat flux and heat surface flux
$\eta_h$	Efficiency of the heating system
$C_0$	Thermal capacity
$f_0$	Heat rate source
G	Diagonal matrix of conductance of size adequate to the number of rows of A
C	Diagonal matrix of capacitances of dimension equal to the number of columns of A
b	Vector of temperature sources location of dimension adequate to the number of rows of A
f	Vector of flow sources location of dimension equal to the number of columns of A
y	Vector of temperature outputs of dimension size A,2
$q_i(t)$	Heat flow rate density – interior
$q_e(t)$	Heat flow rate density – exterior
$\theta_i(t)$	Indoor values
$\theta_e(t)$	Outdoor values
R	Thermal resistance
$C_i$	Interior thermal capacity
$C_e$	Exterior thermal capacity



# Abbreviations

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A.I.	Artificial intelligence
ASHRAE	American society of heating, refrigerating, and air-conditioning
ANN	Artificial neural networks
ARMAX	Autoregressive moving average model
BMS	Building energy management system
CDD	Cooling Degree day
CTMS	Continuous time stochastic modelling
CRUD	Create, read, update and delete data
CMS	Content management system
CSV	Comma separated value
COSEM	Companion Specification for Energy Metering
DD	Degree day (K day)
DHW	Domestic Hot Water
EAHX	Earth to air heat exchanger
EF	Entity Framework
EU	European Union
FIRM	Impulse response models
F	Free force
HTTP	Hypertext transfer protocol
HVAC	Heating, ventilation, and air conditioning
HMI	Human machine interface
HDD	Heating degree day
HED	Heating demand (kWh)
IHG	Internal Heat Gain
IHD	In home display
IoT	Internet of things
LQR	Linear quadratic regulator
MQTT	Message queuing telemetry transport
MVHR	Mechanical ventilation with heat recovery
nZeb	Nearly zero energy building
OHL	Overall heat loss coefficient ( $\text{kW K}^{-1}$ )
OS	Operation System
PID	Proportional-integral-derivative
PI	Proportional integral
Pa	Pascals
PD	Proportional derivative
RAM	Random access memory
SDE	Standard deviation error (prediction error)

SMX	Smart meter extension
S	Entropy
SOAP	Simple object access protocol
SOA	Service oriented architecture
SBC	Smart Building Controller
SQL	Programming language
SD	Secure Digital
TFA	Treat Floor Area
TZ	Trusted zone
T	Temperature
UPB	University POLITEHNICA of Bucharest
VPN	Virtual private network
WSN	Wireless sensor network
WAN	Wide area network
WWW	World wide web
XML	Extendable markup language

# Contents

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# *CHAPTER I – Global general introduction*

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The purpose of this chapter is to present the problem of world's energy consumption, especially in urban area. This thesis responds to nowadays concerns and to the necessity to decrease the energy consumption in buildings.

The potential reduction in energy consumption in Romania shows increased potential as the statistics from EU display. The thesis outline is covered in the upcoming section, along with the control algorithms presentation.

This part gives attention to relevant data, suitable to the achievement provided in this essay.

## 1.1. State of the problem

The world's energy consumption problem has become one of the most appealing subjects in 2020 because of the progress in urbanization and advancement of networking society [1]. The planet is under serious threat due to energy crisis because of fossil energy depletion and global warming determined by harmful gases. Therefore, ideas and projects on "how to save energy", are among the most common subjects on every social debate. New ways of producing energy must be found in order to combat energy crisis.

To be more specific, energy needs to be conserved, saved and produced by other means than the actual ones [2]. In order to understand the energy laws, facts about thermodynamics need to be considered. To put it differently, energy may seem to be the problem but, from a thermodynamic point of view, the increase in entropy is the problem. In physics, energy stands for the ability of moving an object from a location X to a location Y. Location can be taken into consideration as point.

Therefore, it exists two large types of mechanical energy:

- 1) Kinetic energy (responsible for moving an object to one-half of its specific mass and the square of its velocity)
- 2) Potential energy (responsible for storing energy by multiplying mass, gravitational energy and height or location)

Energy can be transformed from one form to another while creating an additional type: thermodynamic energy. When an object is moving from its location to another with a specific velocity, kinetic energy is evacuated progressively, creating heating, representing the 1<sup>st</sup> law of thermodynamics: "In any isolated system, total energy is preserved"[3].

To put it in another illustration, there are different forms of energy:

- 1) useful (stand for kinetic, potential, chemical energy, electricity etc.).
- 2) useless (thermodynamic energy).

To clarify, we might think useful energy as a specific free-force ( $F$ ) applied to an object while useless energy is the multiplication of temperature ( $T$ ) by entropy ( $S$ ) demonstrating the 2<sup>nd</sup> law of thermodynamics: "Entropy is rising in any isolated system" [3]. Additionally, entropy can measure the energy quality inside any object.

All things considered, from a physics perspective point of view, the energy crisis is an entropy crisis due to its property of increasing in any closed system.

The subject proposed in this thesis responds to nowadays concerns and to the necessity to decrease the generated power consumption in buildings, especially in the residential sector. A data report regarding energy efficiency in buildings, realized by ENERGDATA in 2014, shows that the energy price grew with 64 % from 2004 to present. The energy costs of residential sector reached a peak of 40 % consumption for the entire Europe, while in Romania the prices were close to 44.4 % of the electricity price tag [4].

Taking into account the planet's renewable resources, the energy consumption relies on several factors: hydro, nuclear, natural gas, coal, geothermal, wind, solar and, the biggest, oil. In 2017, the global primary energy consumption is divided as shown in Fig. 1-1.

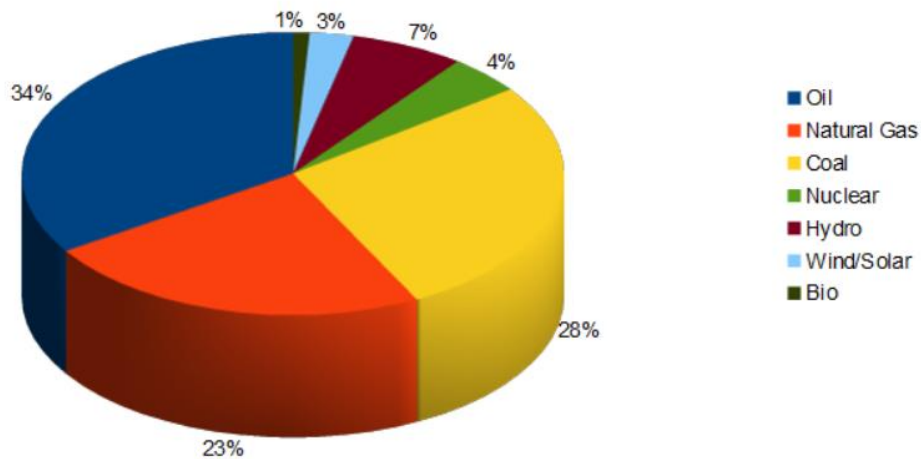


Fig. 1-1 Global primary energy utilization [5]

Due to a strategic energy action plan approved by Romania for 2007-2020 period, a potential reduction in energy consumption was identified for the residential sector. After a statistical analysis, the potential of energy reduction in Romania is estimated, depending on the sector they belong, to 30 – 50 % for residential and 13 – 19 % for tertiary sector. The consumption for space heating in buildings in Europe represents 67 % of the total energy consumed in buildings (Romania has a total consumption of 50 %), dragging attention to the potential energy savings that can be done.

Guidelines of energy savings and energy production from renewable in Romania are set up at 38 % until 2020 [6]. Romania has a potential of 43.2 % of electricity generation using technologies that involve renewable energy sources. The new strategic plan for the upcoming years is aiming to cut 20 % of energy production which is harmful for the environment. For example, 20 % cutoff from residential green-house effect gas emissions is a must until 2020. On the other hand, 20 % more energy production from unconventional sources is listed as a future priority. At the same time, smart technologies come in support from the Romanian’s energy potential proving that real time data collection, small monitoring devices or data awareness administration can increase the energy efficiency by up to 20 % [7]–[9].

Due to the high potential of energy savings, EU’s reports regarding the national targets in sharing renewable energy sources declared Romania as completing her task before the deadline. Bulgaria, Croatia and Montenegro managed to reach their targets as well, while Luxembourg and Malta are on track for reaching this goal. In Fig. 1-2, a detailed explanation regarding the gross in final energy consumption is presented, according to Eurostat.

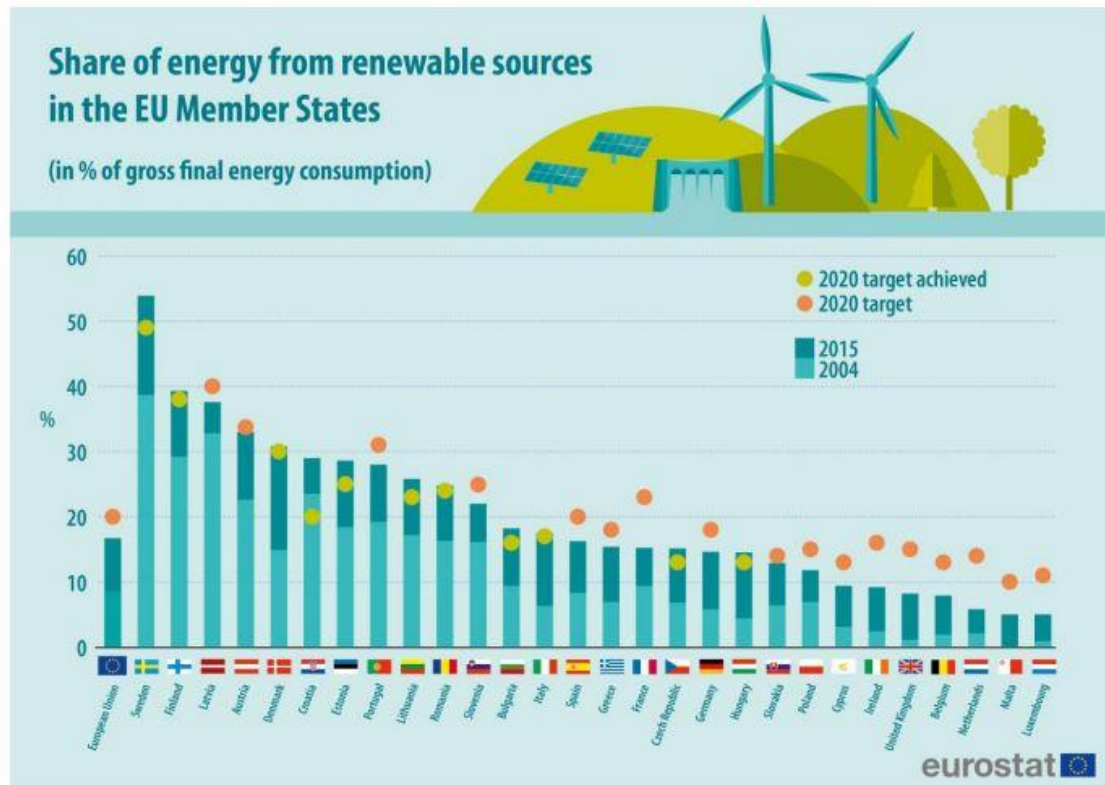


Fig. 1-2 Statistical share of energy from renewable sources in EU member states [10]

The ability of mankind to satisfy the demands of the today's generation without concession the capacity of forthcoming generation to face its own demands is defined as sustainable development [11]. The global economy has to accelerate its growth in order to improve the lifestyle and therefore the progress. The energy consumption rate is one of the major threats that EU member states are confronting, trying to develop methods to improve the energy savings. For a detailed list of global energy data, International Energy Agency is sharing useful information on their website [12].

This thesis focuses on the usage of artificial intelligence to optimize the energy performances of residential buildings, emphasizing a huge impact on sustainable development from two standpoints.

The first angle is the energy management optimization for residential buildings, representing an increase in energy efficiency that leads to sustainable development and draining renewable energy from unlimited sources.

The second angle is the integration of clean technologies through the usage of artificial intelligence to increase the energy performances in buildings. The adoption of this type of technology reduces the incidence of industrial leftovers on the environment by preventing pollution and by savings money [13]. In general, through energy efficiency we obtain:

- reduction in usage of raw materials,
- reduction in pollutant emission,
- reduction in waste,
- financial savings,
- lower interest on gas imports
- power consumption reduction

- improved air quality
- improved living conditions

Therefore, the prediction of energy demand for heating and cooling loads, presents the main factors in identifying measures to lower energy consumption. The thesis aims to develop a set of services that allows modeling, verification, and control of equipment of testing laboratory. In order to create specific conditions of thermal comfort, certain methods can be applied. These methods imply having as inputs a set of measured parameters (indoor temperature, outdoor temperature, energy consumption, solar radiation, humidity or generated energy from renewable energy sources, energy flux) and a set of building characteristics (construction material) to provide an energy prediction with low errors to lower the utilization of energy in buildings.

Residential, educational institutes and office buildings are accountable for the high energy consumption within community energy usage. Considerable amount of energy consumption should be utilized to supply energy systems in order to provide thermal comfort [14]. Moreover, when trying to discover a specific energy benchmark for residential buildings inside and outside circumstances should be taken into consideration [15], [16].

It is important to notice that thermal comfort has always been the highest consumer when talking about human needs. “*A state in which there are no driving impulses to correct the environment by the behavior*” is the characterization of thermal comfort as Hensen explained [17]. To complete the sentence, ASHRAE outlined this phenomenon as “*the condition of mind in which satisfaction is expressed with the thermal environment*” [18]. Based on the above interpretations, thermal comfort could be identified as a state of mind, body, cognitive process, and not referring to a state of condition. Among people, thermal perception may differ radically, even if they are situated in the same environment. A more reliable explanation about thermal comfort methods, physiological comfort, mathematical modeling on energy transfer between human organism and surroundings can be found on N. Djongyang paper [19].

The thesis focuses on three modes of operation for the building:

1. Passive operation, which takes into account thermal conditions using passive sources (operation of window, shutters and doors etc.).
2. Hybrid operation, which implies the simultaneous use of passive installations and active HVAC systems.
3. Mechanical operation, which consists in ensuring thermal comfort by using only the HVAC facilities available in the building.

## 1.2. **Outline of the thesis**

Firstly, a mathematical model that is based on experimental measurements to simulate the behavior of the building was developed. The system was implemented on a passive house from UPB, with a development perspective to a student campus or to a residential district, as figured in Fig. 1-3.



Fig. 1-3 Example of student campus [20] and residential district [21]

The experimental protocol was implemented by following these steps:

- Build the input parameter's database - indicating the system sensors.
- Collect weather data (solar intake, wind, humidity, cloud coverage) – for example, solar intake performs an important aspect for the laboratory, as external parameters influence the thermal compartment of the house.
- Intake of auxiliary flows (the flow injected by the HVAC system)
- Control the house temperature.



Fig. 1-4 Model for system inputs and outputs

The model for the system inputs and outputs, as presented in Fig. 1-4, is consists of three significant areas. The first part, indicated by the left side, contains information about input data of the system such as weather data and auxiliary heat flow rates. The middle part represents a mathematical model able to process the input data and to predict the future input data in order to respond with a precise output. The model is responsible for the connection between inputs and outputs. The right side is the output calculation that has double role. The output is used for:

- Harvest the necessary variables for the system (such as interior temperature or energy consumption).
- Providing the inputs for the transfer function (outputs become inputs for the function).

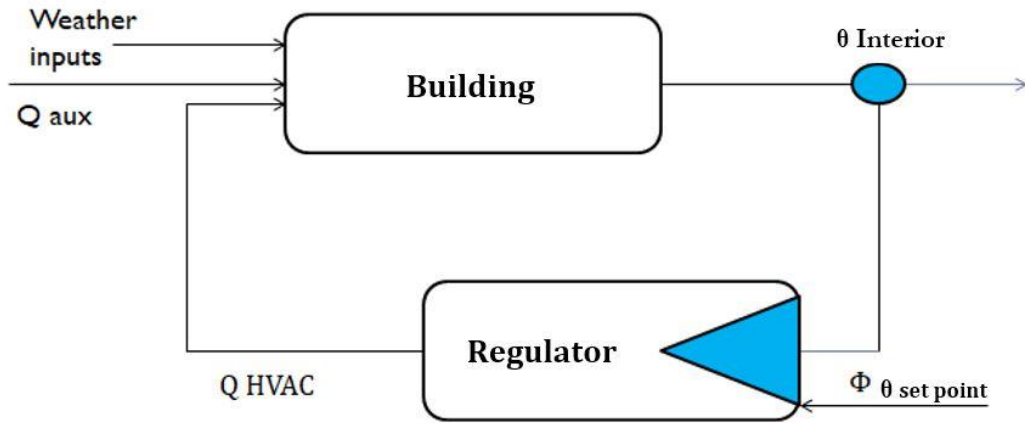


Fig. 1-5 Diagram for mathematical model in-use

A closer sample of system model for entries and outputs is exemplified in Fig. 1-5 with the implementation of a control system into the model. The HVAC heat flow rate is computed as a new input for the mathematical model to control inside temperature. Another modification to the system is the implementation of set-point temperature, as a control system for the mathematical model to receive a new input. In Fig. 1-6, a particular example of such a model is presented. The exterior heat flow is passing through the wall of the house changing into an interior temperature and outputting the flux of the system.

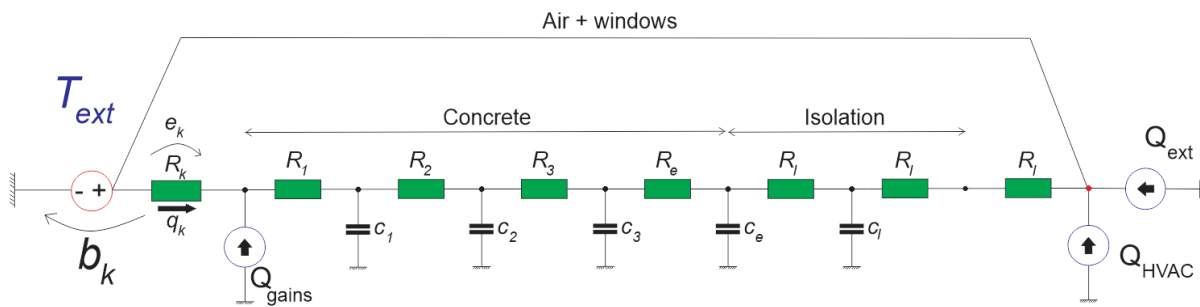


Fig. 1-6 Example of mathematical model for a specific physical part of the house



Fig. 1-7 Simple comparison between examination types [22]

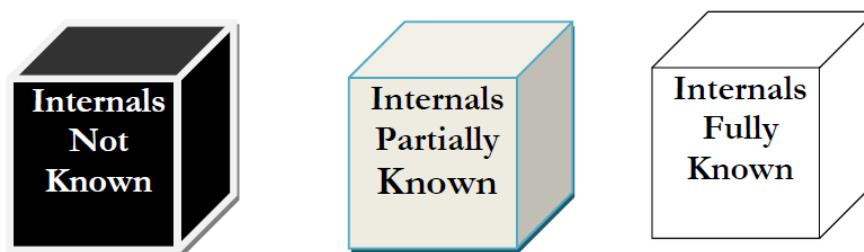


To obtain the numerical model, a full analysis of a physical phenomenon of the house is required. To solve and analyze the mathematical model, we can use several models (Fig. 1-7):

- white box – full knowledge about the implemented system,
- black box – zero knowledge about the implemented system,
- grey box – some knowledge about the implemented system, physical and statistical.

A white box model handles the thermal modeling of the building for solving the heat transfer equations. This method type is very laborious, requiring a large amount of data about the analyzed house. White box is perfectly applied in the context where there are many physical data about the building (material properties, geometry of the building, characteristics, localization, heating and cooling system). The white box type is based on nodal approaches, reviewing the functioning of the applications rather than its functionalities [23].

A black box model handles the correlation between output and input data. This correlation may give good results, but it is not scientifically justified. Within the black box, the system requires huge amount of historical data as input, while requesting none for physical interpretation [24], [25].



Comparison between the Three Testing Types

	Black Box Testing	Grey Box Testing	White Box Testing
1.	The Internal Workings of an application are not required to be known	Somewhat knowledge of the internal workings are known	Tester has full knowledge of the Internal workings of the application
2.	Also known as closed box testing, data driven testing and functional testing	Another term for grey box testing is translucent testing as the tester has limited knowledge of the insides of the application	Also known as clear box testing, structural testing or code based testing
3.	Performed by end users and also by testers and developers	Performed by end users and also by testers and developers	Normally done by testers and developers
4.	-Testing is based on external expectations -Internal behavior of the application is unknown	Testing is done on the basis of high level database diagrams and data flow diagrams	Internal workings are fully known and the tester can design test data accordingly
5.	This is the least time consuming and exhaustive	Partly time consuming and exhaustive	The most exhaustive and time consuming type of testing
6.	Not suited to algorithm testing	Not suited to algorithm testing	Suited for algorithm testing
7.	This can only be done by trial and error method	Data domains and Internal boundaries can be tested, if known	Data domains and Internal boundaries can be better tested

Fig. 1-8 Fast comparison between examination types [22][26]

A grey box model is a hybrid method that can help solving a system in a fast manner, because it is capable to simulate the house's thermal behavior and to optimize the input parameters. Using this method, the prediction of energy consumption can be scientifically justified. Typically, a grey box model is needed when a physical appearance of the residential

house is realized, when it is incomplete or does not provide enough details about the system. In Fig. 1-8 a fast comparison underlining the most important properties of each testing model.

Artificial neural networks (ANN) are frequently used in artificial intelligence (A.I.) applied on human behavior prediction application [27]. Artificial neural networks will be used to build nonlinear systems as they have the ability to adapt to specific operating mode of the building. Special attention will be given to the artificial neural network compartment during the heating/cooling of the building [28]–[30].

As a conclusion, it is fundamental to acknowledge the energy consumption of the house due to the following perspectives [31]:

- Estimation and parameters calculation of a building (sizing of thermal installation and cooling systems).
- Calculation of consumer costs.
- Optimization for reduction of costs.

Therefore, the cost forecast, starting from energy loads for heating and cooling, is important for identifying the parameters that can decrease energy consumption. Some fields of applicability are:

- Financial planning: it is important to know the costs for a month in advance. For example, the users can plan their own financial resources.
- House behavior: artificial intelligence can be used for predictive control. For example, the solar radiation can be estimated so that, if the inside temperature indicates 20 °C and the outside temperature indicates 15 °C, to decide that it's useless the usage of heating.
- Planning of exhaustible sources: if we analyze from another perspective, human behavior impacts directly the house in study. We can build scenarios in accordance with heating/cooling timetables, depending on each user behavior. As an example, we can imagine a network of residential buildings. If it is forecasted that in October the fuel reserves will end, then we can make a planning of the financial resources and we can provide fuel in a timely manner.

### 1.3. General presentation of control algorithms

Buildings efficiency is stated as energy by unit of surface, kWh/m<sup>2</sup> [32], even if EU regulation began to use carbon dioxide production (kg CO<sub>2</sub>/m<sup>2</sup>year) [33]. Regardless the fact that the building temperature can be controlled by classical control algorithms [34], intelligent energy management can learn the behavior of the building [35].

Taken into account buildings control strategies and experience, multiple domestic and outdoor disturbances have been claimed to affect the thermal behavior of any system. Thus, the main task of a controller is to adjust thermal conditions [36]. Moreover, as reported by Wong [37], specific criteria should be implemented in the interest of obtaining the desire thermal comfort depending on human knowledge or judgement.

Distinct control algorithms are behaving on various different levels such as:

- field,
- management,
- control.

In order to be fully efficient, when creating an algorithm, it is required to break the overall procedure in smaller control-command systems. For this, Salsbury separated HVAC control in central units, air pieces and terminal devices [38]. The central units are responsible for generating heating and cooling of the inside temperature using PID (proportional-integral-derivative) controller. The PID will be detailed in the upcoming sub-chapter emphasizing the response of the system with few modifications. Part of the field level control are the empirical model suitable to support dynamic prototype analysis [39]. Secondary control management level refers to all scenes of building's functionality demands like BMS (building energy management). As the system becomes flexible and complex, every buildings component can be automatically controlled [40]. With this in mind, human comfort is presented as the most significant constituent due to the rate of change [41].

### 1.3.1. Classic – PID

A PID controller is composed of:

- P, proportional controller,
- I, integrator and,
- D, differential action.

The proportional part adjusts the error through multiplication of the deviation between the set-point and the measurement with a constant. The Integrator (I) corrects the control signal by integrating the error in time. By including the integral to the systems activity, it dispels the offset but decreases the system stability. In order to combat this situation, the Differential (D) operations further introduced, rectifies the low frequency flaws collected by the Integrator. The benefit of using the Differential action is due to its ability to quickly modify errors values, disregarding the delayed values. For the purpose of getting optimal and accurate results out of a PID control, specific configuration and constant setup must be taken into account. Several auto-tuning [42], open loop steps [43] have been taken as a response, a solution for this issue, as well as adaptive algorithms [44].

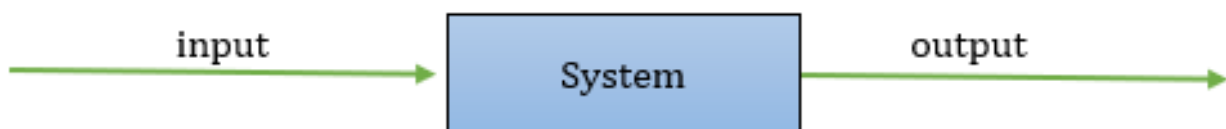


Fig. 1-9 General representation of a system

The PID interacts with system that is controlled. The system has input and output variables. Inputs are presented as the actual signal delivered to the ecosystem as long as output result are the controlled variables. The basic idea of the control system is to understand how to generate the input signal in order for the system to produce the required variable – meaning the output, as shown in Fig. 1-9:

In order to achieve the desired behavior of the system, a set-point variable, or the required values, need to be taken as reference. Additionally, the output of the system is feedbacked and compared with the set-point to assess how far off the system is from where we wanted to be. As displayed in Fig. 1-10, the difference between the feedback and the commanded variable is known as the error term. The goal of the system is to achieve zero error. This is possible by implementing a PID controller. In this regard, if applied to the goal of the thesis, the system is presented as the passive house HVAC, the output is identified as the indoor air temperature while the inputs vary in time. The set-point value the inside comfort temperature while the error is the difference between the desire temperature and the actual temperature.

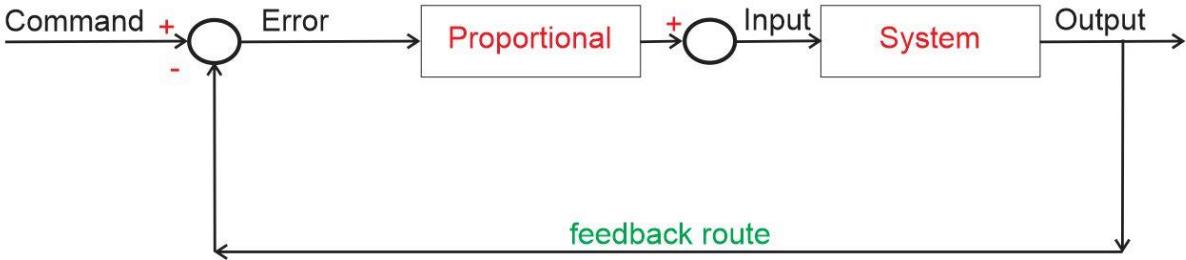


Fig. 1-10 PID controller with feedback

Moreover, a constant steady-state error may occur. Thus, to overcome this issue, an integrator uses past information as identified in Fig. 1-11. Moreover, the integrator sums up the input signal over time. As a conclusion, the proportional controller and the integrator are working together in order to drive the error down to zero. Due to a non-constant reference the system is able to lower the building consumption by varying temperature depending on whether is day or night. Therefore, the system is able to “react” and to “memorize” the past.

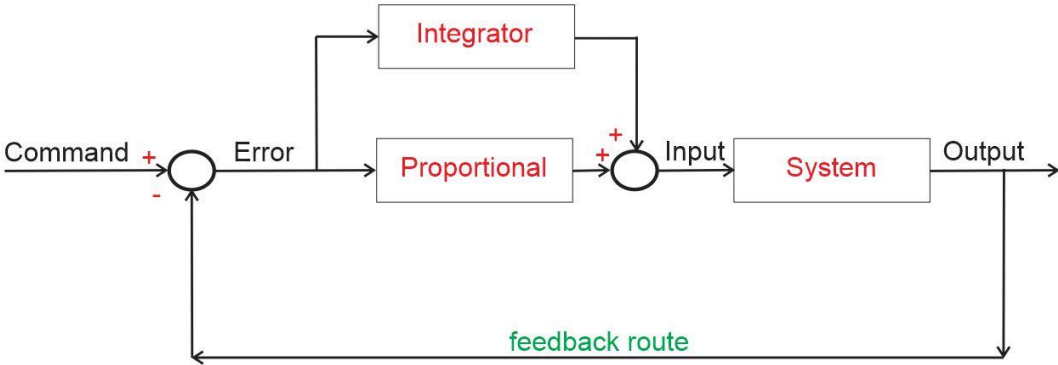


Fig. 1-11 PID controller with feedback and integrator

The time response of the system may be crucial for every user. For this, additional path must be added to the controller predicting future outputs and responding to: how fast the goal will be accomplished. Given this hypothesis, a derivative extension is required. A derivative generates a measure of the rate of variation of the error term. Therefore, the controller is using the changing error to establish the fluffiness of the necessary goal, as demonstrated in Fig. 1-12.

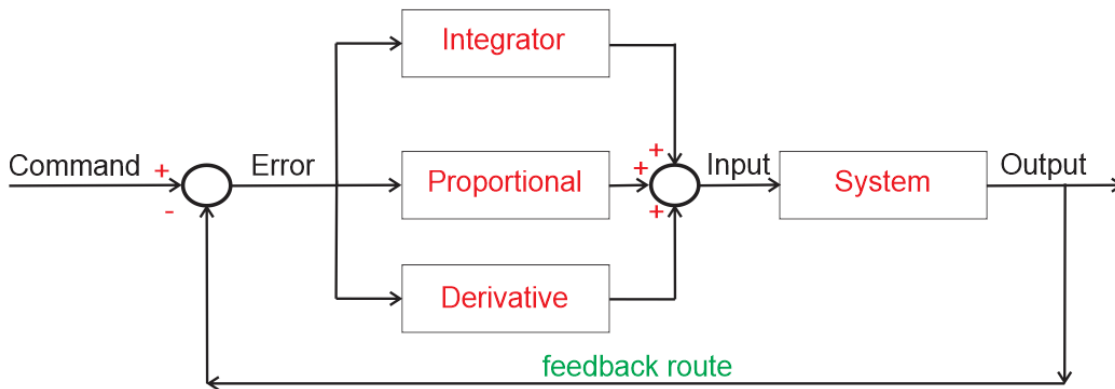


Fig. 1-12 PID controller with feedback, proportional; integral and derivative actions

To conclude, the PID controller uses the present error, the past error and the predicted of the future error to calculate the appropriate actual command values. These values contribute to the controller output with the possibility to decide the weight of each path by adjusting the respective gains. If all three paths are used, the controller is a PID. In case of using only two paths, the controller may become type PI or PD.

### 1.3.2. Modern control: state-space and optimization

The previous subchapter presented a classical PID controller while this subchapter focuses on the modern state-space representation and optimal control. One of the benefits of using state-space representation is the fact that dynamic systems can be modelled by differential equations [45]. The system property of changing at any given time is a function of its current state. For example, the way the system is changing due to acceleration it's a function of its position [46].

For an arbitrary dynamic system, we can calculate how the energy is changing by analyzing the relation between its states and derivatives [47], [48]. As an example, if the energy of the system is being dissipated over time, then we can claim the fact that the current system is stable. Moreover, the faster the energy is dissipated, the systems become stable. As mentioned before, the stability is the property of the system that the states and the derivatives are linked to each other:

$$\dot{x} = f(x) \quad (1)$$

where,

$\dot{x}$  – time derivatives and

$f(x)$  – function of the states.

To be noted that any system can be moved and influenced by external energy, like additional inputs. Hence, the derivatives of dynamic system is a function of its current states and external inputs as presented by Tashtoush [49]:

$$\dot{x} = f(x, u) \quad (2)$$

where  $u$  - inputs.

Multiple control techniques, based on state-space models, are exemplified in the literatures:

- Kalman filter explained by Simon in [50] or by Bierman in [51];
- LQR-linear quadratic regulator, as presented by Murray [52] or by Massoumy [53] for HVAC systems;
- robust control – implemented by Fusco [54] or a detailed clarification in [55],
- model predictive control – creating cooling system in [56] or by Garcia [57]

The general form of a state-space model is:

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \quad (3)$$

$$\dot{\mathbf{y}} = \mathbf{Cx} + \mathbf{Du} \quad (4)$$

Equation (3) represents the state equation while equation (4) is the observation equation. State space representation is created around the state vector  $\mathbf{x}$ . The important thing to realize is how the state vector changes, by its derivatives, due to a linear combination between current state and external inputs. After calculating and seeing how the state change as a function of all inputs and states, a system of linear first order equations is constructed in matrix form. For instance, matrix  $\mathbf{A}$  describes how all internal states are being connected to each other while  $\mathbf{B}$  matrix describes how the inputs are joining the system.

The output equation refers to system values that we want to obtain. The outputs may be, or not, the states of the system. The matrix  $\mathbf{C}$  represents a linear combination of states in order to get the outputs. On the other hand, the  $\mathbf{D}$  matrix allows the inputs to bypass the system in order to feed-forward to the output.

A key role is played by the state variable due to its numerous apparitions in the state-space equations. They are conceived as the minimum set of variables that describes the entire structure in order to accurately predict the future behavior of the system.

To conclude, a good description of the state-space representation is done by Nijssse [58], who compares the results obtained with finite impulse responses from finite impulse response models (FIRM) in air conditioning structures.

### 1.3.3. Intelligent control: fuzzy and artificial neuronal networks

The number of papers on fuzzy controlling system increased drastically. Fuzzy applications can be found in a variety of different domains, including thermal comfort, programming small board or control systems based on fuzzy logic.

Fuzzy logic algorithms are constituted by IF-THEN rules representing a closer knowledge of human behavior within the interaction with the HVAC system. For instance, a fuzzy rule may be, "if interior temperature is lower than your standard comfort and decreases rapidly, then turn the heating system on." Fuzzy algorithms are considered to be complicated code programming system in the cooperation with the user, leading to nonlinear control algorithm. Rules are made of qualitative values while nonlinear algorithms depend on quantitative variables, causing important lack of information. The benefit of using fuzzy algorithms is the ability to model complex control strategies and to transform quantitative variables into real number. Thus, a fuzzy control algorithm is a nonlinear static function. In addition, depending on the pre-setup nonlinear rules, the algorithm may be robust or not. Equally important, when knowing the variation of the parameters of the system, a fuzzy control algorithm may be developed, which can be less sensible to variations than a robust linear algorithm. Such algorithm can be compared with the theory presented by Astrom and Wittenmark [59], specifying that fuzzy control algorithm are more robust when having knowledge about the variation of process parameters.

The fact that fuzzy algorithms are suitable to nonlinear processes lies in the dependency on the chosen input variables. For example, a PID algorithm running on fuzzy logic is superior to a linear PID algorithm in tackling with the nonlinear processes, as long as the system nonlinearities are known.

On the other hand, Elkan provided a different point of view regarding the use of fuzzy algorithms, as they are characterized by multiple defaults. High number of rules, imprecise results, lack of input-output correlations [60]. As Driankov, Hellendoorn and Reinfrank stated, the problematic stability in any fuzzy control system persists [61], [62]. Another pragmatic point of view, expressed by Mandani and Pedrycz is that the demonstration of system stability in fuzzy algorithm is always reported in simple algorithms [63], [64].

An important assent and perspective point of view is related by Zadeh [65], mentioning that fuzzy logic is a form of artificial intelligence, in which neuronal networks are also included. Understanding and processing natural language of the system is part of the artificial intelligent domain, for this reason fuzzy logic belongs to A.I. sphere.

#### 1.3.3.1. Fuzzy controller

Fuzzy control systems can be approached from two perspectives: theoretically and pragmatically. This thesis will focus on pragmatically standpoint, due to local interference of fuzzy rules. A fuzzy control algorithm is considered to be a nonlinear static relation between inputs and outputs, no matter of their variation in time.

From a theoretically point, a fuzzy inference is achieved by applying a set of rules:

$$R = A * B \quad (5)$$

where,

$A$  – fuzzy inputs,

$B$  – set of rules,

$R$  – fuzzy output, by composing  $A$  with  $B$ .

Fig. 1-13 presents a bloc diagram of a control fuzzy algorithm in which the inputs are subjected to a *fuzzification* procedure, followed by fuzzy rules and finally obtaining the outputs through a procedure named *defuzzification*. Input fuzzification and output defuzzification are required due to the fact data is collected as numerical data.

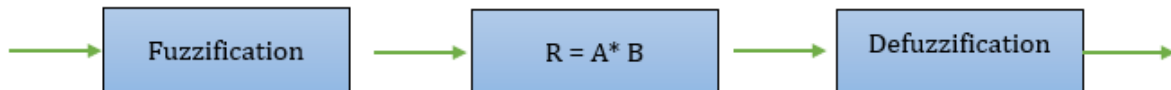


Fig. 1-13 Bloc diagram of control fuzzy algorithm

The *fuzzification* procedure transforms the input of the system into a variable to which a set of fuzzy rules can be applied:

$$A = fuz(x'_i) \quad (6)$$

where,  $fuz(\cdot)$  is the fuzzification function, which transforms a numerical value into a fuzzy variable and  $x'_i$  is the number of input representations.

The *defuzzification* is required to convert the fuzzy output into a numerical value which consists in the command given by the user. The *defuzzification* process can be realized through multiple methods such as: adaptive integration, center of area, fuzzy mean, first of maximum, quality method, weighted fuzzy mean, bisector of area etc. [66]. The most common method is the indexing method, meaning that *defuzzification* method does not accept function values less than a specified value,  $y$ :

$$idfuz(R, y) = dfuz(R) \quad (7)$$

where,  $dfuz(\cdot)$  represents the *defuzzification* function and  $idfuz(\cdot)$  is the indexed version of the sample.

In practice, a fuzzy control algorithm is multivariable. The fuzzy relationships may use local inference, determined as follows:

- find the value of the input entry membership function.
- find the level of satisfaction of each rule.
- determine the results for each rule.
- aggregate the final result of a partial result.

If only numeric input values are considered, the fuzzy inference is reduced to the value of the membership function.





The “AND” operator is essential for the control systems when the system has multiple inputs. The control-rules consist in numerous knowledge about the process. In case of lack of rules, the fuzzy control algorithm may provide a strange behavior. In order to tackle this problem, maintaining constant output when no rule is applied might be an option. Moreover, as Kóczy and Hirota demonstrated, fuzzy rule interpolation can solve this issue easily [70].

Procyk and Mamdani gave a new direction to the fuzzy control algorithms by creating adaptive (with auto organization) algorithms leading to fuzzy neuronal networks [71]. Applied by Wakileh and Gill [72] and Linkens [73], an adaptive fuzzy algorithm consists of a control algorithm with an adaptive mechanism to the system. The mechanism is built from a specific module which measures the efficiency of the system and a mechanism which modifies the controller based on a minimal model.

A numerical value describes the system’s efficiency  $p[kT]$ , provided by a fuzzy set of rules with inputs related to system’s error and variation error:

$$p[kT] = f(e[kT], \Delta e[kT]) \quad (13)$$

where  $f$  is a reference model.

The applicability of fuzzy control algorithms is large: cameras, washing machines, color TV, car’s transmission control, climatization or even heating, ventilation or air conditioning.

### **1.3.3.2. Artificial neural network (ANN)**

ANN is destined to provide an algorithm that "learns" building behavior based on actions taken and future intentions already planned based on predictions. They are widely used models of machine learning in terms of applications for predicting human behavior [74]. Artificial neural networks have the adaptability in modelling a specific building operation mode, ideal to each network user. Particular attention will be held to the encompassing of artificial neural network during heating/cooling of houses [75].

A neural network is formed by interconnecting a group of input neurons (Fig. 1-14). The ANN receives a set of input data, called themselves entry nodes. Starting from this point forward, this set of data generates intermediate states in which neurons are involved, also known as hidden nodes, and a set of output data, identified as exit nodes [76].

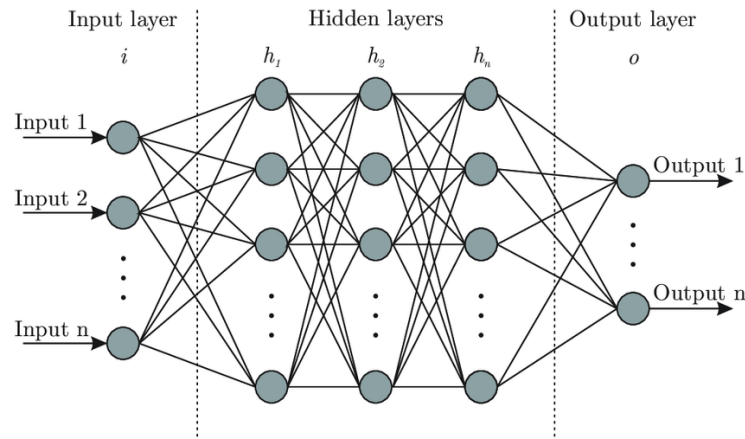


Fig. 1-14 Artificial neural network architecture [77]

Fig. 1-14 explains how the hidden layers work. The input data are gathered in the input layers and a weight is given to it. Each weight is processed before combining inputs into a node and then outputting a result. The simplest approach to exemplify the working procedure is:

- The choice of inputs considering the output of the system. A discretization step associates each system input to a specific weight establishing the 1<sup>st</sup> layer of the algorithm.
- Applying a specific mathematical function in order to activate the input data and transforming into unprocessed output data.
- Error calculation – by minimizing the error, adjusting the weight of every neuron until the result of the error is very small.

For the learning algorithm, it will be used input data composed by events recorded and harvested by the monitoring system. The decision to achieve user thermal comfort will be performed by combining activation elements of the neural network based on transfer functions of type step, log-sigmoid, tan-sigmoid discrete in a matrix of intermediate layers.

In this thesis, it will be determined a mechanism to identify the resources allocated for a particular room and how comfort policies are implemented in a multi-user access system [78].

	<b>MLR</b>	<b>ANNs</b>	<b>SVR</b>	<b>Ensemble model</b>
<b>General</b>	+Ease of use; +Efficient and Economical; -Inability to deal with complex problems; -Hard to predict short-term energy usage.	+Solve complex nonlinear problems; +Good performance for short-term prediction; -Fails to interconnect building parameters with energy usage; -Many parameters need to be determined.	+Good balance between prediction accuracy and calculation speed; +Few parameters need to be determined; -Kernel function is crucial and difficult to be determined.	+Best prediction accuracy and stability; -High level of knowledge requirement; -Relatively low computation speed.
<b>Accuracy</b>	Below average	Average	Good	Better
<b>Computation speed</b>	High speed	Medium speed	Medium speed	Low speed
<b>Computation difficulty</b>	Easy	Medium	Medium	Difficult
<b>Energy sampling type</b>	Long-term	Long-term; Short-term	Long-term; Short-term	Long-term (Daily energy usage)

Fig. 1-15 Comparison between artificial intelligence (AI) algorithms [78]

Fig. 1-15 presents the main advantages and applications of different types of artificial intelligence: linear regression, vector regression or neural networks. Each of the above types presents advantages and disadvantages, being able to integrate in any system.

The advantage of intelligent algorithms is that they can be used without knowing details about the controlled building. One of the strongest advantages of neural networks is their ability to make large and complex data maps. The relationship between inputs and output is robust, even if input data presents white noises. Those white noises are extracted and removed from the algorithm once the error dissemination begins.

A major disadvantage of using the AI technique is benefit of the bonding between data entries and house physical characteristics. For example, in cases of building's renovation strategy, physical parameters may be impossible to extrapolate the energy periodically. To enhance the building energy efficiency, parameter estimation is significant in conserving and reducing environmental impacts.

The building's behavior is influenced by:

- weather conditions,
- thermal properties,
- materials used for construction,
- occupants,
- lighting system,
- HVAC system.

Table 1-1 Potential of distinct forward and data-driven algorithms

Methods	Usage <sup>a</sup>	Difficulty	Time Scale <sup>b</sup>	Computing Time	Inputs <sup>c</sup>	Accuracy
ANN	D, ES, C	Complex	S, H	Fast	T, H, S, W, t, tm	High
Thermal Node	D, ES, C	Complex	S, H	Fast	T, S, tm	High
Degree-Day	ES, DE	Moderate	H	Medium	T, S, tm	Medium

Notes: <sup>a</sup> Diagnostics (D), energy savings (ES), control (C), design (DE),

<sup>b</sup> hourly (H), sub-hourly (S),

<sup>c</sup> temperature (T), humidity (H), solar (S), wind (W), time (t), thermal mass (tm)

To conclude with, this chapter offers information on the selected classical and data-driven model used in this thesis. Table 1-1 offers knowledge about degree of difficulty, time scale, inputs gathered by sensors, computing time and the accuracy of the output.

## *CHAPTER II – Testing facility*

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The goal of this part is to present basic characteristics about testing facility from University POLITEHNICA Bucharest. Basic properties include knowledge about construction materials, cooling, and heating system (HVAC), off grid system, smart solution implementation, or PV panel power.

This section gives special attention to essential information, related to passive house requirements and concept, with preponderation on surveillance system.

## 2.1. Introduction

The passive house POLITEHNICA was built in 2011 through joined efforts of three universities (UTCB, UAUIM, UPB) and two research institutes (ISPE, ICPE), with three main objectives: education, research and dissemination of best practices (Fig. 2-1). The testing facility from POLITEHNICA University, Bucharest (UPB), is also known as the Passive House from the UPB Campus [79], located at latitude  $44.43843374^\circ$  and longitude  $26.04730994^\circ$  at altitude 78 m above sea level. The estate is situated on a plane surface, having N-S orientation and  $140 \text{ m}^2$  treated floor area [80]. The house is split in two identical buildings “East part” and “West part”, both being included in a similar thermal envelope.



Fig. 2-1 UPB Passive House

Its geometrical characteristics are given in Table 2-1. Both houses share a common thermal envelope which is composed of 30 cm of insulated layer of mineral wool. The building is air tightened. The windows are triple glazed, with low-e coating and insulated frame.

Table 2-1. Geometrical aspect of the UPB Passive House

Name of Area	East	West
Used surface	$139,95 \text{ m}^2$	$139,95 \text{ m}^2$
North Glazed surface	$2.80 \text{ m}^2$	$2.80 \text{ m}^2$
East Glazed surface	$9.13 \text{ m}^2$	0
West Glazed surface	0	$9.13 \text{ m}^2$
South Glazed surface	$17,94 \text{ m}^2$	$17,94 \text{ m}^2$
Door	$2.19 \text{ m}^2$	$2.19 \text{ m}^2$
Exterior Wall	$182.52 \text{ m}^2$	$182.52 \text{ m}^2$
Roof	$96 \text{ m}^2$	$96 \text{ m}^2$
Floor	$94.40 \text{ m}^2$	$94.40 \text{ m}^2$
Volume	$435 \text{ m}^3$	$435 \text{ m}^3$

### **2.1.1. Heating ventilating and air conditioning**

The HVAC system of eastern house is composed of air-to-air heat recovery system with an efficiency of 91 % and earth to air heat exchanger. The earth to air heat exchanger uses the natural property of the soil to maintain a constant temperature at depth greater than 1.5 m. The earth to air heat exchanger of the eastern passive house is composed of 40 m of piping systems, with a diameter of 200 mm, buried horizontally in U-shaped form at depth of 2.5 m. The earth to air heat exchanger is used to preheat or precool the outdoor air during cold and warm seasons, respectively. To increase the energy efficiency of the building, the preheated air is injected into heat recovery unit, which assures a comfortable indoor environment. During warm season, the cooled air is injected in the building bypassing the air to air heat recovery unit.

The western house uses an HVAC system composed of air to air heat recovery unit and geothermal heat pump. During cold season, the geothermal heat pump collects the energy stored in the ground and transfers this energy to the building through radiant panels on the walls. During summer, the geothermal heat pump does the opposite.

### **2.1.2. PV panels**

Both houses have 13 PV panels with a nominal power of 1.5 kW which are located on the roof of the building. Moreover, the eastern part is equipped with 36 semitransparent PV panels with a nominal power of 1000 W for the illumination system. The previous solution did not have a storage capacity for the produced electric energy.

### **2.1.3. Off grid system**

Currently, the eastern house is equipped with a smart controller and an energy storage unit. The smart controller has some well-defined policies which can implement the best way to consume or store the energy produced by PV panels.

The passive house laboratory can test the efficiency of different HVAC systems, renewable systems and digital technologies for residential purposes. The in-house developed monitoring system collects comfort, air quality and electric data of the buildings.

The interior comfort and the air quality of the building are monitored using Sparrow nodes [81]. Sparrow is a WSN able to design and check wireless apps. Their components are small-sized sensor nodes with preponderation on low-cost and power usage. They are able to collect data from the atmosphere, systematize in network topology and connected to multiple structures.

The electric parameters are monitored using digital platform for smart meters, formed of software and hardware features. Its components consist of three software plans to:

- Data gathering
- Server Data stockage
- Data view



### **2.1.4. Smart solution system**

The Western house has an intelligent control unit based on Honeywell solution. The implemented smart solution is built on top of geothermal heat pump allowing the control of comfort in each room, separately.

Many features of heating and cooling strategies are promoted by EU, switching from old technics to current technology. Although challenges such as interoperability, technology maturity, return of investment, health impact, privacy, and security issues break the markets, intelligent devices pursued an increasing growth introduction.

## **2.2. Passive house concept**

This concept was developed by “Passivhaus Institute” from Germany. It seeks to reduce as much as possible the necessary energy load through an effective insulation, removing thermal bridges and usage of efficient HVAC [82]. Passive house concept can be implemented by any independent user in order to develop a standard building with low energy consumption and a proficiency in thermal behavior. Usually, a passive house can be easily confused with nZeb (nearly zero-energy building); the substantial difference relies on energy consumption terms. One of the benefits of analyzing a passive house is the remarks of lower energy consumption in comparison with standard buildings. Moreover, one of the key aspects of a passive house is the usage of oil or gas, per  $\text{m}^3/\text{year}$ , that is considerably less than nZeb or other typical low energy building.

Its ability to use sustainable energy resources makes the house to be rated as “green-energy”, taking advantage of the energy received from the sun, the internal heat gains and the air recovery unit system. Each passive house is built in accordance with a strategic plan developed by the energetic auditor, making use of passive cooling techniques in order to have a comfortable indoor temperature. Due to the high tightness of the envelope, the air exchange between the indoor and outdoor is very low. Another major aspect of the house is the triple glazed windows that permit the radiation from the sun to rise the indoor temperature, lowering the usage of the heating system. The most important key-aspect of any passive house is defined by the ventilation system. Having a constant movement of the air implies having a fresh air inside. With the help of the recovery unit, the fresh air is supplied into the house, recovering 91 % of the heat of the exhausted air.

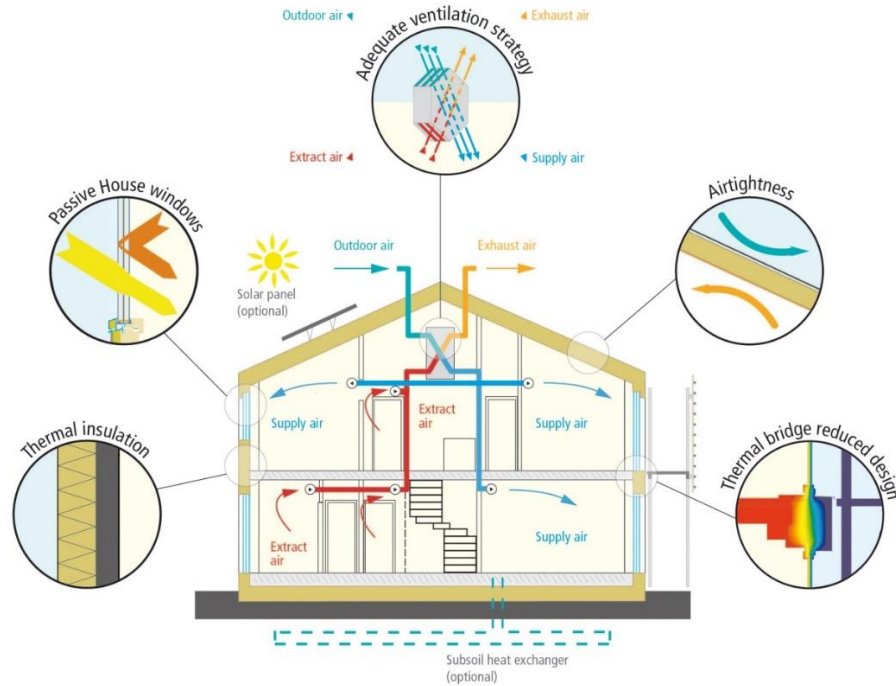


Fig. 2-2 Basic principles of a Passive House [83]

An explicit example of the main principles of any passive house is presented in Fig. 2-2, where the accent is put on thermal insulation. The heat transfer between indoor and outdoor air throughout walls must be limited as much as possible, losing maximum 0.15 W/K. Windows must be triple glazed, preventing heat loss. The recuperation heat piece runs constantly, improving the air quality, and maintaining a good CO<sub>2</sub> level. The absence of thermal bridges is a key factor to an efficiency low consumption house.

### 2.3. Passive house requirements

In order to acquire the certificate for a passive house, each building needs to comply to the following criteria [84]:

1. The energy demand for heating should not surpass 15 kWh/m<sup>2</sup>/year or 10 W/m<sup>2</sup> peak demand of living area. Usually, the cooling energy demand are higher due to dehumidification.
2. The total amount of energy used for domestic operations should not be more than 60 kWh/m<sup>2</sup>/year of treated floor.
3. The exchange rate between indoor and outdoor air with at test pressure of 50 Pa needs to be  $N_{50} \leq 0.6 \text{ h}^{-1}$ .
4. Thermal comfort has strict requirements for every living space, with less than 10 % of the hours in a given year (i.e. less than 876 h) with temperatures higher than 25 °C.
5. The overall heat exchange coefficient for windows should be less than 0.80 W/m<sup>2</sup> K.
6. The heat exchange coefficient for outside walls should be less than 0.15 W/ m<sup>2</sup> K.
7. The efficiency of the heating recovery unit system should be higher than 75 %.
8. Thermal bridges lower than 0.01 W/ m K.

Table 2-2. Thermal characteristic of the UPB Passive House [85]

Envelop components	Elements		Surface [m <sup>2</sup> ]	Width [mm]	$\lambda$ W/m/K	
<b>WALLS</b>	<b>Roof top</b>	Plaster	96	22	0.8	
		Reinforced concrete		130	1.74	
		Mineral Wool		400	0.04	
	<b>Overall heat exchange coefficient U = 0.107 [W/m<sup>2</sup>/K]</b>					
	<b>Exterior</b>	Plasterboard	182.52	22	0.8	
		Self-clated cellular concrete YTONG		250	0.27	
		Mineral wool		300	0.04	
	<b>Overall heat exchange coefficient U = 0.122 [W/m<sup>2</sup>/K]</b>					
	<b>Ground floor</b>	Parquet	94.40	22	0.2	
		OSB plaque		8	0.13	
Reinforced mortar		50		1.1		
Expanded plysyrene		150		0.04		
Reinforced concrete		120		1.74		
XPS polystyrene		180		0.04		
Reinforced mortar		50		1.1		
<b>Overall heat exchange coefficient U = 0.114 [W/m<sup>2</sup>/K]</b>						
<b>Wall Spliter</b>	Plaster	86.72	22	0.8		
	Solid Brick		250	0.8		
	Plaster		22	0.8		
<b>Windows</b>	Element	Surface [m <sup>2</sup> ]	G value	U [W/m <sup>2</sup> /K]		
	Low-E SAINT GOBAIN Window	29.17	0.5	0.6		
	REHAU Frame		-	0.78		
<b>Door</b>	REHAU	2.19	-	0.8		

Studying the reduction of energy consumption, especially the passive house models, it was realized that the concept suggests a different and bigger insulation for its components. The components have specific properties with a low value of thermal conductivity. Each element of the envelope is composed of several layers. The HVAC system is used for heating, cooling, or ventilating the house. With a 284 m<sup>2</sup> surface, the passive house from UPB was made by two identical parts working simultaneously, the difference being made by the system they use to heat or cool the treated floor area. Moreover, the East part of the house serves as

research laboratory for students that want to analyze the behavior of the house while in the West part, Honeywell oversees analyzing that energy performance.

## 2.4. Physical characteristics

The physical characteristics of the building is the information indicating: length, height, dimension, and surface area, material of interest or conduction property. In other words, a house can be described by physical characteristics depending on roof, ground floor, wall, thermal properties, energy efficiency or electrical characteristics [86].

In Fig. 2-3, the roof of the UPB Passive House is described. The roof has 96 m<sup>2</sup> of surface and 562 mm width. The roof has three distinctive elements, each one representing an important layer:

- plaster,
- reinforced concrete,
- mineral wool.

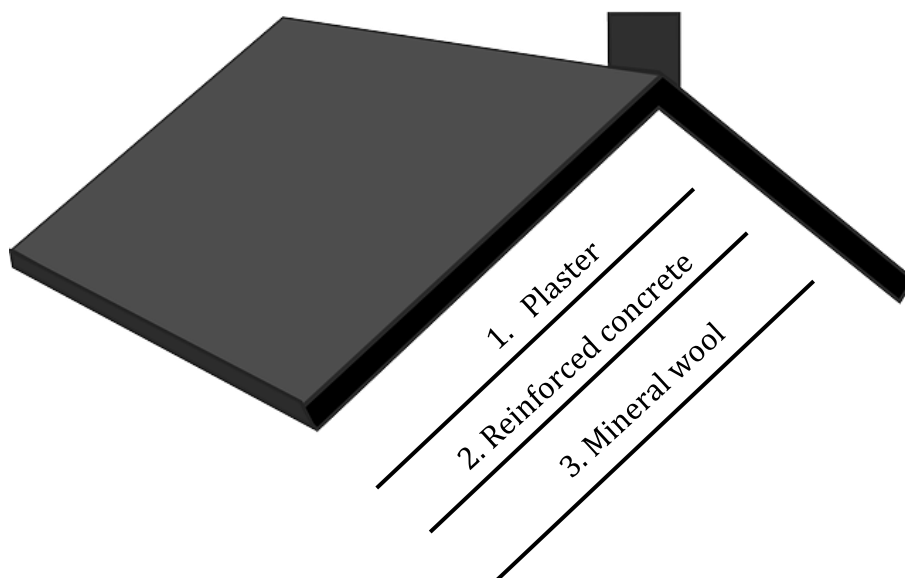


Fig. 2-3 Rooftop elements of the Passive House UPB

The plaster is used as a protective membrane of walls and ceiling covering, made of gypsum material, characterized by a thermal conductivity of 0.8 W/mK with a thickness of 22 mm [87]. The second layer of the roof is made of reinforced concrete; it is the dominant element of the roof. The last layer is represented by mineral wool, a material full of fibrous composition assembled by the rotation of molten mineral or rock matter, utilized as thermal and sound insulation.

The living area of the house is covered with an exterior wall of total area of 182.52 m<sup>2</sup> with a 0.122 W/(m<sup>2</sup>K) average U-Value, and a floor as pictured in Fig. 2-4. The materials of the exterior walls are:

- interior plaster (having a 0.800 W/mK thermal conductivity with a thickness of 22 mm),

- cellular concrete Ytong (having a 0.270 W/mK thermal conductivity with a thickness of 250 mm),
- mineral wool (having a 0.045 W/mK thermal conductivity with a thickness of 300 mm).

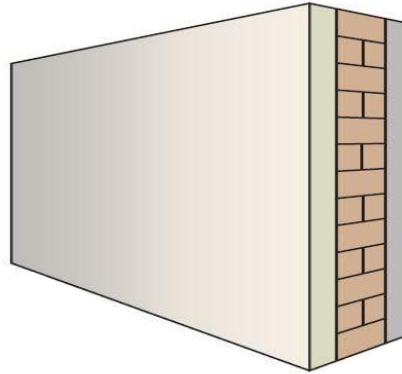


Fig. 2-4 Exterior walls of the Passive House UPB

The UPB Passive House has two types of walls. The first is composed of brown timber and insulation while the second is made of blue timber and insulation. Both types of walls have similar properties including an insulation with a thermal conductivity of 0.040 W/mK and a timber with thermal conductivity of 0.130 W/mK. A total of 30 cm of exterior wall thickness with insulation and brown/blue timber are counted.

The southern exterior wall was designed with a large window to take advantage of the free solar rays. The testing laboratory's pilot project include triple glazed windows which have been developed in high accordance with the reduction factor of solar radiation. In Fig. 2-5 Low-E Saint Gobain window is covering a total of 29.17 m<sup>2</sup> with a thickness of 0.5 mm. The windows are playing an important role as their main ability is to permit only solar radiation to enter inside the house and to block the air infiltration.

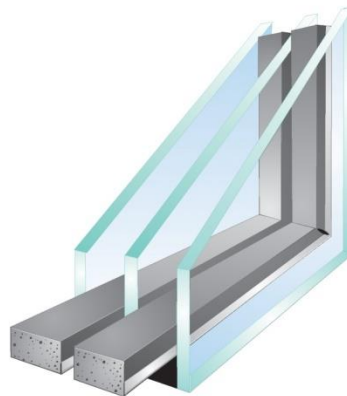


Fig. 2-5 Triple glazed windows of the Passive House UPB

Table 2-3 Main properties of window triple glazed windows

Building: <b>Passive House - Pilot project</b>		Annual Heat Demand: <b>12</b> kWh/(m <sup>2</sup> a)		Heating Degree Hours							
Climate: <b>BUCURESTI</b>		77,0									
Window Area Orientation	Global Radiation (Cardinal Points)	Shading	Dirt	Non-Perpendicular Incident Radiation	Glazing Fraction	g-Value	Reduction Factor for Solar Radiation	Window Area	Window U-Value	Glazing Area	Average Global Radiation
maximum:	kWh/(m <sup>2</sup> a)	0,75	0,95	0,85				m <sup>2</sup>	W/(m <sup>2</sup> K)	m <sup>2</sup>	kWh/(m <sup>2</sup> a)
North	138	0;70	0,95	0,85	0,586	0,50	0,33	2;80	0,82	1;6	141
East	304	0;69	0,95	0,85	0,696	0,50	0,39	9;13	0,77	6;4	359
South	568	0;71	0,95	0,85	0,718	0,50	0,41	17;24	0,77	12;4	560
West	309	0;75	0,95	0,85	0,000	0,00	0,00	0;00	0,00	0;0	309
Horizontal	480	0;75	0,95	0,85	0,000	0,00	0,00	0;00	0,00	0;0	480
Total or Average Value for All Windows:						0;50	0;40	29;17	0;78	20;4	

Transmission Losses	Heat Gains Solar Radiation
kWh/a	kWh/a
178	66
544	633
1025	1996
0	0
0	0
1747	2695

Table 2-3 describes the main properties of the windows. Each side of the window area is explained in global radiation value, shading, dirt, glazing fraction, g-Value and the transmission losses and solar radiation heat gains. Due to constant heat sharing between ground-floor and earth land, the most complex component of the passive house contains up to seven layers. The ground floor surface area has a floor slab area of 94.4 m<sup>2</sup> with a floor slab perimeter of 27.8 m. The average U-value of the ground floor is 0.114 W/(m<sup>2</sup>k) and its thickness is 580 mm (Fig. 2-7). The properties of each unique layer of the floor slab are presented in Fig. 2-6.

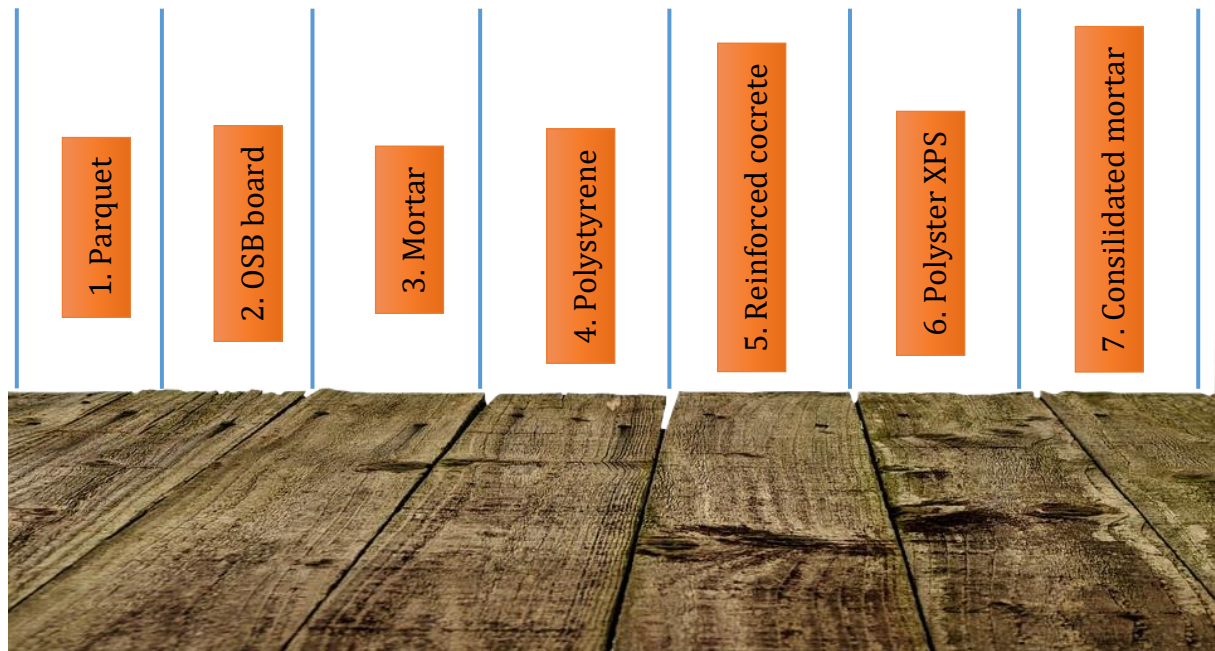


Fig. 2-6 Floor slab of the building

Table 2-4 U-values of the buildings elements floor slab

3		Floor slab				
Assembly No.	Building Assembly Description					
Heat Transfer Resistance [m <sup>2</sup> K/W]		interior R <sub>si</sub> :	0;17			
		exterior R <sub>se</sub> :	0;00			
Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width
						Thickness [mm]
1. Parquet	0;200					22
2. OSB board	0;130					8
3. Lightly reinforced concrete	1;100					50
4. EPS high density	0;040					150
5. Reinforced concrete	1;740					120
6. XPS polystyrene	0;040					180
7. Lightly reinforced concrete	1;100					50
		Percentage of Sec. 2		Percentage of Sec. 3		Total
						<b>58;0</b> cm
		U-Value:		<b>0;114</b>	W/(m <sup>2</sup> K)	

The interior wall that connects the two houses of the duplex is defined as being the partition. With a total width of 294 mm thickness and a U-value of 1.594 W/m<sup>2</sup>K, the partition wall is built from two identical materials, plaster, and one reliable component, solid brick (Fig. 2-7).

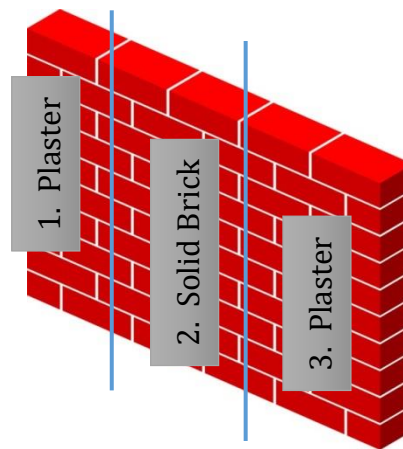


Fig. 2-7 Partition wall of the passive House UPB

The plaster layer has a thermal conductivity of 0.800 W/mK with a 22 mm thickness while the solid brick has 250 mm thickness. The thermal conductivity of the second element has the same value as the plaster layer and the heat transfer resistance for interior and exterior is 0.13 m<sup>2</sup>K/W.

The last physical element of the house is the connection between inside and outside, presented in Fig. 2-8. The exterior door has a 2.19 m<sup>2</sup> surface area with a thermal conduction of 0.8 W/mK.

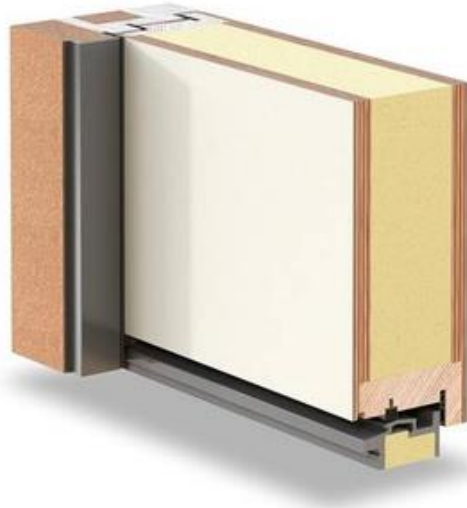


Fig. 2-8 Exterior Door of the passive House UPB

During the building process, the passive house requirements imply the testing of airtightness. The test must be held at a pressure of 50 Pa with an air change of max.  $0.6 \text{ h}^{-1}$ . Depressurized and pressurized tests must have the same condition in order to pass the requirements [88].

## 2.5. Heating, ventilation, and air conditioning system

Since more than 80 % of the energy losses are generated by the thermal envelope, the experimental house was designed to have two similar parts, each one serving for a different purpose. Both houses share a common envelope which is composed of 30 cm of insulated layer of mineral wool. The building is air tightened. The difference between the two houses is the running system. The eastern part furnishes a HVAC system made-up of:

- air-to-air heat recovery system (91 % efficiency),
- earth to air heat exchanger (EAHX).

Natural property of the soil is used by EAHX, to maintain a constant temperature at depth greater than 1.5 m (Fig. 2-9). EAHX of the eastern passive house is composed of 40 m of piping systems, with a diameter of 200 mm, buried horizontally in U-shaped form at depth of 2.5 m. EAHX is used to preheat or to cool environmental air throughout every period of time. To enhance the energy effectiveness of the building, the preheated fresh air is injected into heat recovery unit, which assures a comfortable indoor environment. During warm seasons, the cooled air is injected in the building, bypassing the air to air heat recovery unit.



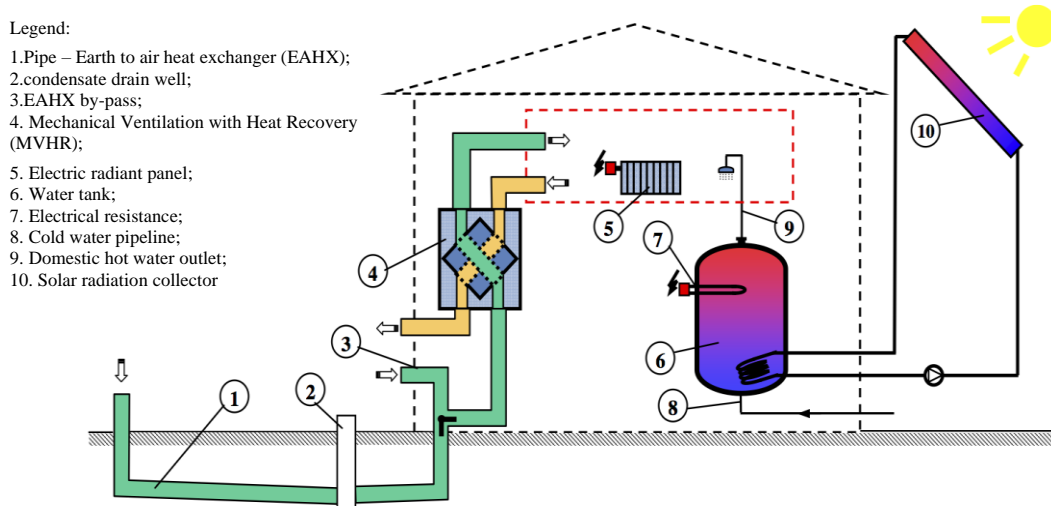


Fig. 2-9 The HVAC system of eastern house (EAHX) [89]

The first system consists of EAHX used to inject the air into the house with the help of a small fan. The recovery unit used in the eastern part of the duplex house is a FOCUS 200, produced by PAUL HEAT RECOVERY company, specialized in Passive House equipments. Its efficiency is higher than 90 % with a maximum volumetric airflow rate of 200 m<sup>3</sup>/h. It is equipped with an electrical resistance of 2.4 kW, used only if necessary. The air is moving constantly, traveling through steel pipes, and being controlled by the mechanical ventilation. Each room of the building, such as bathroom, upstairs room and kitchen, has fresh air inside through adjustable louvers.

The western house uses a HVAC system having the components:

- air to air heat recovery unit,
- geothermal heat pump (Fig. 2-10).

During the cold season, the geothermal heat pump collects the energy stored in the ground and transfers it into the building through radiant panels on the walls. During the summer, the geothermal heat pump does the opposite. For the heat-loss compensations, a REHAU system with preheat, domestic water preparation and passive cooling is being used. The heat pump has an electrical power of 5.4 kW for an average ground temperature of +5 °C providing an instantly hot water at 55 °C.

A 500l tank and a domestic hot-water preparation station with a flow rate of 35 l/min are used in the REHAU system. Similar to the eastern side, REHAU SOLECT WK solar panels are installed on the rooftop of the facility. On the other hand, solar panels heat the domestic water inside the water tank and administrate hot water to the radiators inside the house.

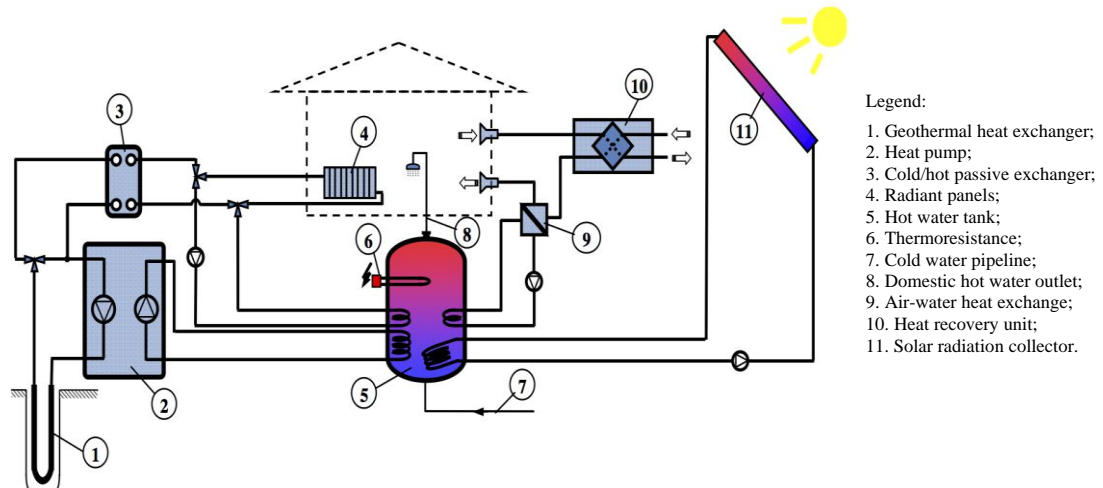


Fig. 2-10 The HVAC system of western house [85]

The well of the heat pump has a depth of 80 m where a geothermal pump is being placed. The geothermal pump is working within a U-shape-two-circuits, providing advantage of its usability during the summer, for cooling. As for the winter, similar to the first solution, an electrical resistance is being used for heating.

## 2.6. Monitoring system

The actual monitoring system of the testing facility has been implemented and improved by a group of scientist and engineers from UPB, fulfilling the criteria of a passive house. Thus, the efficiency of different HVAC systems can be measured. The in-house developed monitoring system collects comfort, air quality and electric parameters of the building.

### 2.6.1. Software

The software is composed of three main distinct applications: DataLayer, DataLogger and DataViewer. This type of organization is well structured because it allows backend maintenance when new changes are required. In parallel with the monitoring system, a DataLogger application and a storage unit are running on background, to save important data for future analysis purposes. For example, the data acquisition system is composed of multiple sensors gathering real time information with a time step of 1-10 minutes. The time step is customizable depending on the user preferences. These sensors can measure multiple parameters such as:

- inside temperature,
- outside temperature,
- luminosity,
- humidity,
- CO<sub>2</sub> concentration,
- solar radiation,

- energy consumption.

Fig. 2-11 presents an example of the layout of each wired sensor, from  $t_1$  to  $t_8$ . Each sensor is able to provide useful information about the data variation of temperature changes. Sensors are facing exterior walls, being protected of direct sunlight. To measure the flowrate between two air currents, sensors  $t_2$  and  $t_6$  are equipped with flow meters. The monitoring system has a complex structure being able to gather CO<sub>2</sub> concentration level and the relative air humidity in each room of the house.

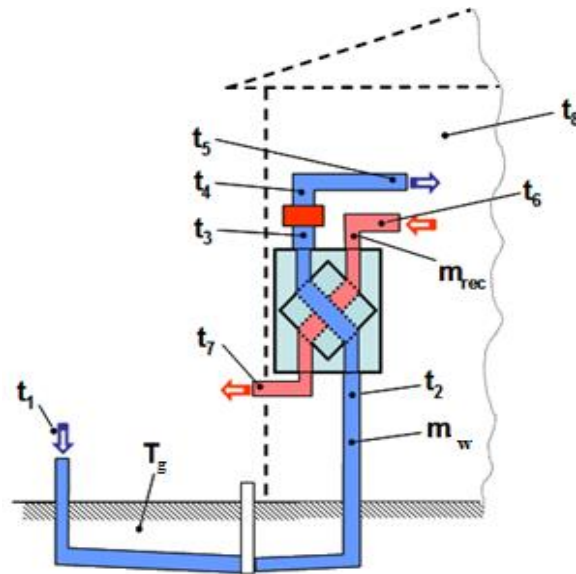


Fig. 2-11 The placement of wired sensors in the HVAC system [90]

Besides wired sensors, the house has in its composition five wireless sensors, namely W1 - W5. These types of sensors are providing the same parameters but in a different manner. Their capability is to collect data in a smart approach through a wireless connection. In Fig. 2-12, the location of each wireless sensor has been chosen in order to have direct connection with the server, where no interference is allowed. Temperature, luminosity and humidity parameters are being collected and transmitted to the server by the wireless sensors.

The energy consumption of the house is monitored using seven smart energy meters. The following instruments can be seen and analyzed on the building server:

- lightning system,
- living room (radiant panel),
- kitchen apparatus,
- surveillance system,
- electrical resistor,
- mechanical ventilation with heat recovery (MVHR) unit,
- radiant panel from the 1<sup>st</sup> floor's bathroom.

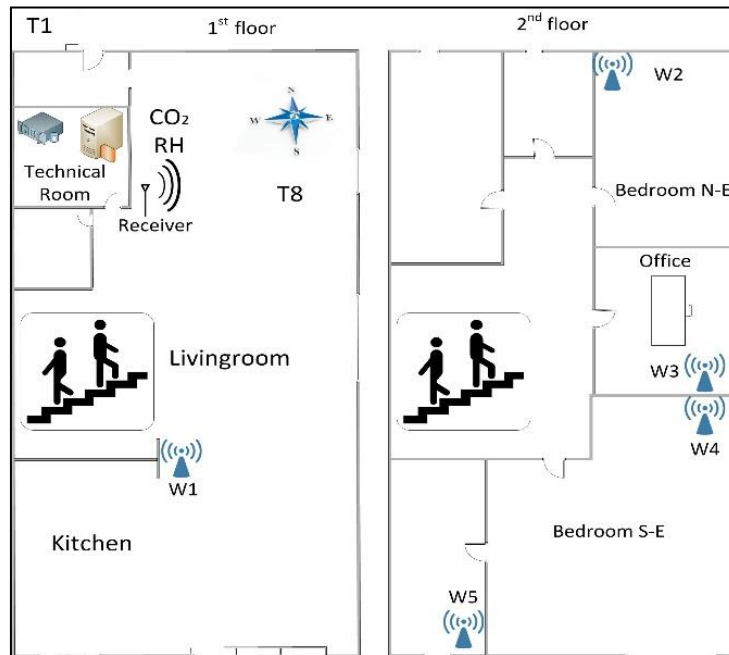


Fig. 2-12 Monitoring system structure [91]

Besides the wireless and wired sensors in the house, a rooftop pyranometer collects the solar radiation. All the information is gathered from sensors which transmits data in a database on a server through a serial connection, once, every ten minutes. The lower consumption of the building is supplied with the help of the PV panels, which are able to produce electricity. The inverter software gives information about the performances of the PV panels. This type of management is developed as a hardware and software infrastructure for Smart Buildings Controller (SBC). The use of SBC is to assure an efficient performance of the facility, raising the comfort for the occupants and reducing energy consumption [92]. Most compelling evidence of the advantage of SBC is the centralization of data that is gathered from the sensors through a complex set of rules, named policies. Policies are the guidelines for the house to use, because the user can customize the working schedule of any component. In this manner, the occupants can create complex scenarios in order to attain the comfort, with slightest energy usage.

Fig. 2-13 displays an example of a working application of the System Policy Editor. On the lower part of the policy editor window, html code is written in order to control the electrical resistance and to preserve indoor temperature higher than 20 °C. Providing maximal energy-saving, the recursive routine of 20 °C heating puts on electrical resistance only when indoor temperature is between 20 °C and 22 °C. Multiple sets of rules are triggered depending on the outside temperature, especially when temperature drops below 15 °C. For instance, the first rule of the routine, compares the data received from sensor T1 (outdoor temperature) with a chosen basic value. Then, in case of heating, it activates the electrical resistance as follows:

- period must be around 17:01 to 18:00,
- outside temperature must be beneath 15 °C.

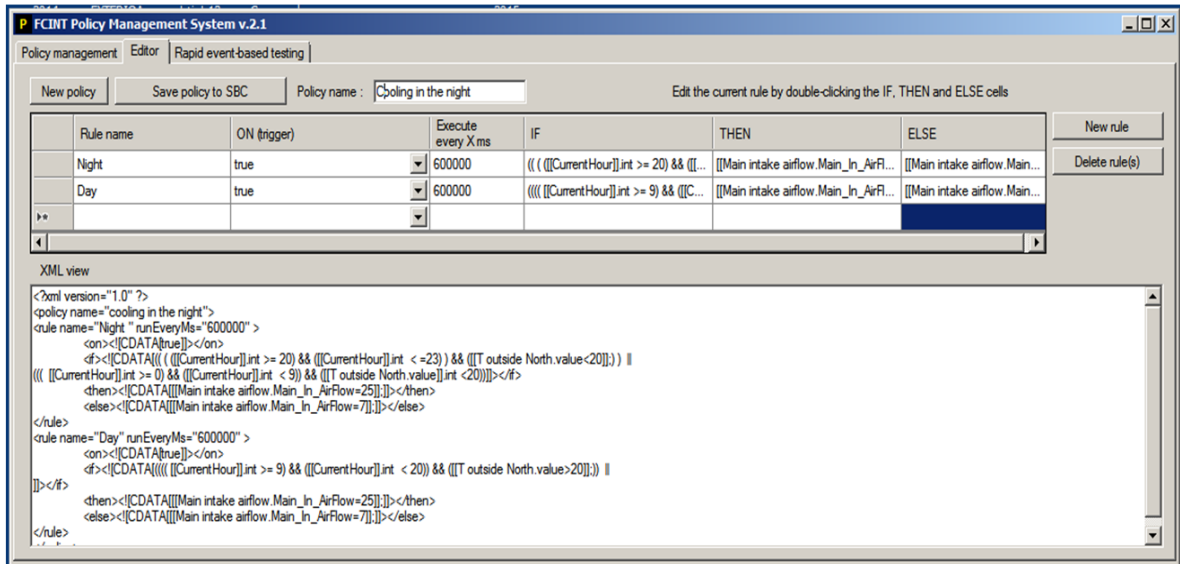


Fig. 2-13 Policy Management System – FCINT

## 2.6.2. Data storage and database

The monitoring system was divided in two parts, serving different functionalities. The hardware parts consist of the usage of multiple devices to gather important data to be analyzed by the software applications. The software analyzes the data received from the sensors. In order to be analyzed, the data needs to be stored inside the server into a database.

The database was created by using Microsoft SQL Server Management Studio 2012 which connects the smart devices to the main acquisition server. The connectivity with the server is based on data transfer bus. Fig. 2-14 presents the system, pointing the mapping system of each table in C# class language. Once created, the C# class table can acquire information from the sensors installed in the house. Besides the Database Model, the Entity Framework technology (EF) has been used to create a conceptual model in order to simplify the developing work by structuring the datasets without knowing the entire database architecture. The main advantage of using EF is the simplicity and the timesaving capability of the model.

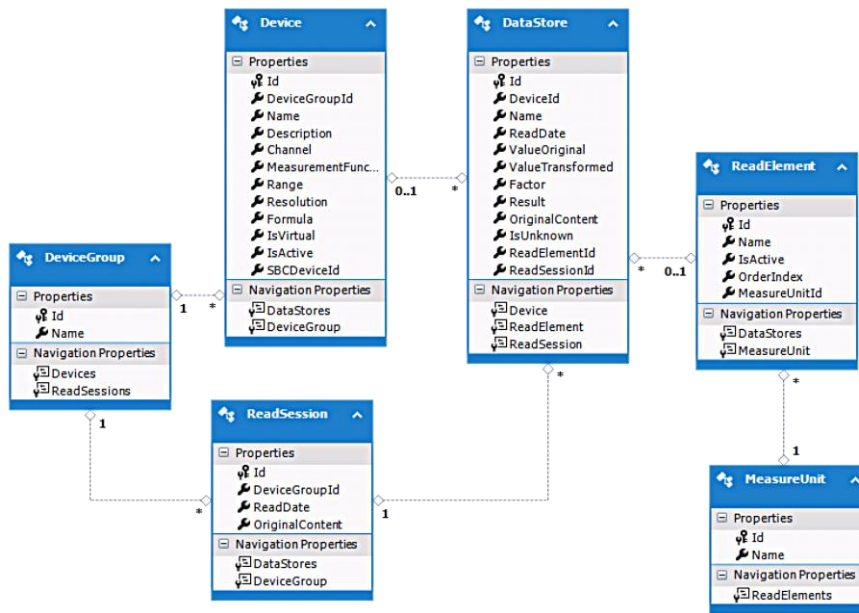


Fig. 2-14 Visual Studio software - data mapping system of UPB passive house [93]

The data storage structure is built from 6 elements that are part of the SQL table construction, as mentioned in Table 2-5. Each element completes important tasks, gathering useful details about the building’s characteristic and its thermal assets.

Table 2-5 Server data storage table

	Device	Read Session	Measurement Unit	Device Group	Data Store	Read Element
<b>Database storage unit</b>	Knows the name of the sensor;	Each readout is identified with an unique sessionId	Memorize the unit’s measurement for	Identifies the running hardware	Collects the data in sessions	Gives a current status to each readout from the sensor.
	Knows the communication channel	Allows the identification of all the realized measurements				Sends NULL values in case of outside measurement values
	Knows the measurement interval					
	Knows resolution and groupingID					

The database construction relies on a complex structure based on a multiple step line transition. One of the most important items of the database is the acquisition of the ID of the device that sends the information to be stored. Each device has a unique ID, a channel through which communicates with the server.

The next step of the acquisition system is the reading data session. Every readout is identified through a unique ID session which allows the identification of all measurements.

The measurements session is able to memorize each unit assessment, allocating to a specific DeviceGroup. Furthermore, the DataStore stage collects the data in particular sessions. In the end, for each redundant sensor, an individual status is given, transmitting NULL values in case of outside measurement values.

The most important component of the monitoring system, the DataLogger software, is in charge of the analysis of the incoming data from the sensors. The C.R.U.D. operation stands for:

1. Create data – Inserting data in a SQL database through a HTTP communication.
2. Read Data – Selecting the data and getting the most relevant information.
3. Update data – Updates the data through put/post/patch operations.
4. Delete data – Delete the unnecessary data from the SQL database.

The data flows are organized in a strategic manner through a system event, including two execution threads:

1. Exchange data with the database from the server.
2. Collect the information received from the sensors.

### **2.6.3.Communication**

As mentioned before, the monitoring system records real data information with a time step of 1 to 10 minutes. During the tests of the data acquisition system, it was identified a small bug of the system consisting in delaying the time step for 2-3 seconds in a 24 h interval. An open source “Quartz library” was used to remove the delay. The time loop is realized of three components: StdSchedulerFactory, JobBuilder and TriggerBuilder. Firstly, the StdSchedulerFactory builds the necessary environment for the Triggers to create numerous task jobs while the JobBuilder is always at maximum priority. The JobBuilder is used to force turn on any services or actions the server might need. As an example, this type of service is used to read data gathered from the sensors. The TriggerBuilder launches the job execution that is scheduled to begin at a specific hour. For a distinct amount of time, an interval is being set to follow upcoming procedure:

1. Launch the DataLogger.
2. Empty the buffer and sets a reading timer.
3. Readout of data through the RS232 communication protocol or using an USB connection. These data are being processed using libraries.
4. After the completion of each cycle, the time-step creates a specific ID for the upcoming reading session, stocking them up in the ReadSession table.
5. Use ID to identify the entire measurement gap.
6. After the parsing of collected data, store in a DataStore table.

In order to have accuracy on the results, there are 5 sensors reading and sending wireless information to the main hub server as shown in Table 2-6. Furthermore, to keep track of the building’s parameters, all the devices are equipped with radio antennas.

Table 2-6 UPB WiFi sensor

Parameter acquired	Measurement	
	<b>Range</b>	<b>Error</b>
Moisture	0 - 100%	± 2% RH
Brightness	40 - 100%	±0.5°C

Parameter acquired	Measurement interval
PRR	0 - 1000
Luminosity	0 - 1000

The indoor comfort and the air quality of the building are monitored using *Sparrow* nodes [81]. This type of sensor runs on a wireless network structure made for research purposes. The Sparrow architecture comprises inexpensive, energy-saving and reduced sized sensor nodes. The benefit of using such sensors is their capability of collecting data from close surroundings, systematizing in a mesh topology, and binding to diverse systems across a specific gateway.

Electric parameters are monitored using a content management system (CMS) for metering, formed of software and hardware. There are multiple software objects, with specific functional capability: collect, store, and display the obtained data from the database.

The distribution of the wired and wireless sensor is presented in Fig. 2-16. [CG1]The Main hub of the monitoring system have triple role:

1. to collect measured parameters from wireless sensors (Fig. 2-15).
2. to transmit the data, through USB connection, to the software application.
3. to accumulate the measured parameters from the main hub.



Fig. 2-15 WiFi sensor



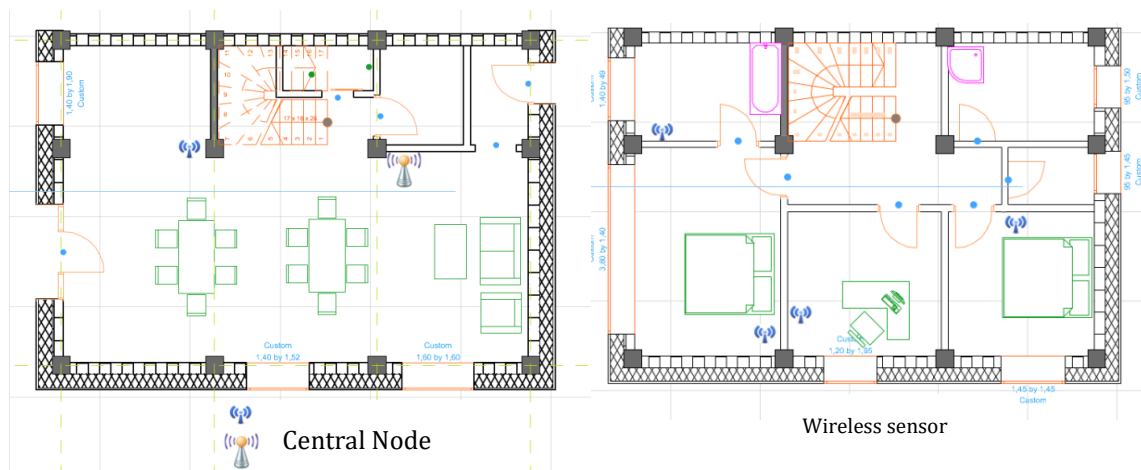


Fig. 2-16 Distribution of the wired and wireless sensors

The PHPP file is a Microsoft office Excel file, containing all the information about the Testing Laboratory from UPB as follows:

- Brief instruction about the house,
- Verification of the house,
- Areas,
- U-list,
- U-values,
- Ground,
- Windows and windows type,
- Shading and summer shading factors,
- Ventilation,
- Annual Heat Demand,
- Monthly Method,
- Heating Load,
- Summer ventilation,
- Cooling, cooling units and loads,
- DHW + distribution,
- Solar DHW,
- Electricity demand,
- Electricity non-domestic use,
- Auxiliary electricity,
- Primary energy value,
- Compact unit with exhaust air heat pump,
- Boiler,
- District heat,
- Climate data,
- IHG (Internal Heat Gain),

- IHG Non-Domestic,
- Data,
- Conversion,
- TFA (treated floor area) and volume.

## 2.7. Conclusions

The experimental house of UPB was built as a standard duplex house with one floor. It is divided into two houses, East and West wing. The East wing of the house serves as a student research laboratory running an EAHX system, which uses ground temperature to preserve a constant temperature inside the house. The West wing has the same thermal properties as the East wing, running on a different HVAC system: air to air heat recovery unit plus a geothermal heat pump.

The building was designed as a passive house in order to reduce the thermal load through efficient insulation and air tightness. Each wall has a minimum of three distinctive layers characterized by good thermal conductivity level. Triple glazed windows are positioned on the southern part of the building.

In order to increase the efficiency of the HVAC system, a Canadian well was used, because of soil constant temperature. A small electric pump inserts the fresh air from the environment into the heating recovery unit.

None of this can happen without the solid monitoring system implemented into the experimental house by a team of researchers and engineers, testing the HVAC efficiency and digital technologies. The monitoring system collects information such as: temperature, air quality and electrical power. Being equipped with both software and hardware solutions, the monitoring system offers a low-energy consumption policy accordingly to user's needs. The monitoring system is composed of multiple wired and wireless sensors, spread inside the building, providing useful information data about selected parameters. For this reason, a Policy Editor is running as a desktop application where html code is needed to control the HVAC system and electrical resistance.

The passive house laboratory from UPB delivers optimal conditions for measuring and data acquisition, especially connecting smart meters to the grid. In the upcoming chapter, more information about the data collection and information flow is provided.

## *CHAPTER III – Measurements and data acquisition*

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The objective of this section is to emphasize how data and measurements have been acquired for the thesis purposes. With a short introduction on the devices that gather real time data, smart meters, this chapter presents the interaction between user and smart meters through an HMI software.

Different modules of the SMXcore are described as a solution for data collection. Moreover, physical, and electrical acquisition data are underlined with a statistical analysis of weather inputs.

For the relevance for this thesis, examples and interpretation of results are being presented as a conclusion of this chapter.

### 3.1. Introduction

In the upcoming section, information about data acquisition methods as well as different measurements techniques are being detailed. A smart meter system is needed to measure how much electricity and energy is used. They are the newest engineering products that aim to replace the regular meters of gas and electricity systems by 2020 according to European Commission [94]. This system is necessary to measure the energy consumption and the use of the buildings 24/7 while sending data to service supplier, wirelessly. The use of the smart meter system saves plenty of time due to no manual reading and incorrect estimation bills. With smart meters, instant data are sent to a supplier, having precise energy data such as the system implemented in the experimental house described in Chapter 2. The difference between the supplier and the experimental house is that all the data from the testing laboratory is gathered to a specific server and maintained under constant observation.

Usually, when choosing to work with smart meters, separate meters for gas and electricity are provided, along with an in-home display (IHD). The IHD connects to the smart meters and receives real data about how much energy is used, as well as how much it costs. On the opposite side, the experimental house from UPB is connected to a localhost website reading instant data.

The smart meter passive house system can gather three distinct types of data: real-time data, persistent data and archived data. Each data is linked to a smart meter equipped with an SD slot card where a Raspbian operation system is installed.

Multiple applications are running on the system proving constant data collection. The interaction between the SMX and the HMI is made via a remote computer connected to the internet. Numerous modules are operating within the smart meter, creating a fluent workflow with the system.

Systems energy requirements and consumption precisely influence any building's performance in terms of costs and comfort. In this chapter, two methods for estimating the energy usage will be presented:

1. forward modeling
2. data-driven modeling.

There are three main components that describe a mathematical model and its behavior:

- input variables (defined as independent variables which are known to the system),
- system structure and parameters (serving as mandatory physical characterization of the running system), output variables (which is often known as the reaction/answer of the method).

Two basic procedures might be applied to any mathematical model, in the interest of determining the 3<sup>rd</sup> component or the output:

1. forward approach,
2. data-driven approach.

As we will be using both approaches, Fig. 3-1 is explaining the working procedure and the main objective of each. The forward approach is employed to forecast the output

parameters of a stated prototype, taking into consideration the knowledge about architecture and parameters when subject name the inputs. Forward approaches employ a physical characterization of structure's system or element of concern. In other words, location, building's properties, house's position, HVAC system or construction's material are known.

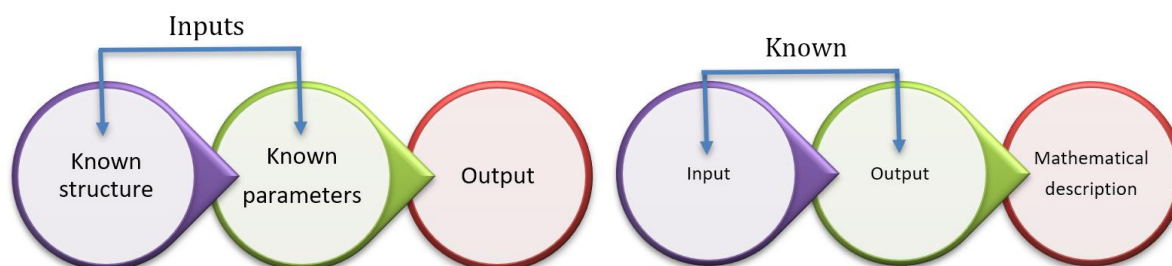


Fig. 3-1 Forward and data-driven approach

The data-driven approach implies knowing a big amount of data on entries and outputs. The major advantage of this method is the easiness of implementation of the system that does not require physical characteristics to forecast building behavior. This type of method performs in optimal condition when information is accessible for analyzation. To sum up, the second approach identifies system prototype with rigorous prediction of structure efficiency.

The difference between approaches consists into the number of gathered parameters due to reduced and recurrent data enclosed into database. Generally, forward approaches are more permissive than data-driven methods when it comes to energy estimation of building characteristics.

A recent development of smart meter system made possible the connectivity of every device to the IoT system, as long as the system is connected to the internet. Moreover, the IoT ecosystem can exchange information with any device connected, at any time or location via a unique platform.

A smart meter indicates the total amount of energy use, in real time, plus the total costs of the situation in country currency. One of the major advantages of using a SMX platform is the remote communication every device can have, due to the fact that, as long as mobile data connection is available, actions can be taken with a third-party application. Payments and house balances can be seen directly through a remote connection to the smart meter saving time and resources. The management usage can be registered and setup according to user preferences, implementing a better control on the energy consumption.

For the purpose of this thesis, weather data has been directly gathered from the external sensors, as well as confronting daily updates from the forecast website: Accuweather, Wunderground, Weather-forecast or Ventusky. Complex database was created by monitoring several cities from Europe (Lyon, Rome, Berlin, Bucharest) including 30 days forecast data. Additionally, Energy Plus website was used to identify weather inputs.

Taking into consideration the above information, the system implemented in the experimental house is able to gather real time data and solid databases, helping in numerical

methods, especially on estimating monthly energy consumption. Thus, fundamental methods of heat transfer will be presented along with a predictive control approach.

### 3.2. SMX (smart meter extension)

Smart Meter Extension (SMX) is a system implemented on a Raspberry Pi2 board, having a concentric data base architecture [95]. Within the data base, the communication with the application is not directly but through specific channels. This type of system protects the data with a RBAC (Role Based Access Control) software, allowing the information transfer to be done without interruption.

The first step in creating a SMX architecture based on a Raspberry PI2 single board computer is to create an image with the necessary files to allow application execution. The image consists of a package and a REST-API for the Mongo data base. To be noted that the image for the open-source SMX has all the essential programs already installed in a previous configuration. Thus, it allows the user to develop his own modules and to interact with the system according to his needs.

From a dynamic point of view, the SMX is able to detect three different types of data:

- 1) **Real-time data**, which is non-persistent data, and which is expected to be frequently modified (such as reactive power P and Q, voltage U or currents I)
- 2) **Persistent data**, which are memorized after the system turns on/off. The process of data written on the storage is assured by the SMX solution. On the other hand, the persistent data is used to create the Mongo database. If the user is not familiar with the MongoDB solution, NoSQL is proposed for storing this kind of data.

In communication with certain apps, the data can be exchanged as follows:

- the real-time communication with the SMXCore can be realized through a MongoDB module of the SMX.
  - the communication between the REST Api and the MongoDB can be established with any application trusted by the system. The benefit of using this sort of communication is the data-privacy, as well as for designing security policies.
- 3) **Achieved data**, which is very related to persistent data. This type of data has a time step interval from 1 to 60 seconds, depending on the user's needs. A considerable advantage of using this technique is the data-retrieval through offline readouts on separate files. Files are classified as: 1) daily; 2) weekly or 3) monthly files.

Valuable parameters such as P, Q, U, I or energy registers A+, A-, R+, R- can be seen into the database. Additionally, the evolution of data can be displayed using the SMX method where:

- Active Power (P), Reactive Power (Q),
- Voltage(U), Current(I), Frequency(F),
- Energy registers A+, A-, R+, R-.

The collection process of the data is exemplified with special modules such as FileStorage or FileRetrieve. In Fig. 3-2, the connection between the internet and the Smart Meter eXtension, with trusted and untrusted zones, is being presented. Specific modules are created in order to allow automatic readout of archived data.

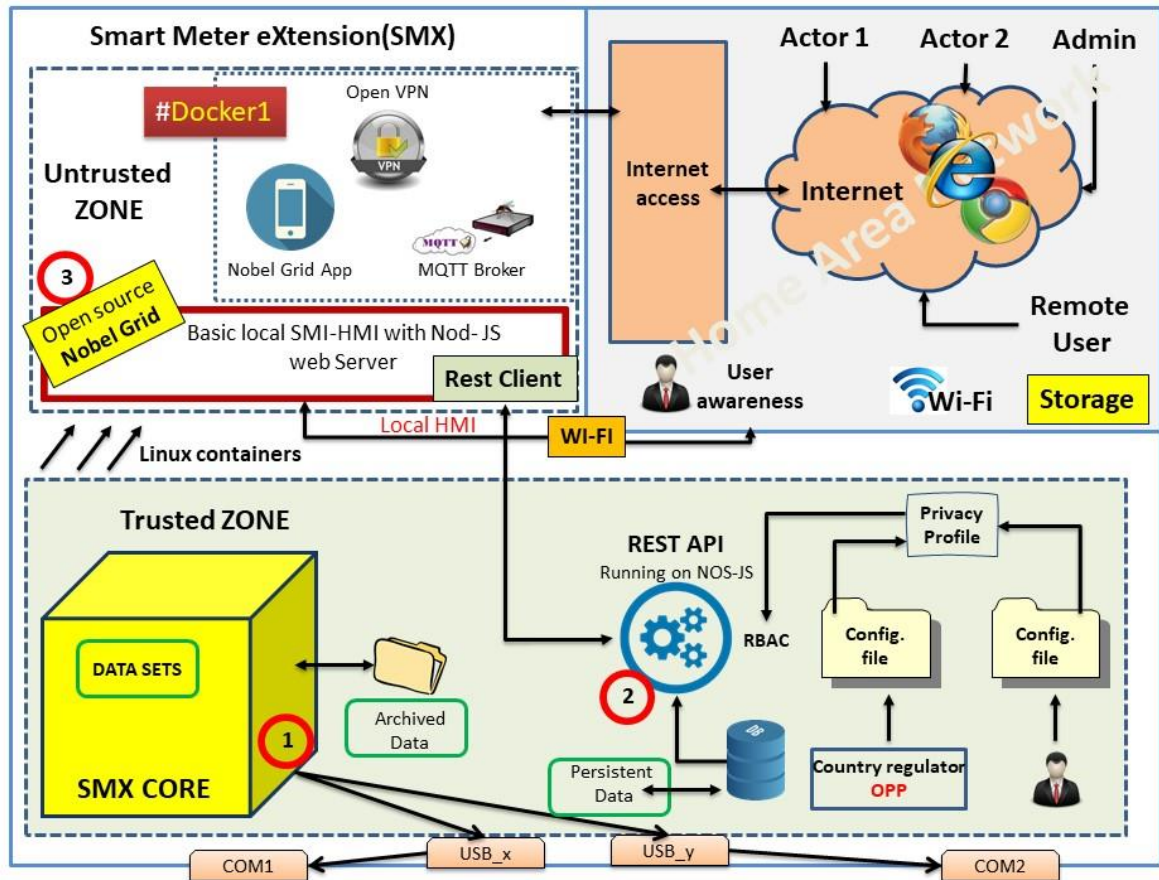


Fig. 3-2 Basic architecture of Smart Meter eXtension modules

The SMX is equipped with a SD slot card for multiple purposes. One of the advantages of using a SD card is the installation of a free *raspbian-jessie-lite-16-11-image*. Multiple modules are set to be turned on, once the connection SMX - SDcard is established:

- **Set of modules** - which are installed in the TZ (trusted zone). An important asset is the “MQTT Client” (Message Queuing Telemetry Transport) which can communicate with any external device. The client uses a Mosquitto MQTT broker and two Dockers: #0 and #2.

To be noted that any Docker “#x” is a group of Docker applications which can interact, even if they work under Docker restrictions, with the Trusted Zone through the REST Api of MongoDB or through an MQTT client of SMXCore. For security and privacy reason both will have RBAC system implemented.

- **MongoDB package** - available on the internet as an open-source package and is installed in TZ. This broker allows the connection of trusted applications to the real-time database.
- **REST API** - responsible for the direct connection between Apps and MongoDB. By using a token, only permitted data is allowed to be exchanged within the

communication with the database. Each user must have a mandatory PP (privacy profile) and an RBAC system installed.

- **Web-Server app** – running on a web-oriented Human Machine Interface (HMI) for local readout of SMX data. The App has Java script language-code, creating a powerful and stable NOD-JS web server. In particular, the image having the Basic-SMX-HMI works with two instances: 1) docker environment; 2) trusted zone. Both instances have two different ports, working complementarily.
- **OpenVPN** - strictly installed for the purpose of creating a safe remote connection to the server. As long as the network administrator is connected to the internet, it can access the system through the VPN connection.

Fig. 3-2 shows the packages that are installed on the SD card due to the fact that they are available on the internet as open-source. For instance, packages like MongoDB, Mosquitto Client and Nod-Js are available on the SMX basic architecture. Under these circumstances, a huge advantage of the SMX implementation is the further development of HMI applications in accordance with user's needs.

### 3.3. Starting the SMX application

There are several steps to follow in order to start the basic SMX application system, which are exemplified in the Appendices 7.4. First, the user needs to copy the installation-image on a 16 GB or more SD-card. Secondly, the user needs to insert the card in a Raspberry Pi 2 board in order to connect to a local network. Thirdly, a secure OpenVPN connection, for purposes of easy development, needs to be opened. Testing and security approval are required during this step because of the connection with the SMX. For this, when connected to a local network, through Ethernet cable, SMX will receive a random local address (such as 192.168.x.y). The exact allocated address should be found by using specific software which scans and discovers all the IP addresses on the network. Another solution for finding the right IP for the SMX is by looking into the DHCP server and recognizing the newest Linux machine.

Once the address is found (e.g. IP=192.168.6.97), the user can interact with SMX by two possibilities:

- 1) Through the Basic-SMX-HMI, by interacting with the NOD-JS webserver which is located in the untrusted zone.
- 2) Through an MQTT client, such as MQTT Lens, in order to have a publish-subscribe interaction with an existing MQTT Client in the SMXCore.

#### 3.3.1. Interaction with the publish-subscribe mechanism

The interaction with the publish-subscribe mechanism requires a couple of variables to be installed. On the condition of an uninterrupted interaction with the SMXCore, variables need a MQTT-Lens viewer or an MQTT client. Similar apps may be installed on the remote computer as long as they are compatible with the system.



In order to benefit from a fast and secure connection with the SMXCore, an MQTT broker was installed in the Trusted Zone. The only method that this can be accessed by SMXCore is through the IP address: “localhost:1883”, where 1883 is the port used for connection. As a result of the trusted application allowed, multiple Docker groups must have their individual MQTT Brokers. The interaction between the MQTT broker and the Third-party apps is assured by the Inverter – 6LoPan.

The communication process is simple and starts by turning on the MqttLens for the connection to the MQTT Broker. As exemplified in Fig. 3-3, the windows users must run the broker with the bellow configuration:

The screenshot shows the configuration interface for an MQTT broker. It is divided into several sections:

- Connection Details:**
  - Connection name:** LOCAL1
  - Connection color scheme:** A green color bar.
  - Hostname:** tcp:// localhost
  - Port:** 1883
  - Client ID:** lens\_1ymcrBBIT6IZ6zAU8DgXdMGDGK. A blue button labeled "Generate a random ID" is next to it.
  - Session:**  Clean Session
  - Automatic Connection:**  Automatic Connection
  - Keep Alive:** 120 seconds
- Credentials:**
  - Username:** Enter username
  - Password:** Enter password
  - Hash password with MD5
- Last-Will:** A dropdown arrow.

Fig. 3-3 Configuration of a MQTT broker

There are several fields to be completed in order for the connection to be well-established. The connection name field is strongly related with the name of the machine while the Hostname indicates the connection type to be used. Client ID is unique and can be manually generated, by the right blue button as seen in Fig. 3-3. Username and Password fields are the account details needed for to login into the SMXCore system.

Once the connection is stable and successful, the operator can choose the topic to be shown on the platform. Multiple topics can be selected at the same time having different codes stamps. The data readouts are exemplified with code core such as: “1-1-32-7-0-255”. Each code is correlated to a specific system parameter gathered from the server:

For voltage U1 on phase 1:	1-1-32-7-0-255
For active power P1 on phase 1:	1-1-36-7-0-255
For active power P2 on phase 2:	1-1-56-7-0-255
For active power P3 on phase 3:	1-1-76-7-0-255
For reactive power Q1 on phase 1:	1-1-151-7-0-255

For 3-phased active energy plus A +: 1-1-1-8-0-255

For 3-phased active energy minus A -: 1-1-2-8-0-255

To point out the exact SMXCore we are referring to, a specific prefix has been added to the SMX, with the pre-configuration: G3M40000001. The virtual meter data is registered in the collection of LD01 of the SMX database. In other words, the complete topic for identifying voltage U1 is subscribed as:

“G3M40000001/SMX/LD01/1-1-32-7-0-255/-2”

Correspondingly to this topic, the code needs to be introduced in the MQTT Lens and QoS must have the value equal to one. After clicking the Publish button, the MQTT-Lens retrieve data from the server, displaying the requested information on the lower part of the platform, as presented in Fig. 3-4.

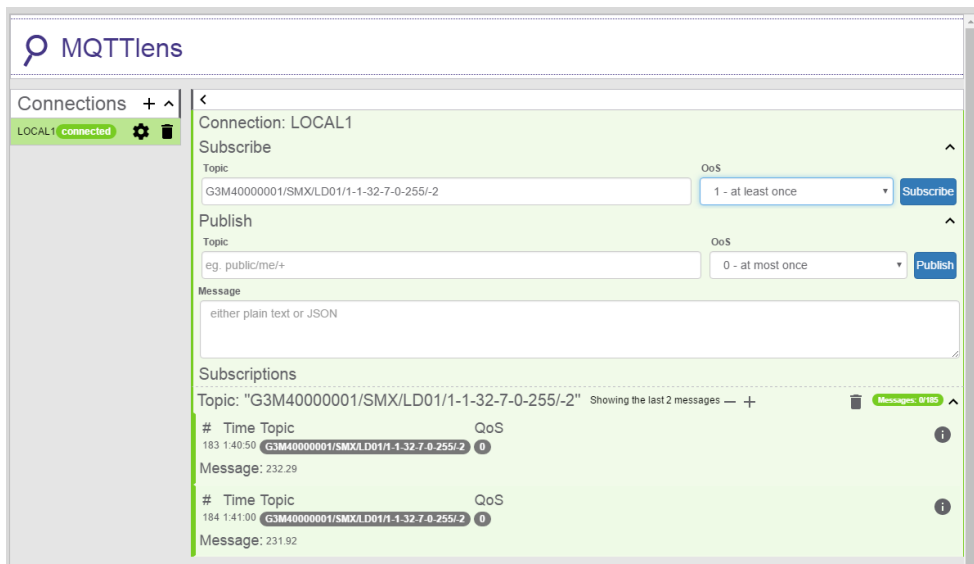


Fig. 3-4 MQTT Lens visualization of the voltage on phase 1

The users can organize, configure, and customize the files from SMXCore, especially the rate of publishing the selected data. For example, the voltage U1 can be selected from the panel to be displayed once per 5 seconds. Also, the system is able to memorize values as “preferred parameter” to display on the front panel. In Fig.3-4, it is illustrated the time gap between two consecutive publishes of voltage U1, 1:40:50 and then 1:41:00. The data collecting system was configured to gather information with a time step of 10 seconds between each print. The value of voltage U1 changed between periods, growing from 231.92 V to 232.29 V. Due to the fact that the virtual meter is changing randomly, the value of voltage should be maintained around 230 V with  $\pm 5\%$  error.

Fig. 3-5 is underlying the complementary publish of three different parameters in the same instance of time. The MQTT-Lens client assembles voltage, active power and three-phased active energy A+ in the LD01 collection stage.

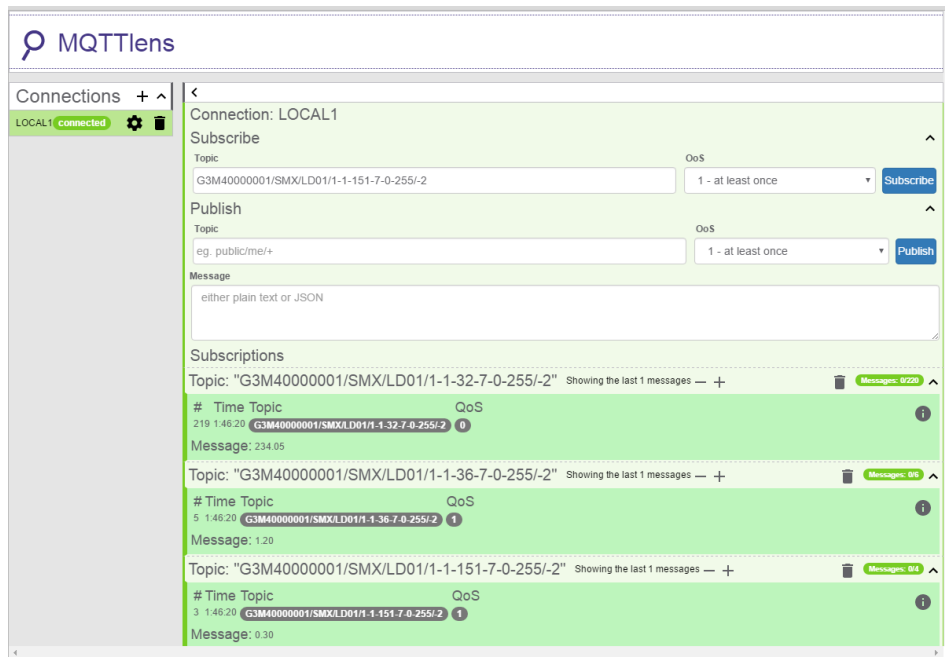


Fig. 3-5 MQTT Lens visualization of the 3 different measurements U, P1, and A+

The applications written by Nobel Grid partners or by third parties, is be able to connect in an analogous way by subscribing on similar topics and getting at 1 - 10 seconds intervals the requested data such as MQTT-Lens is doing.

### 3.3.2. Interaction between SMX – HMI

In order to realize the relation between the SMX and the HMI via a remote computer, an example of basic HMI is administered on the SD card image. The example explained in the below paragraphs is not a project related to HMI but simplifies an internal testing interface.

The REST Api server and the SMX-HMI need to start automatically, as simple services. There might be particular cases when the user starts the services manually, but the event only happens in Windows operation system (important notice: Apps can run in Windows operating system, not only in Linux).

Two steps are required to be filled in:

- 1) The user can access **REST Api** directory location. Usually, path is standard and can be found at the following address:

“C:\home\pi\data\apps\ngapi”,

After locating the Rest Api directory, the user needs to type the following line-based command:

```
“Node server.js”
```

For windows users, the following CMD (command prompt) messages must be written:

```
C:\home\pi\data\apps\ngapi>node server.js
js-bson: Failed to load c++ bson extension, using pure JS version
Express server listening on port 3000
```

Once completed the first step, adding the above command line-based, the **REST Api** is running and accepts requests on port 3000 (which is the default port for connecting to MongoDB).

- 2) In due time, the **Web Application** from the trusted zone needs to be turned on and have access to the root directory:

“C:\home\pi\data\apps\ngclient”

After the Web application is turned on, the JavaScript file needs to be accessed with the following command:

“Node app.js”

For windows users, the following CMD (command prompt) messages must be written:

```
C:\home\pi\data\apps\ngclient>node app.js  
listening on *:2000
```

As long as there is no error message displayed, the second step is considered to be complete and the application will start to interact with the REST Api (started with the previous command) being able to display values brought from database. In order to access the SMX-HMI, an external device must be used. The user can navigate in the trusted zone through a local IP address as well as a second session of the SMX-HMI, the Docker.

The application runs on a NOD-JS web server and provides information about the meter data of a virtual meter. This virtual meter can be simulated by SMXCore under the module VirtualMeter1. In Fig. 3-6, a print-screen of a typical SMX-HMI data retrieval is presented. The user requested values depend on the zones, time and parameter. Additionally, the organigram of the HMI is systematized in several tabs, choosing to display only the preferred parameters such as: voltage, current, reactive power, active power or active energy. The standard platform is being organized in three main tabs: home, new and new2. The name of these tabs can be chosen by the user in order to create simple identify situations. For instance, the Home tab may be representing the Living room and the “New” tab may be assigned to bathroom. Each tab of the platform can be defined by one or several zones.

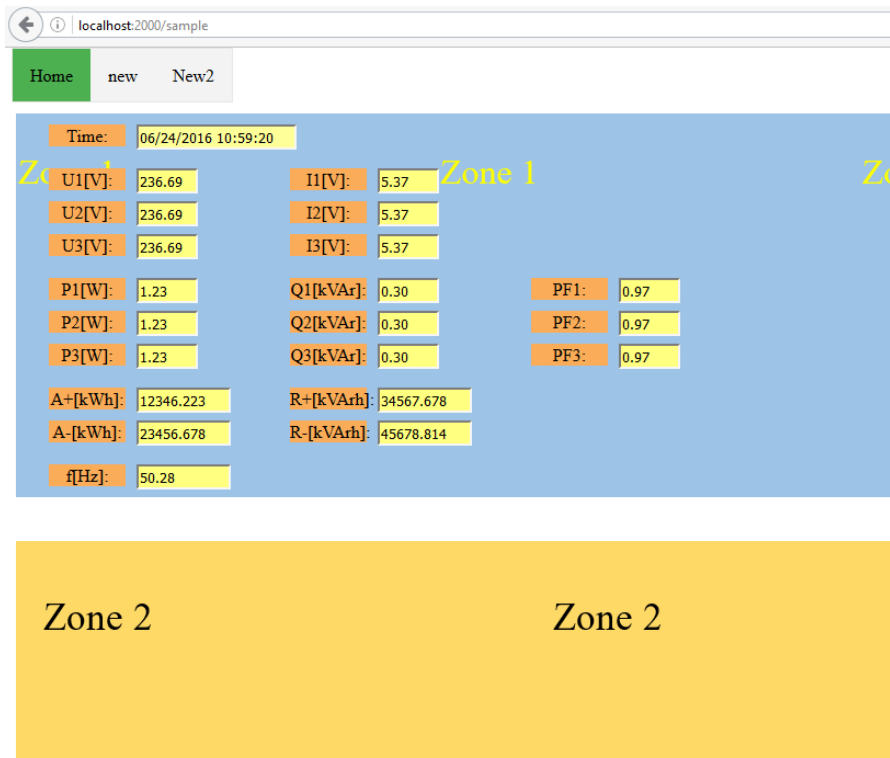


Fig. 3-6 SMX-HMI example

In general, the first TAB (called Home) has two zones, which have background images of different colors. Outlined, using caps lock it is written the name of zone: “Zone 1” (on blue for the first zone) and “Zone 2” (on yellow for the second zone). The background color can be chosen by the user, each zone having a default dimension. Based on user’s parameterization, different variables can be displayed inside the zones. To exemplify, a set of values belonging to the virtual meter are displayed in the Fig.5, namely: Voltages (U1, 2, 3), Currents (I1, 2, 3), Active powers (P1, 2, 3), Reactive powers (Q1, 2, 3), Index of active and Reactive energy, Power factors on each phase and last, the Frequency. Values are changing with a time step of 10 seconds, as the refresh rate for these values has been preset up.

### 3.4. Description of SMXCores

The Raspberry Pi2 is being part of a series of small designed computers with a size of a credit card, developed for promoting the computer science in schools or universities. In the below exemplification of a Raspberry Pi2 board, there are two packages of open-source software developed within Nobel Grid project [96]:

- the SMXCore package,
- the SMX REST-Api package.

Examples of how to connect apps to the databases were developed within the Nobel Grid projects, as proof of concepts, to inspire other providers to develop different apps [96]. One example is the SMX-HMI web-interface, emphasized below, where a Nod-JS and Javascript based interface are in a strong connection. SMXCore is part of a SW package which implements in JavaScript a set of functionalities inside standard modules.

Fig. 3-7 shows the complex structure of SMXCore and its modules, as it is developed at the moment.

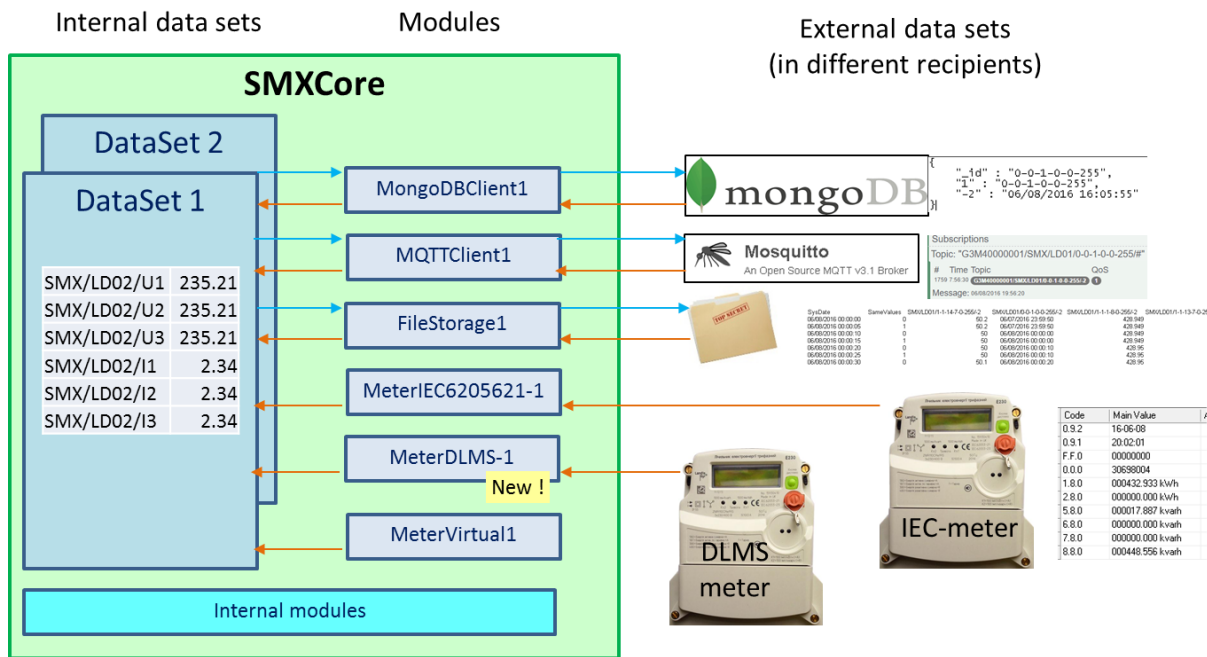


Fig. 3-7 SMXCore modules (current situation, other modules may appear)

SMXCore is developed to run in a database centric concept, having real-time inputs, organized in data sets (DataSet1 and DataSet2 on the left side of the figure are given as examples). The user can define as many sets as needed, in order to separate and improve efficiency in searching information from separate sets.

Every module interacts with a recipient outside the SMXCore and with Data Set, inside. In the presented version, as seen in Fig.3-6, the supported recipients are:

1. Metrology meter (SMM).
2. MongoDB database.
3. Mosquitto MQTT broker.
4. Archive files on the SMX storage (SD card).

It is possible to administer more than one recipient of the same type, each having different initialization of the corresponding module. For instance, if the SMXCore need to read two different meters with a standard protocol (e.g. IEC62056-21), then each meter should be controlled by a distinctive module. (e.g. MeterIEC6205621-1 and MeterIEC6205621-2, both modules having individual parameterization file).

If the database needs to be connected to two different MQTT brokers, then every MQTT connection should be managed by a different MQTTClient module (e.g. one in the TZ and one in the UTZ). For instance, a good example is taking a random MQTT broker from TZ and sees the exemplification to a unique MQTTClient. On the other hand, taking another MQTT broker from UTZ it will be exemplified by a separate MQTTClient.

Fig. 3-8 presents two meters and two MQTT brokers while establishing a connection in the communication with the SMXCore is granted. The SMX Untrusted Zone is always linked to the Internet having secured and safe connection. The MQTT broker is used as a

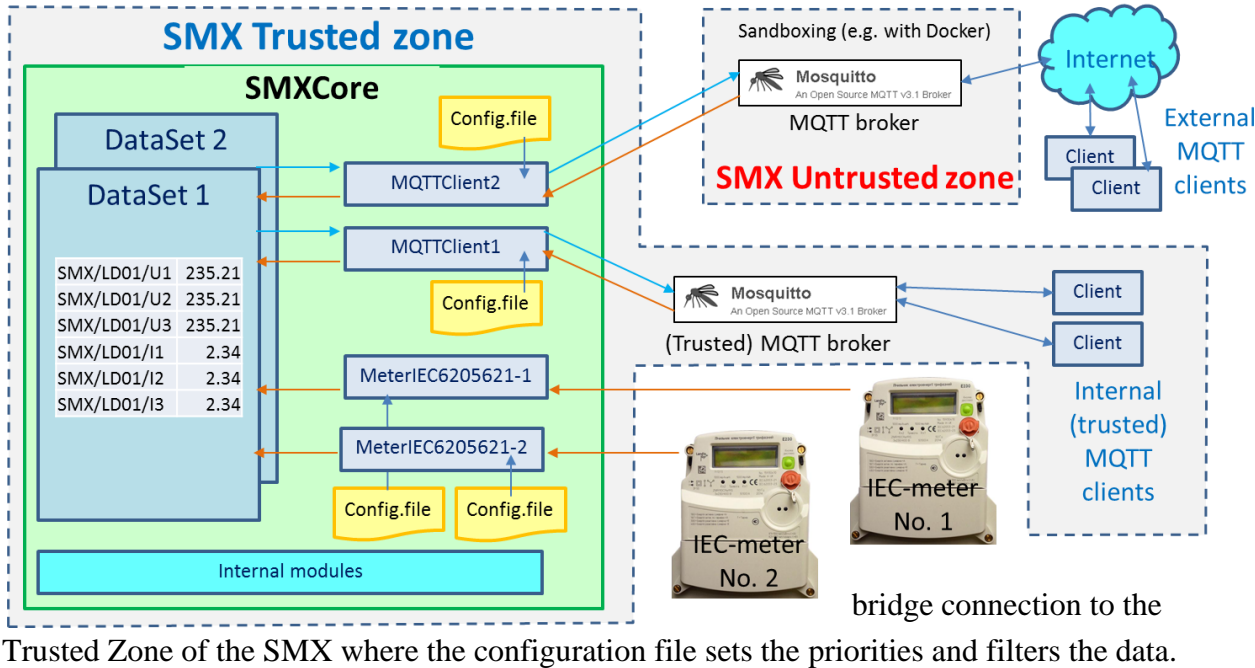


Fig. 3-8 Example of SMXCore modules instantiation

With a complex data exchange between the MQTT client and server through lightweight messaging, the client receives all the necessary data in seconds after the request. Generally, the network service protocol is working on a strengthened relationship between the client, broker and server. There are two basic connections between the client and the server. The first one, implies the client (device) to send data to broker with a publish request, while in the second one the broker subscribes the information and retrieves what it was asked for. For example, the IEC-meter No. 2 sensor is able to gather information about temperature and luminosity from the environment. The device is sending his readings to a specific broker inside the SMX core while another device (e.g. phone) is asking to receive this temperature value. In the first phase, the device describes the subject and publishes to the MQTT broker, then issues a note with Outside Temperature Value, that will be displayed on the device. Last, the task of the broker is to determine the note (Outside Temperature Value) and transfer to the phone's application.

### 3.5. Starting SMXCore modules

SMXCore can initiate different modules at startup, which is exemplified in Appendices 7.4. For this, the SMXCore needs to be started by Java with a parameter pointing to the configuration file. Also, Modules.txt, the content file describing the module is detailed. To put it differently, below it can be found the content of "SMXCore.bat" which allows

starting SMXCore with “Modules.txt” as an argument. In case of missing the argument, the name “Modules.txt” is taken by default.

By looking at the content from “Modules.txt” in Appendices, explanations can be seen in blue color (not existing in the file). The content of the text file includes the number of modules which can be higher than the SMX number of modules. Moreover, each module has a name, type and attribute assigned by the user, in order to easily identify the requested parameter.

### **3.5.1. MeterVirtual - Module**

This module type has been developed for testing purposes. In the configuration file, the Modules.txt has been chosen to initiate a MeterVirtual module. This module has assigned a text file named MeterVirtual1.txt, which can be found at the root location exemplified below:

C:\home\pi\data\SMXcore\App1	(Windows version)
home\pi\data\SMXcore\App1	(Linux/RPI2 version)

The pre-developed configuration file is exemplified in Appendices 7.4 showing important assets about the data collecting system. In the beginning stage of the collecting data, a preset default name is being assigned to the Data Set where variable will be stored. Each database has a specific prefix for easy recognition and a specified period for refreshing the data values. As seen in Appendices 7 the user can select what parameters the system should return for analysis. Values of voltage, current, power factor, average power factor, frequency or energy index are some of the possibilities that user can select. In order to observe the distinction between data sets, the user can select the number of decimals to be used after point, giving the resolution precise information about each parameter.

These values are stored in the collection “LD01” inside the “DataSet1” in a form which can be retrieved by using COSEM codes. For instance, U1 voltage is stored as a variable with COSEM related code ID= “1-1-32-7-0-255”. Both MQTT messages and JSON data in the MongoDB database will have associated this COSEM related ID.

### **3.5.2. Physical meter module**

This module type is a driver for reading meters through the IEC62056-21 protocol. Comparing with a DLMS module, this protocol is easier and available by default in the existing meters. Based on the configuration file from Modules.txt, it has been customized with “MeterIEC6205621-1” name and a text file named “MeterIEC6205621-1.txt”, which can be found at specified location:

C:\home\pi\data\SMXcore\App1	(Windows version)
Home\pi\data\SMXcore\App1	(Linux/RPI2 version)



As mentioned before, the pre-developed configuration file with text code and information (blue text) can be seen in Appendices 7. The contents of the meter module values are stored under a particular data set showing information about the collection type and database assignment. Also, the period of refreshing data values is visible at preset at 10 seconds. Likewise, the communication with the meter is based on and USB port with a 300 baud speed band. The 7 bits communication message has a timeout period of 20 seconds and an address assigned. If no address is nominated, the meter will entrust a default address for a reliable communication with the system.

### 3.5.3. Database module

This module type is a driver for allowing communication with MongoDB connection.

In the current configuration file described in “Modules.txt”, the module type has been initiated with the name “MongDBCClient1” and has a configuration file named “MongDBCClient1.txt”, which can be found at this location:

C:\home\pi\data\SMXcore\App1	(Windows version)
home\pi\data\SMXcore\App1	(Linux/RPI2 version)

The pre-deployed configuration file is exemplified in Appendices 7 outlining the communication of data set with Mongo database. As specified above, each database, data readings and internal SMXCore have a specific prefix. There’s a specific path for each Mongo database that has a name and a collection tab attached to the period between two automatic queries. First, an association file reads the data then writes the data into the MongoDB. Secondly, as seen in Appendices 7, the readout association text has an internal attribute, reading real time parameters from the devices.

### 3.5.4. MQTTClient - Module

This module type is a driver for allowing communication with an MQTT module.

In the current configuration file of Modules.txt this module is initiated with the name “*MQTTClient1*” and has a structure file of *MQTTClient1.txt*, which can be found at this upcoming location:

C:\home\pi\data\SMXcore\App1	(Windows version)
home\pi\data\SMXcore\App1	(Linux/RPI2 version)

In the pre-development version, the file contains specific datasets to communicate with the MQTT and preset prefixes for data and database, as seen in Appendices 7. The broker is assigned with address and account information in order to be accessed. Username and password are required for the connection to the MQTT broker. There is a publish and a subscribe association text file created inside the MQTT broker services that decrypt the messages received from any device and returns the requested information. In Appendices 7, multiple examples of how data is received can be seen.

### 3.5.5. Storage module

This module type is a driver permitting data to be saved in a specific file from the disk. This archived data is saved daily under selected name files. The script from the *Modules.txt* file demands initialization for multiple modules: “*FileStorage X*” respectively “*FileStorage Y*”, where X is the first module and Y is the last module. Each one has a different configuration file, starting from *FileStorage1.txt* and ending with *FileStorageY.txt*. All files can be found at the location presented below:

C:\home\pi\data\SMXcore\App1	(Windows version)
home\pi\data\SMXcore\App1	(Linux/RPI2 version)

The content of *FileStorageX.txt* has a SMX prefix, gathered on Dataset 1 with a time step of 10 seconds. The storage association file is saving information about format, clock, exact date time and certain parameters selected by the user, as presented in Appendices 7.

### 3.5.6. MeterDLMS client modules

This module type is a driver that allows the communication between a meter and DLMS (distribution line message specification) protocol. The module is an adaptation of Gurux open-source DLMS module in Java, which has a GNU-based GPL license. In the current configuration of “*Modules.txt*” this module type is initiated with the name “*MeterDLMSClient1*” and has a configuration file named “*MeterDLMSClient1.txt*”, which can be found at the location below:

C:\home\pi\data\SMXcore\App1	(Windows version)
home\pi\data\SMXcore\App1	(Linux/RPI2 version)

In the pre-development version, the file is able to detect the prefix of the DLMS meter showing the collection folder and the database assigned. The period refreshing data values is 10 sec while the Gurux description files are reading data from the meter in blocks. OBIS (Object Identification System) codes are used as logical names of data objects, in order to determine the identification of data in DLMS protocol. As described in Appendices 7, the Gurux objects are gathered in blocks, more than one at time if the value of block read is equal to 1. [97].

The most complex line from the data readout can be submitted as follows:

```
sCmdLineArgs = /m=lgz /sp=COM13 /b=9600 /s=DLMS /a=Low /pw=00000000
```

where

/m=lgz describes the manufacturer, in this case lgz means Landis+Gyr, [98],

/sp=COM13 describes the serial connection to the meter, in this case being COM13. To be noted that in Linux platform, if the serial link is obtained through a USB-RS232 module, it might have as serial connection like “USBtty0”,

/b=9600 gives the communication speed (in this case being 9600 baud),

/s=DLMS shows the used protocol (DLMS),

/a=Low gives the security level when connected to read data (in this case being “Low”). To be noted that DLMS defines three security levels of connection: Low, Medium and High,

/pw=00000000 gives password for the chosen security level. To be noted that the password can be changed by the meter owner according to its security policy. To put it another way, different meters may have different passwords.

In the current implementation, there are three different requests during each period. If all requests take more than the time declared in the first period, then one period is lost every time this situation occurs. For instance, if *first\_period* = 1000 ms, then all the requests need to be finalized (three question + three answers) in less than 1000 ms. In the *trace.txt* file (see example bellow) it can be identified of how the exchanged messages between the module and ZMG310CT meter are recorded.

```

<- 10:54:47.000      7E A0 20 03 41 BA EB 00 E6 E6 00 05 06 02 31 D0 02 32 60 02 32 F0 02 3B C0
02 3C 50 02 3C E0 5B D5 7E
-> 10:54:47.124      7E A0 32 41 03 DA 22 5F E6 E7 00 0C 06 00 05 00 00 08 E5 00 05 00 00 00
00 05 00 00 00 00 00 05 00 00 00 00 00 00 00 05 00 00 00 00 00 97 74 7E
<- 10:54:47.132      7E A0 20 03 41 DC DB 06 E6 E6 00 05 06 02 3B 30 02 3D 70 02 35 C0 02 34 10
02 34 A0 02 35 30 E0 FE 7E
-> 10:54:47.254      7E A0 32 41 03 FC 16 1B E6 E7 00 0C 06 00 05 00 00 00 00 00 05 00 00 00
00 05 00 00 01 F2 00 05 00 00 00 00 00 05 00 00 00 00 00 05 00 00 00 00 BA 56 7E
<- 10:54:47.264      7E A0 23 03 41 FE 06 21 E6 E6 00 05 07 02 3B C0 02 3C 50 02 3C E0 02 10 98
02 11 30 02 11 C8 02 12 60 F2 B1 7E
-> 10:54:47.422      7E A0 48 41 03 1E E1 59 E6 E7 00 0C 07 00 05 00 00 00 00 00 05 00 00 00
00 05 00 00 00 00 00 14 00 00 00 00 00 00 00 00 14 00 00 00 00 00 00 00 14 00 00 00
00 00 00 00 00 14 00 00 00 00 00 00 00 DD AC 7E
<- 10:54:48.001      7E A0 20 03 41 10 BB 0A E6 E6 00 05 06 02 31 D0 02 32 60 02 32 F0 02 3B C0
02 3C 50 02 3C E0 5B D5 7E
-> 10:54:48.124      7E A0 32 41 03 30 76 17 E6 E7 00 0C 06 00 05 00 00 08 E4 00 05 00 00 00
00 05 00 00 00 00 00 05 00 00 00 00 00 00 05 00 00 00 00 00 A3 B1 7E
<- 10:54:48.132      7E A0 20 03 41 32 AB 08 E6 E6 00 05 06 02 3B 30 02 3D 70 02 35 C0 02 34 10
02 34 A0 02 35 30 E0 FE 7E
-> 10:54:48.254      7E A0 32 41 03 52 62 57 E6 E7 00 0C 06 00 05 00 00 00 00 00 05 00 00 00
00 05 00 00 01 F3 00 05 00 00 00 00 00 05 00 00 00 00 00 05 00 00 00 00 F3 C5 7E
<- 10:54:48.262      7E A0 23 03 41 54 56 2B E6 E6 00 05 07 02 3B C0 02 3C 50 02 3C E0 02 10 98
02 11 30 02 11 C8 02 12 60 F2 B1 7E
-> 10:54:48.423      7E A0 48 41 03 74 BD 95 E6 E7 00 0C 07 00 05 00 00 00 00 00 05 00 00 00
00 05 00 00 00 00 00 14 00 00 00 00 00 00 00 00 14 00 00 00 00 00 00 00 14 00 00 00
00 00 00 00 00 14 00 00 00 00 00 00 00 DD AC 7E
<- 10:54:49.000      7E A0 20 03 41 76 8B 0C E6 E6 00 05 06 02 31 D0 02 32 60 02 32 F0 02 3B C0
02 3C 50 02 3C E0 5B D5 7E
-> 10:54:49.124      7E A0 32 41 03 96 4A D7 E6 E7 00 0C 06 00 05 00 00 08 E5 00 05 00 00 00
00 05 00 00 00 00 00 05 00 00 00 00 00 05 00 00 00 00 00 97 74 7E

```

Fig. 3-9 Trace file message analysis

In other words, by analyzing the trace file after the initialization took place, additional information is requested by the meter. Also, it may take longer time to process the examination of all three sets of messages as seen in Fig. 3-9. In fact, the first request is marked with yellow highlight color at 10:54:47.000, and the reply (answer) for the third

message set is highlighted with green color, marked at 10:54:47.422. The meaning of the data obtained during the request-period could be obtained in less than 1000 ms (less than one second). Most compelling evidence is the time gap for each data acquisition giving additional time to make supplementary request during the second request.

Different meters can react individually from a perspective reaction-time point of view, as each type of meter needs to be assessed by the required period to read all the suggested data (as OBIS codes).

### 3.6. Physical and electrical input parameters acquisition

#### 3.6.1. Data collection and experimental wall details

Information about data collection and wall characteristics have been acquired from empirical setting configured in support of a dynamic examination ability. Testing facility's wall was made with a surplus of insulation having 5 x 2.5 m<sup>2</sup> width and height. Also, testing zone covers 2 x 1.2 m<sup>2</sup> width and height and is oriented SW. In Fig.3-9, testing wall composition is exemplified, underlying three main components:

- 2 x glass layers
- 1 x gas layers
- 1 x wood fiber layer
- Protection material

The width of the experimental wall is 204 mm while the HF metering are installed in the wood layer. Moreover, temperature sensor's location is outwards the glass fiber layer as represented in Fig. 3-10:

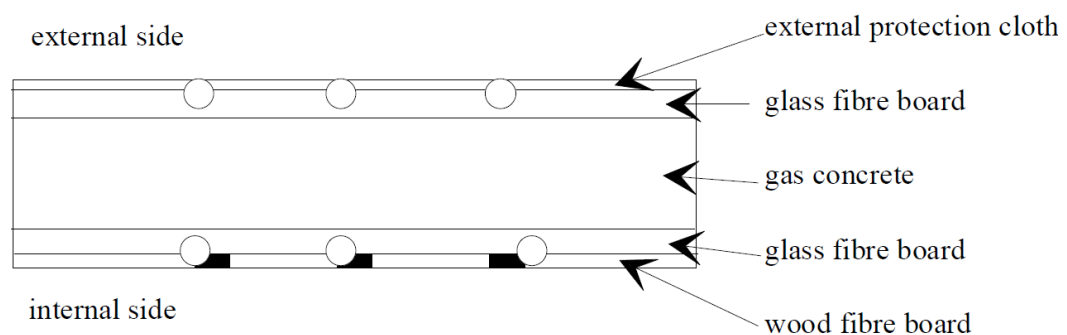


Fig. 3-10 Location of temperature sensors and heat flux meters

The sensors are gathering temperature information every 5 minutes as interval observation. There are two data sets extracted from the database containing 30 minutes mean values which are prepared for this three-layer wall analysis. Data-Cseries1 is responsible for the estimation of the data set, consisting of mean values of three variables: two temperatures (interior and exterior) and one heat flow such Table 3-1. During the measurement period, the wall was exposed to solar radiation.

Table 3-1 Data\_Series1 example

<b>Exterior Temperature</b>	<b>Interior Temperature</b>	<b>Heat Flux</b>
11.72967	22.379	1.924219
12.11367	22.34567	1.904193
12.23733	22.31533	1.963261
12.569	22.26967	1.962753
12.92667	22.23833	2.018257
12.877	22.211	2.036569
12.847	22.17467	2.077734
12.974	22.14733	2.089618
13.333	22.11767	2.13365
13.639	22.09566	2.136929
13.73467	22.064	2.17889
13.736	22.04833	2.196409
13.81667	22.024	2.231098
14.054	21.99767	2.226425
14.33267	21.97567	2.25561
14.35667	21.96767	2.259986
14.59133	21.94833	2.276707
15.62033	21.92733	2.276377

On the other hand, Data\_C\_series2 is subject to the prediction sets. They are composed of mean values regarding inner and outer temperatures. Within the evaluation interval, the wall was covered with a protective cloth. Data\_series1 and Data\_series2 are two different measurement sequences out of identical wall testing set-up as represented in Table 3-2.

Table 3-2 Data\_Series 2 example

<b>Text</b>	<b>Tint</b>
<b>14.35033</b>	22.07567
<b>14.30067</b>	22.06267
<b>14.248</b>	22.05633
<b>14.16633</b>	22.037
<b>14.15067</b>	22.03833
<b>14.203</b>	22.02833
<b>14.13067</b>	22.016
<b>13.92933</b>	22.01533
<b>14.05767</b>	22.002
<b>14.051</b>	21.99267
<b>14.24567</b>	21.981
<b>14.467</b>	21.963
<b>14.67333</b>	21.95167

<b>15.009</b>	21.95533
<b>15.46</b>	21.94867
<b>16.01367</b>	21.94
<b>16.296</b>	21.94133
<b>16.70833</b>	21.94267
<b>17.407</b>	21.943

To calculate the heat flux density, three consecutive values of HF were taken in this work and made an average. In the same manner, outer and inner temperatures were calculated. All 31 days includes 1500 data samples (once per 5-minute data collection) of estimated average values of data record. Density and humidity are stable in the walls layer. To deliver parameters estimation of R and C, their standard deviation needs to be determined first (sR and sC).

### 3.6.2.Types of data

Physical and electrical input parameters are useful to determine the initial status of the problem and to have a reference point for the running algorithm. These values are being transmitted by the smart meter implemented on the testing facility with an extended digital meter installed. This extension sends real-time information about energy consumption of every electrical device connected to the house's electrical grid. In addition, web services are used to send data to the platform and connect 3rd party application to the system. These services are the basic functionality for which Service Oriented Architecture (SOA) relies on. A simple data request between two or more services is based on communication protocols such as SOA. For instance, the communication can be translated as an activity of message request to a specific provider from the customer. In consideration, the supplier replies with an identical service communication to the client.

Detailed and exemplified information about the communication process is being presented in

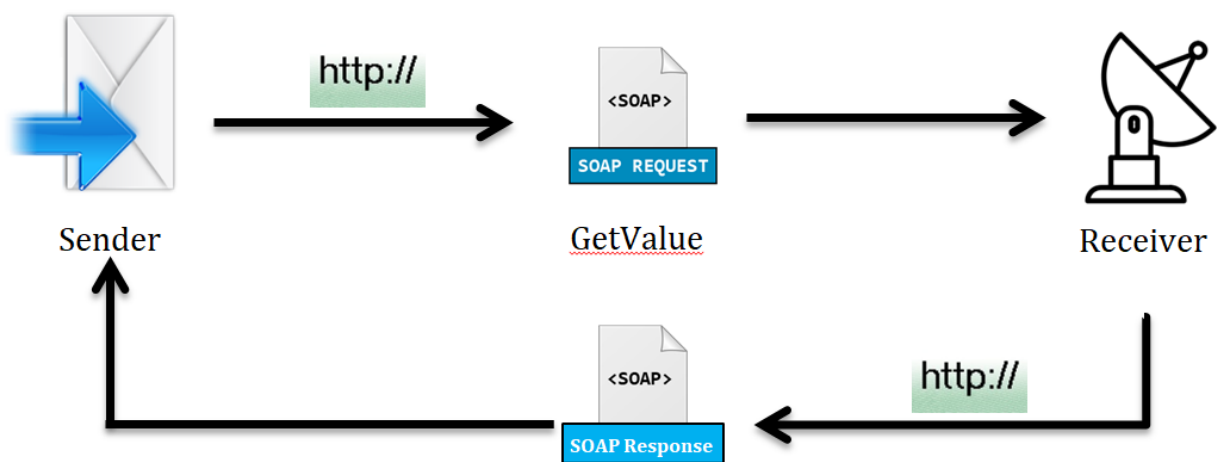


Fig. 3-11 Communication protocols [99]

Fig. 3-11 is pointing out how the applications are exchanging information. The sender addresses a web message through HTTP (Hypertext Transfer Protocol) protocol on WWW (World Wide Web), as SOAP (Simple Object Access Protocol) request to get a value from the server hosting. The function defined to request a value is GetValue. The server receives the message, uses a web service to combine the client with the server and uses Extensible Markup Language (XML) to understand the code from the message. In return, using the same HTTP protocol, the receiver is delivering the message to the sender in an XML form. As an advantage of the monitoring system that is used, a diversity of web services is offered to the user's selection in accordance with the data he needs to know about.

### **3.6.3. Classification of data and acquisition**

The SMXCore offers a variety of important data to be harvested using Smart Meters:

- Real-time data
- Persistent data
- Archived data

The first type of data is frequently modified and can be obtained from the SMXcore by using smart meters. Since this type of data is achieved using MQTT, the SMXCore knows how to access the memory panel from where data is preserved as friendly variables. An important asset is that real-time data are not saved on the disk. MongoDB is responsible for saving persistent data and assuring the dataflow transaction with the smart meter. There are two ways to communicate with the smart meter and database: 1) through a MongoDB entity; 2) with an application using REST API (representation of state transfer for application program interface).

The 3<sup>rd</sup> type of data that the system is able to harvest is the archived data, which are very common with persistent data, collecting information with a time-step of 1 up to 10 minutes. Archived data have hourly, daily and monthly logs supplying information for each consumer for a better understanding and analysis of the system.

According to a pre-setup time implementation, data can be collected by the SMX platform and can be summarized in 3 main block chains: Internet zone, trusted zone and untrusted zone. The working module presented by the SMX architecture is providing a secured connecting with 3rd party applications, as Fig. 3-12 is demonstrating. The data access and the collection of information can be accessed through the first block chain of the system Untrusted Zone. All the data gathered from the smart meters can be access by using web application from this particular zone.

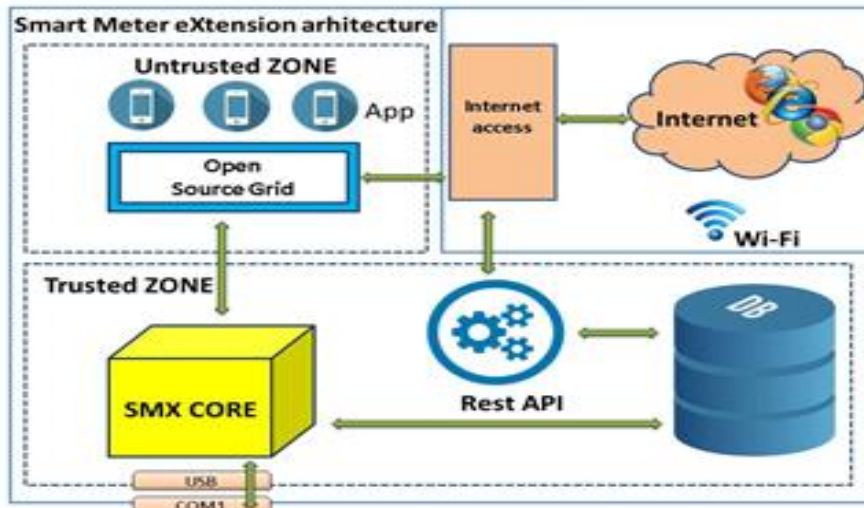


Fig. 3-12 SMX architecture [99]

Referring to the trusted zone, the SMXCore and smart meters are communicating via a software, namely MQTT Protocols. The principle of having a MQTT Protocol is simple and can be similar to a cutting off the signal between the subscriber and the publisher. Disconnections of any publisher and connections of every user with the MQTT protocols are settled by the broker, regardless the network used.

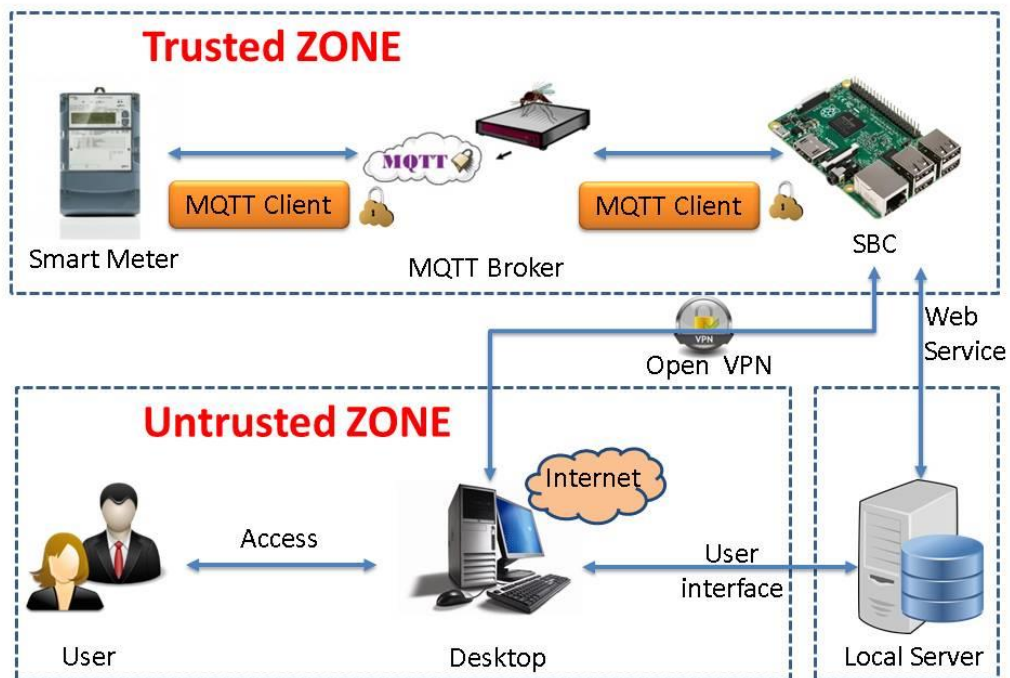


Fig. 3-13 Connectivity and zones [99]

To understand the connection grid and the channels of communication Fig. 3-13 was designed. Also, the components of the network are pointing the zones in clear identification. On the top of the image, marked with red color, the *Trusted zone* is defined as being the link between the Smart Meter and the MQTT Broker to the SBC controller board. An important



asset about the MQTT broker is the range of connecting multiple devices to the server at once. One Broker can handle responsibilities such as:

- Message receiver
- Message sender
- Set-up Priorities
- Message filtering
- Data holding sessions
- Decisions
- Authentication of clients

The channel communication system of any type of data in the untrusted zone is simple and based on strict principles. Firstly, every smart meter from the testing laboratory collects electrical and thermal parameters. Secondly, a MQTT client transports data without any losses to the broker. Thirdly, the connection with the SBC board is being kept safe and ready for analysis. The MQTT broker receives a message request from the device and transfer it to the board computer for additional guidance. In order to have a constant development on the system the local machine has been equipped with an open source project, grating uninterrupted connection to the server. Finally, with an open VPN connection, every user can interact with the SBC system and develop an individual algorithm for the residential building in order to maximize the energy savings.

Quite the opposite, trusted zone is where the secured information is being stored up. The database of the system is filtering and analyzing every data received, waiting for further commands. The connection between the local server and the smart meter is fulfilled by an event of the broker (MQTT), fully displayed in the below Fig. 3-14.

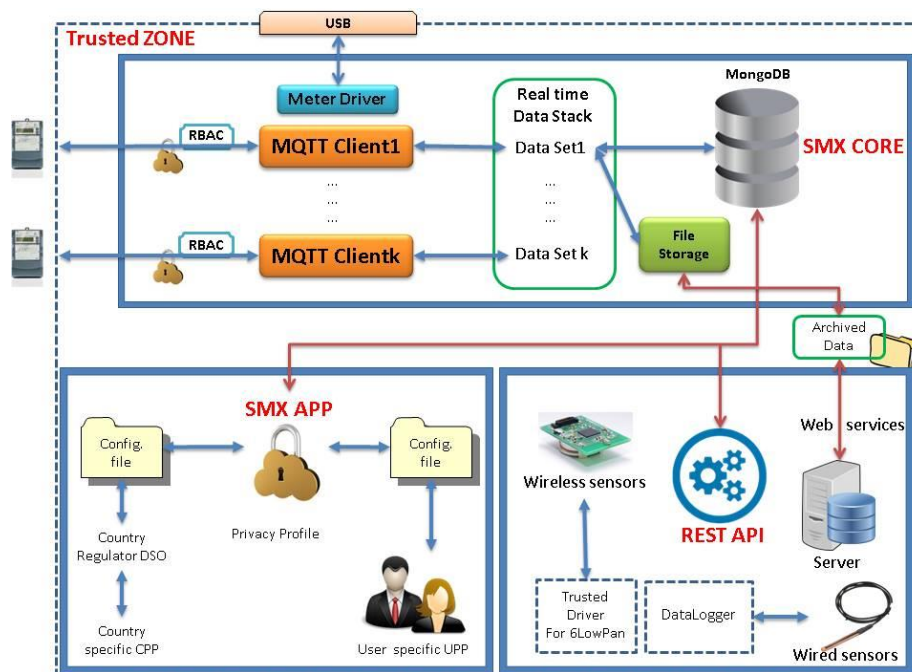


Fig. 3-14 Data workflow [99]

This particular instance generates a request to the metering systems device and in exchange, data is transferred to Smart Building Controller for analysis. Each user has privacy

data stored in a local server to better understand the behavior of residential building. There are two methods to interact with the SMX platform: HMI or Rest Api. These friendly applications are triggered at the same time with the operating system (OS), lowering data losses or further malfunctions.

Each phase has its own SMX interface, adjusting and creating numerous tabs for each smart meter connected to the network system. Applications are responsible for cooperating with every module from the SMXCore while real-time values are systematized in data sets and withdraw from Mongo database. Another important advantage of the data collection security level is that any client can set up different privacy profiles on the RBAC, having exclusive data for each corresponding module.

### 3.7. **Data collection and integration through IoT**

An ongoing dispute on the energy sector is the implementation of Internet of Things (IoT) within any eco-system or residential buildings. Sustaining the modernization of IoT direction, there was a constant struggle between gathering data and providing the best solution to secure this information acquisition.

The prediction of input data is related to the newest technologies recently implemented into the testing facility form UPB, which is running on an IoT working module. The goal of the chosen purpose is to understand the behavior of the people living inside the building. The system is programmed to analyze and monitor input data, especially the comfort parameters in any kind of residential constructions. Moreover, a platform has been created to investigate the data collected and to assimilate it with current technology in order to save energy as much as possible. In addition, by connecting 3<sup>rd</sup>-party apps to the IoT system model, the experience level for each individual is adequate to a friendly and easy utilization. The experimental design is working under wireless network sensors capable of sending instant data to the IoT system.

The first IoT device was set up in 1974 [100], [101]. The EC Directive from European Commission estimates an increase in devices connected to the IoT which will consist the next generation of Smart Cities [102]–[104]. The use of computerized automation is advancing daily, introducing new opportunities and approaches to higher comfort. User and buildings behavior has been adapted to this continuous monitoring system to the Internet, saving time and fixing financial issues [102]. Nevertheless, sensors and exchanging data with higher rate developed a necessity to organize and to reduce energy consumption through cloud monitoring.

Even though this type of communication is fast and reliable, data awareness dragged many privacy complications of WAN (wide area network) networks [105].

On other hand, many researchers proved that security is no longer a problem when it comes to IoT communication needs. The improved monitoring system and security measurements create a powerful ecosystem able to analyze and to protect data gathered from any connected devices [106], [107]. If these devices are linked to a safety grid network, the

approach of improving comfort and security in smart houses can be implemented with IoT systems [108].

A new study revealed that in the upcoming years every individual will have in its possession more than 7 devices able to connect to the internet, thus to the cloud. IoT comes with a solution providing full connection to any kind of object linked to the internet. In the testing facility from UPB, each user has a specific profile created.

The purpose is to enhance the system evaluation and of the information accumulated from the smart devices. IoT can be outlined as global framework that harvest important information about specific data, including input data for mathematic models. This type of knowledge is analyzed through distinct parts relying on three dimensional states: time, place and device, as presented in Fig. 3-15 [109].

When it comes to IoT ecosystem, one of the most important elements of the system is the device. The devices can be found as physical equipment (things/objects) working as collector information. Every device can exchange information with another device, no matter the time or the place, via a particular platform. Depending on the user needs, each device may be programmed to save information on a specific database with a pre-setup time step.

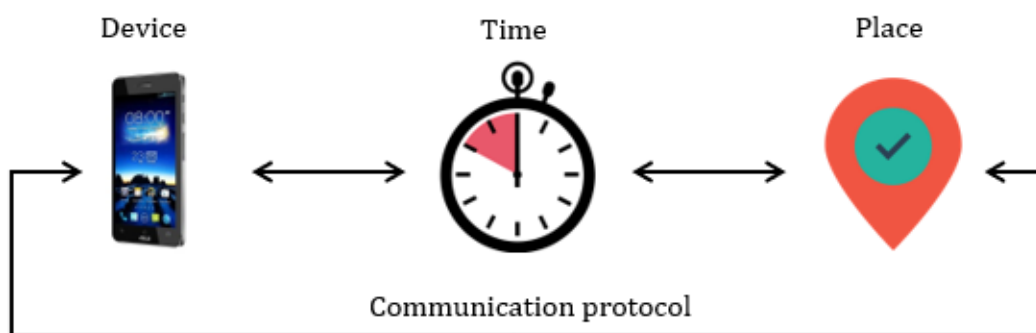


Fig. 3-15 Three dimensional states of the IoT model

As shown in Fig. 3-15, all the dimensional states are communicating with each other through stable protocols, making the IoT infrastructure a good solution for analyzing and data awareness. Intelligent tools or controllers can be recognized as physical sensors able to transmit useful parameters about the surroundings.

Every sensor has in its compeonence a small motherboard. Taking into consideration that most of the devices have a software routine, it implies a hardware entity that needs to be present all the time. Hardware solution for the IoT infra-structure is cost effective and functionality wise. In

Table 3-3, the main elements of an IoT structure are presented. Each layer of the structure has an important role, inflicting directly the energy consumption of the testing laboratory. The devices are responsible with the connection with the system and prepared for monitor and organization.

Table 3-3. IoT ecosystem – important elements [109]

Device	Data collection	Data analysis	Application
One or multiple objects that are controlled and monitored	Signal conversion (input analog output digital)	Data handling, data analytics, cloud-based computing.	Interchange information between 3rd party application and user synergy
	Safety or protection manners		

The 2<sup>nd</sup> layer of the IoT eco-system is responsible for the data collection implying the signal conversion from an input analog into an output digital signal. The transformation of signals depends on the following:

- Measured physical signal
- Diversity of sensor type
- Time period of data compilation

The 3<sup>rd</sup> layer analyzes and processes the filtered data within the cloud computing files. The end user receives only the most relevant information as graphics or statistical documents. After a complex analysis of the processed data, this layer provides only the necessary information for the inhabitant to evaluate.

The final layer is dedicated to the application center, connecting the upper layers with the party system via all sorts of protocols. In Fig. 3-16, a technical communication model is provided, showing the operational assumption of data access to the network gateways. This type of communication is done through multiple secured VPN channels, being controlled by a set of procedure that authorizes security guidelines.

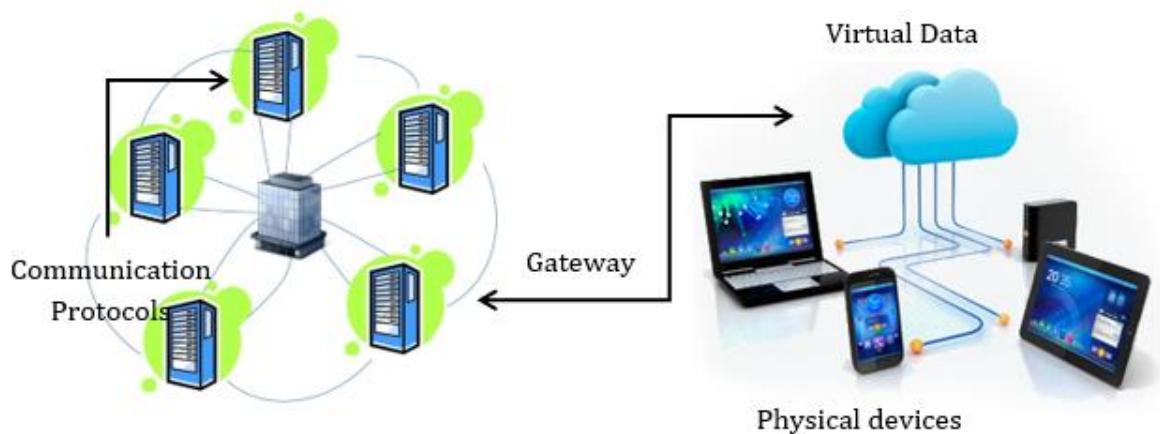


Fig. 3-16 Data exchange information prototype [109]

Constantly supported by the IoT network architecture, the energy consumption and the comfort parameters are kept under regular surveillance, improving sensors communication without interruption. In addition, a 10 kW off grid system has been installed at the testing laboratory from UPB, maintaining a stable lighting system in case of power cutoff. The management control system can be triggered by user, generating a power signal. The signal is able to produce a specific operation based on data stored on the acquisition center and customer standard behavior. Coupled with the advantages of implementing a smart system,

the running solution can trigger a maximization in the energy savings of the passive house along with fulfilling the human needs.

The testing laboratory is running on an IoT working module that is structured in multiple sparrow sensors suppliers that are in strong correlation with an acquisition center (working on IEEE 802.15.4 standard). Built up for development a purpose, a *Sparrow* is a wireless sensor network (WSN) operating on different standards for testing wireless applications. As given in Fig. 3-16, one *Sparrow* wireless node is composed of various elements with small dimensions, low-power consumption and low-cost sensors. Those sensors are systematized in a regular structure able to gather data from the environment and to connect to nearby networks over a specific gateway. The *Sparrow* wireless sensor node is composed of five sections as presented below, in Fig. 3-17 [81].

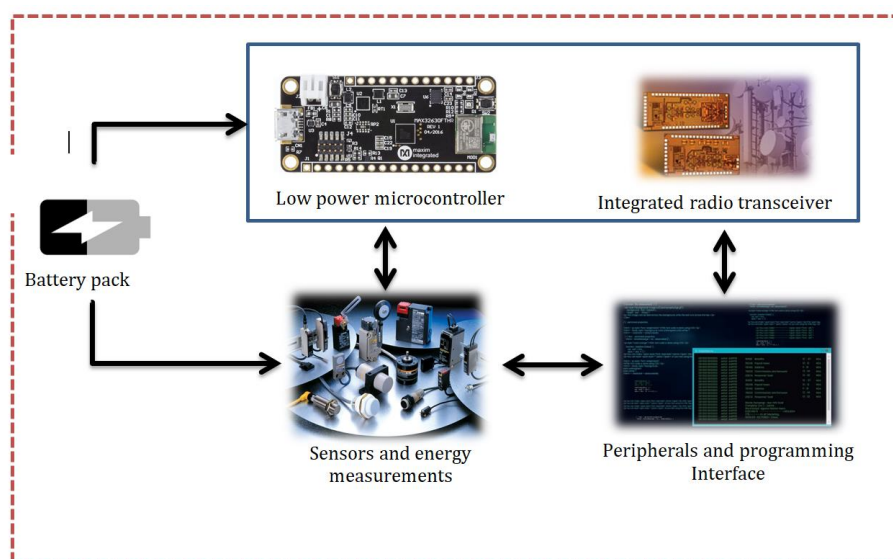


Fig. 3-17 Functionality of a Sparrow node block diagram

The first branch of a *Sparrow* sensor is an energy-saving ATmega128RFA1 microcontroller, transferring 8-bit of AVR with a radio receiver on a 2.4GHz band. The device has up to 16kB SRAM and 128kB RAM for software purposes, having sufficient memory capacity to operate a Zigbee center-point pile. The second block is composed of a special integrated radio transceiver conceive to use different standards (IEEE 802.15.4) and digital data buffering. With only one small antenna and two oscillator-decoupling capacitors, the radio transceiver is connected with the microcontroller through an exterior cable.

The principal source of energy for the sensor is the battery pack, which is composed of 2 x AA 1.5V CR2477N batteries that stores an average amount of energy (950 mAh). For monitoring the energy consumption rate of the battery pack, an energy management sensor was preferred to be part of the *Sparrow* node sensor.

By transforming analog into digital signal, the blocks functionality gathers information about important parameters of the testing facility:

- indoor air pollutants: dust particles (1 to 10  $\mu\text{m}$ ),
- leaks of combustible gas such as: methane, propane or carbon monoxide,
- ammonia,
- sulfide,

- benzene steam,
- temperature or humidity.

Last section of the *Sparrow* sensor is the programming interface, where a connector can be plugged into a computer to run maintenance and debugging issues. This section is linked to the *Sparrow* wireless sensor with a sequence of conjunction like:

- 5 input analogs to digital converters
- 2 UARTs signals
- 3 digital output (routed to 3 LEDs)

### 3.8. Statistical analysis of weather prediction

The weather prediction is an important issue of the thesis because of the direct impact on the building. Taking into consideration the weather aspects, any building is subject to temperature modifications, thus energy consumption losses may appear. The environmental parameters are directly impacting the consumption of any residential structure being able to increase the temperatures in rooms, cooling the inside air temperature or even triggering the system for unnecessary heating.

For the data prediction with the algorithm proposed, two distinct methods must be acknowledged. The grey box algorithm is specific for its ability to output certain parameters, as well as multiple inputs. For the purpose of this thesis, we propose two algorithms that are based on Grey Box models, that are able to gather and to predict both physical and statistical parameters.

The first algorithm is referring to the physical part of the building as: materials used for building construction, shape of the house, orientation, multiple layers of building components or energy losses from thermal bridges.

The second algorithm is a statistical algorithm used to create a database of the input data in terms of weather selected parameters. Weather data can be downloaded from various authorized websites such as: Accuweather, Wunderground, Weather-forecast or a complex solution, Ventusky.

For the development of the weather database, certain parameters such as: temperature, humidity, precipitation, wind speed, cloud cover, pressure, time stamp (date, hour) had been chosen. The period of the year is very important because the weather parameters can vary from January to August. In order to prove good accuracy of the data acquisition, tests were done for a specific period of the selected months.

As presented in the screenshot below (Fig. 3-18) MaxTemperature and MinTemperature are determined by the highest and lowest daily temperature. In this manner, the temperature limits are being setup for daily examination. MeanTemperature displays the average temperatures occurred during the day, between the max and the min temperature. Moving to the next column, DegreeDay is a computation between heating and cooling, calculated as a function of time, implying a reference base temperature. On the other hand, the humidity parameter has been chosen in the interest of attaining a better and more accurate input weather prediction data. The role of humidity parameters can affect important properties



of the air or buildings materials in contact with the air. For example, water vapor is a crucial factor in both climate and weather prediction.

Fig. 3-18 Weather parameters

EET	MonthNr	Max TemperatureC	Mean TemperatureC	DegreeDay	Min TemperatureC
1/1/2015	1.00	-6	-13	-33	-19
2/1/2015	1.00	-2	-7	-27	-12
3/1/2015	1.00	3	-1	-21	-5
4/1/2015	1.00	1	-1	-21	-3
5/1/2015	1.00	3	-3	-23	-10
6/1/2015	1.00	1	-3	-23	-8

Dew PointC	MeanDew PointC	Min DewpointC	Max Humidity	Mean Humidity	Min Humidity	Max Sea Level PressurehPa
-7	-14	-22	100	86	56	1037
-3	-7	-11	100	89	63	1032
2	-2	-6	100	92	68	1025
0	-2	-6	100	91	67	1019
-4	-6	-9	100	78	40	1017
-4	-8	-13	95	67	35	1025

Mean Sea Level PressurehPa	Min Sea Level PressurehPa	Max VisibilityKm	Mean VisibilityKm	Min VisibilityKm	Max Wind SpeedKm/h	Mean Wind SpeedKm/h
1033	1030	10	6	1	19	8
1027	1021	10	8	4	24	16
1022	1018	10	7	2	23	10
1012	1008	10	6	1	14	8
1015	1013	10	9	7	13	6
1018	1015	10	10	3	27	6

Max Gust SpeedKm/h	Precipitationmm	CloudCover	Events	WindDirDegrees
	0	6		270
	0	6	Snow	257
	0	3	Fog-Rain	260
	2.03	8	Snow	271
	0	5		286
	0.51	6	Snow	2

The database is stored into a server from the testing laboratory, formed of a Comma Separated Values (CSV) file. Much more, basic parameters values were used to calculate the average and to set up the baseline temperature value of the residential house from UPB. Starting from the left side, in the first column it was identified the time parameter, underlying the exact date of the month for the running test phase. On the middle column, outside temperature is displayed, while in the far-right column the inside temperature is given, as shown in Table 3-4.

Table 3-4 Inside and Outside temperature variation

Time	T outside	T inside
20/10/2014	9.7	21.7
20/10/2014	9.4	21.5
20/10/2014	8.9	21.4
20/10/2014	8.1	21.2
20/10/2014	7.5	21.0
20/10/2014	7.3	20.9
20/10/2014	7.6	20.9
20/10/2014	7.5	20.8
20/10/2014	7.9	20.9

20/10/2014	10.5	22.2
20/10/2014	13.1	23.0
20/10/2014	15.2	23.5
20/10/2014	17.1	23.9
20/10/2014	18.4	24.3
20/10/2014	19.2	24.7
20/10/2014	19.5	24.9
20/10/2014	19.0	24.9
20/10/2014	17.8	24.5

---

A considerable difference can be spotted between the two temperatures as a result of the selected period for testing. The inside temperature is constant during the entire period, showing minor changes that does not affect the energy consumption pattern of the passive house. On the contrary, the outside temperature fluctuates between 9 and 18 degree Celsius.

### 3.8.1. Weather data acquisition

The monitoring system is building a solid database from daily data collection, resulting in a compilation of input elements used for the prediction algorithm. With this intention, a selection of four different city in the European Union has been made in order to have a diversity of data, for a period of three months. Weather parameters have been tracked down and saved on the server.

Taking into consideration that the weather prediction algorithm is reading the inputs and submits the outputs for a period of 30 days in advance, multiple input parameters were gathered from the following websites:

- [www.accuweather.com](http://www.accuweather.com) [110]
- <https://www.wunderground.com/>[111]
- <http://www.weather-forecast.com>[112]

Four cities were monitored for the input database by taking into consideration geographic position. The cities were chosen between a distance range of 1000 km with the condition of having opposite weather climate. For a better understanding of the weather prediction algorithm, for a period of two months four cities were monitored:

- Bucharest (as reference)
- Lyon
- Rome
- Berlin

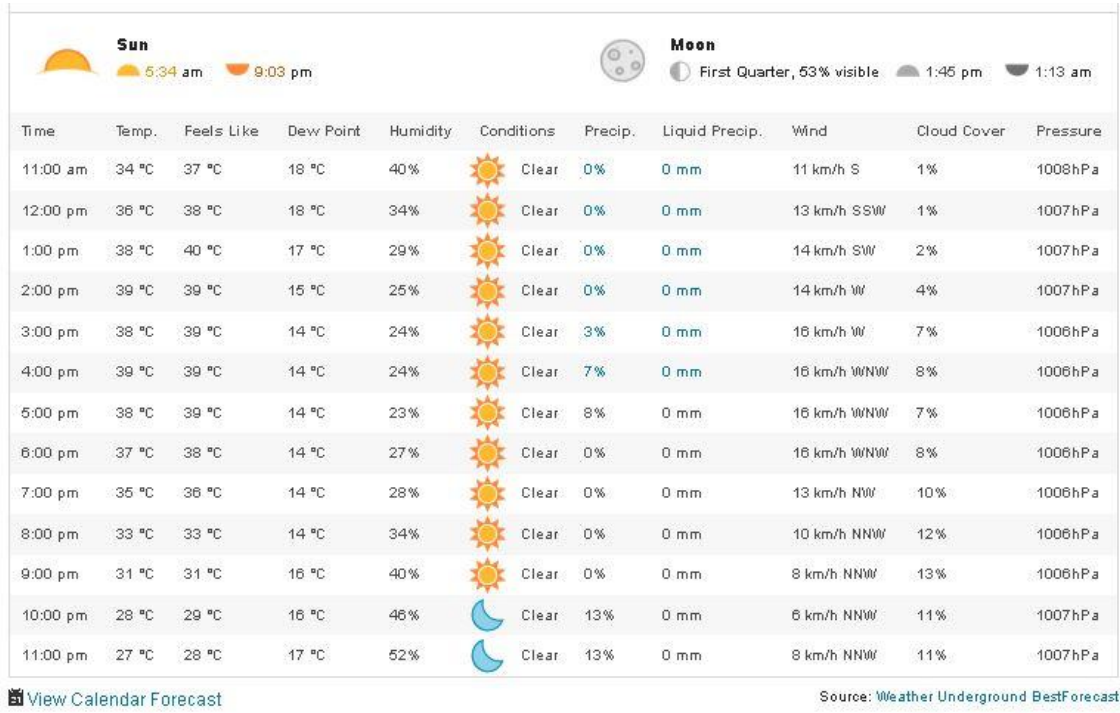
Exemplified in Fig.3-18, hourly weather parameters are collected as inputs for the algorithm computation. During a 24-hour period, the following parameters have been selected following parameters in order to achieve a superior accuracy:

- Outside temperature,
- Real feel temperature,
- Humidity level,
- Condition (clear sky or cloudy),



- Precipitation level,
- Wind Speed,
- Cloud cover,
- Pressure.

For the condition of the skies, it has been picked one for clear sky and zero for partially cloudy. Moreover, parameters have been chosen in their scale used by the International System of Units (SI) for a better precision of the system.



### Almanac

Fig. 3-19 Hourly weather parameters

Even though Bucharest is the reference city for the residential appliances, cities like Lyon, Berlin and Rome also provided information about required parameters. For instance, Accuweather website, Fig. 3-19, displays average values for each parameter mentioned above. For a detailed examination, further statistical calculations must be done. An example of the monitoring period over the four selected cities is presented in Fig. 3-20.

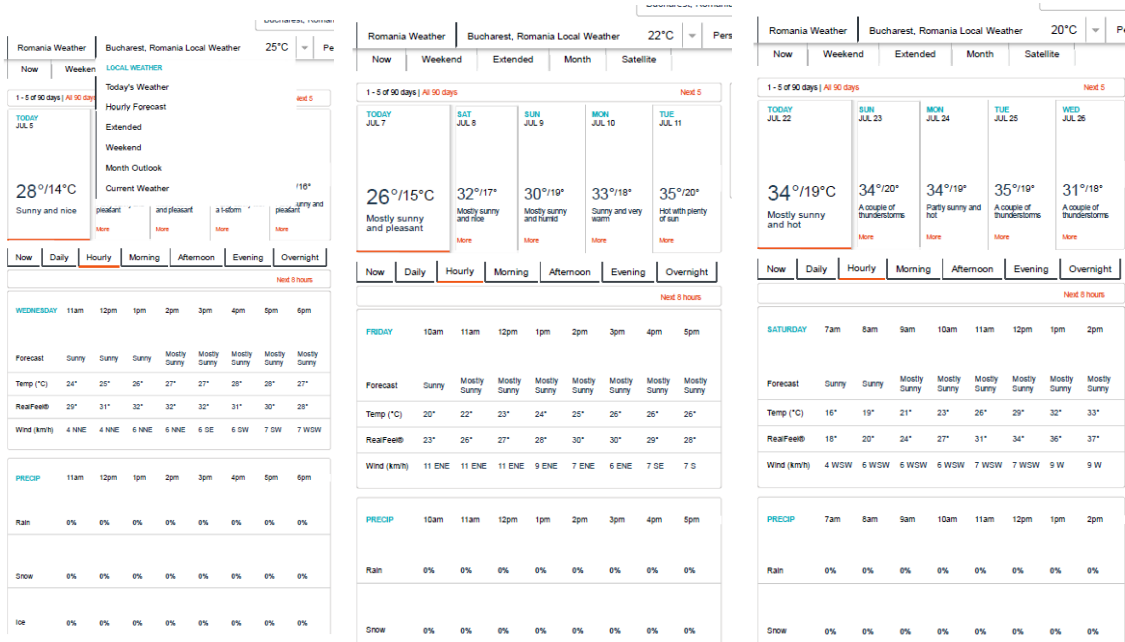
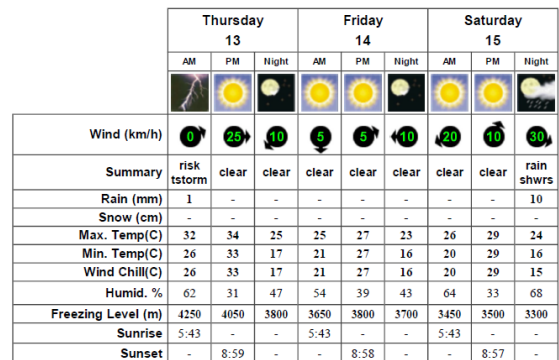
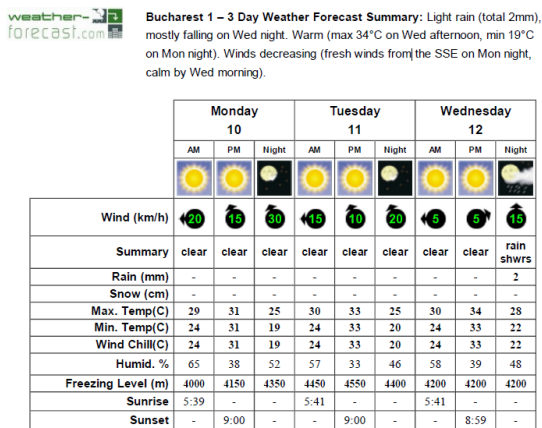


Fig. 3-20 Weather data prediction for 4 days ahead

As seen in Fig. 3-20, a clear perspective can be done over the temperature output predicted by the website Accuweather. On the other hand, by confronting the prediction from the two websites: Accuweather and WeForecast website, Fig.31, an improved accuracy was discovered on the last website. Nevertheless, the input data were limited because the only prediction available was the 10-day-ahead solution. As presented below, Bucharest 10-day prediction has a strict number of inputs with detailed summary options.



**Bucharest 7 - 10 Day Weather Forecast Summary:** Light rain (total 6mm), mostly falling on Sun morning. Warm (max 32°C on Wed afternoon, min 14°C on Sun night). Winds increasing (calm on Sun night, fresh winds from the NE by Tue afternoon).


Fig. 3-21 Prediction input data from WeForecast

Complex website selected to work with, giving the most detailed parameters for the forecast to be made. The website presents the forecast for today's parameters, as displayed in Fig. 3-21, with a 3-days ahead prediction but with addition conditions from the nearby weather stations.

Forecast History Calendar Rain / Snow Health

**Active Advisory:** Potential disruption due to extreme high temperatures from 9AM EEST THU until 9PM EEST THU


Elev 0 m 44.45° N, 26.12° E | Updated 31 min ago



**33.9 °C**

Clear Feels Like **36 °C**

Wind Variable Gusts **5.0 km/h**



**1.9**

Pressure **1011 hPa**

Visibility **10.0 kilometers**

Clouds **Few 1280 m**

Heat Index **36 °C**

Dew Point **20 °C**


Humidity **44%**


Rainfall **0 mm**

Snow Depth **Not available**

Today is forecast to be **WARMER** than yesterday.



<p><b>Today</b></p> <p>High <b>31</b>   Low <b>19</b> °C</p> <p>0% Chance of Precip.</p>	<p><b>Yesterday</b></p> <p>High <b>36.8</b>   Low <b>21.2</b> °C</p> <p>Precip. <b>1.3</b> mm</p>
--	---


 **Allergy Warning**

 **UV Warning**

[Sign up for your Daily Forecast Email](#)

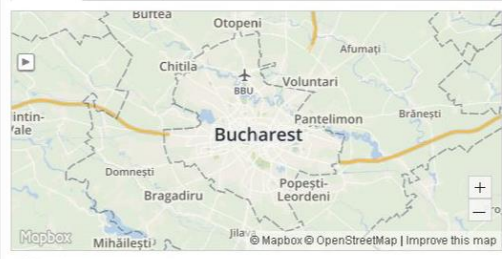
**Sun & Moon**

 5:33 am  9:04 pm

 Waxing Crescent, 24% visible

**METAR LRBS 281030Z VRB04KT 9999 FEW042 29/19 Q1011 NOSIG**

**Radar** **Satellite** WunderMap



Show Webcams

Fig. 3-22 Wunderground prediction data

Even if the number of forecasted days is necessary an average can be displayed to help the user to understand the environment temperature fluctuation. For this, the hourly tab from Wunderground provides a detailed forecast for the parameters in case. Even though this thesis addresses 30-days ahead forecast, it's better to see the evolution for each parameter from the database. The calendar option-tab, Fig. 3-22, is offering the exact input evidence in order to have a comparison of the prediction for each selected city.































Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
				1 Tstorm 	2 Clear 	3 Partly Cloudy 
				Actual: 30°   13° 2.03 mm	Actual: 28°   14° 0.00 mm	Actual: 27°   15° 0.00 mm
				Average: 24°   13° 0.23 mm	Average: 24°   13° 0.23 mm	Average: 24°   13° 0.23 mm
4 Fog 	5 Scattered Clouds 	6 Clear 	7 Scattered Clouds 	8 Tstorm 	9 Rain 	10 Mostly Cloudy 
Actual: 26°   16° 0.00 mm	Actual: 27°   12° 0.00 mm	Actual: 27°   13° 0.00 mm	Actual: 30°   11° 0.51 mm	Actual: 24°   16° 2.03 mm	Actual: 17°   14° 4.06 mm	Actual: 27°   15° 0.00 mm
Average: 24°   13° 0.23 mm	Average: 24°   13° 0.23 mm	Average: 25°   13° 0.23 mm	Average: 26°   14° 0.20 mm	Average: 26°   14° 0.20 mm	Average: 26°   14° 0.18 mm	Average: 27°   14° 0.18 mm
11 Scattered Clouds 	12 Rain 	13 Scattered Clouds 	14 Partly Cloudy 	15 Partly Cloudy 	16 Partly Cloudy 	17 Tstorm 
Actual: 27°   12° 0.00 mm	Actual: 28°   12° 0.00 mm	Actual: 30°   17° 0.00 mm	Actual: 29°   18° 0.00 mm	Actual: 26°   15° 0.00 mm	Actual: 28°   11° 0.00 mm	Actual: 25°   12° 4.06 mm
Average: 27°   14° 0.18 mm	Average: 27°   15° 0.18 mm	Average: 27°   15° 0.18 mm	Average: 27°   15° 0.20 mm	Average: 27°   15° 0.18 mm	Average: 27°   15° 0.20 mm	Average: 27°   15° 0.20 mm
18 Rain 	19 Rain 	20 Rain 	21 Tstorm 	22 Rain 	23 Partly Cloudy 	24 Overcast 
Actual: 17°   12° 21.08 mm	Actual: 28°   12° 0.00 mm	Actual: 29°   14° 0.00 mm	Actual: 32°   14° 0.00 mm	Actual: 30°   14° 0.00 mm	Actual: 33°   15° 0.00 mm	Actual: 33°   15° 0.00 mm
Average: 28°   15° 0.20 mm	Average: 28°   15° 0.20 mm	Average: 28°   15° 0.20 mm	Average: 28°   15° 0.20 mm	Average: 28°   15° 0.18 mm	Average: 28°   16° 0.18 mm	Average: 28°   16° 0.15 mm
25 Clear 	26 Partly Cloudy 	27 Tstorm 	28 Scattered Clouds 	29 Clear 	30 Clear 	
Actual: 32°   16° 0.00 mm	Actual: 33°   15° 0.00 mm	Actual: 28°   17° 6.10 mm	Forecast: 31°   19° 0 mm	Forecast: 34°   21° 0 mm	Forecast: 36°   21° 0 mm	
Average: 28°   16° 0.15 mm	Average: 28°   16° 0.15 mm	Average: 28°   16° 0.18 mm	Average: 28°   16° 0.18 mm	Average: 28°   16° 0.18 mm	Average: 28°   16° 0.18 mm	

Fig. 3-23 Wunderground calendar - forecast for 30 days in advance





The image shows a screenshot of an Excel spreadsheet with a CSV file imported. The spreadsheet has 15 columns (A to Q) and many rows of data. The data is a comma-separated list of values representing weather parameters over time. The first row of data is: 1992,1,1,1,60,C9C9C9C9\*0?9?9?9?9?9?9?9A7A7B8B8A7\*0\*OE8\*0\*0,-3,-5,5,81,101500,0,1415,237,0,0,0,0,0,0,0,0,1,1,9,9,77777,9,999999999,0,0,16,0,88,0,0,0. The spreadsheet interface includes the ribbon with tabs for File, Home, Insert, Page Layout, Formulas, Data, Review, View, and Help. The Home tab is active, showing options for Clipboard, Font, Alignment, Number, and Styles.

Fig. 3-25 Energy Plus CSV file [113]

As mentioned before, there are 15 columns in the presented weather data file, described as:

- C1, \field Year
- C2, \field Month
- C3, \field Day
- C4, \field Hour
- C5, \field Minute
- A1, \field Data Source and Uncertainty Flags
- C6, \field Dry Bulb Temperature\units C
- C7, \field Dew Point Temperature\units C
- C8, \field Relative Humidity
- C9, \field Atmospheric Station Pressure\units Pa
- C 0, \field Extraterrestrial Horizontal Radiation\units Wh/m2
- C11, \field Extraterrestrial Direct Normal Radiation\units Wh/m2
- C12, \field Horizontal Infrared Radiation Intensity\units Wh/m2
- C13, \field Global Horizontal Radiation\units Wh/m2
- C14, \field Direct Normal Radiation\units Wh/m2
- C15, \field Diffuse Horizontal Radiation\units Wh/m2

In Appendices 7 the MATLAB algorithm code is presented, exemplifying the working procedure of the analyzed system. Firstly, the algorithm read and visualize the data by plotting different parameters, in function of time and period. The starting time and period are delimited at the top of the algorithm while the plotting parameters are displayed at the bottom.

Secondly, the implementation of the physical analysis and the mathematical model of the house's walls into the algorithm is required. Important to realize is the consideration of each layer of the wall's properties, together with the choice of discretization method. For this, Euler method was used and von Neumann stability analysis for heating equation [115]:

$$\frac{\kappa/\rho c \Delta t}{\Delta w^2} \leq \frac{1}{2} \quad (14)$$

or

$$\frac{\kappa S/w}{w S \rho c} \Delta t = \frac{\Delta t}{RC} \leq \frac{1}{2} \quad (15)$$

with  $R = \frac{w}{\lambda S}$ ;  $C = w S \rho c = V \rho c = mc$ .

This is applicable for heat equation. In general, the stability condition for explicit Euler method requires that all eigenvalues  $\lambda_i \in \mathbf{Z}$  of the transfer matrix satisfy the condition [116]:

$$|1 + \lambda_i \Delta t| \leq 1, \forall i \quad (16)$$

or, if the eigenvalues are all real (as is the case for thermal networks):

$$-2 \leq \lambda_i \Delta t \leq 0, \forall i \quad (17)$$

The formulas for Euler forward (explicit):

$$\boldsymbol{\theta}_{k+1} = (\mathbf{I} + \Delta t \mathbf{A})\boldsymbol{\theta}_k + \Delta t \mathbf{B} \mathbf{u}_k \quad (18)$$

and for Euler backward (implicit)

$$\boldsymbol{\theta}_{k+1} = (\mathbf{I} - \Delta t \mathbf{A})^{-1}(\boldsymbol{\theta}_k + \Delta t \mathbf{B} \mathbf{u}_k) \quad (19)$$

## 3.9. Example results

### 3.9.1. Physical and electrical acquisition

For the purpose of achieving an amelioration on the energy consumption rate and the power usage of the building, each user has a configurable setup to customize. For example, in order to have a good assumption about the energy consumption of the harvesting data, time-step needs to be as low as possible. Depending on the level of analysis, each user can customize the smart meter to collect data for a specific period of time.

Smart meters are the main cores of the system, being able to gather useful information about electrical parameters such as P, Q, U, I or energy registers A+, A-, R+, R-.

Thesis results are obtained upon a constant monitoring period. In Fig. 3-26, the system was monitored during a one-day period showing the evolution of energy savings of the testing laboratory. The evolution of energy gathered from sensors M1D1, M1D2 and M1D3 were kept under constant variation without any noticeable issues. The green line (heat-radiation panel) is marked for the M1D1 sensor; the red line (group of loads - multiple devices such as laptops, Monitor, etc.) is associated to M1D2 sensor while the M1D3 sensor is designed with blue line – refrigerator in the kitchen; all recording information about the voltage parameter.

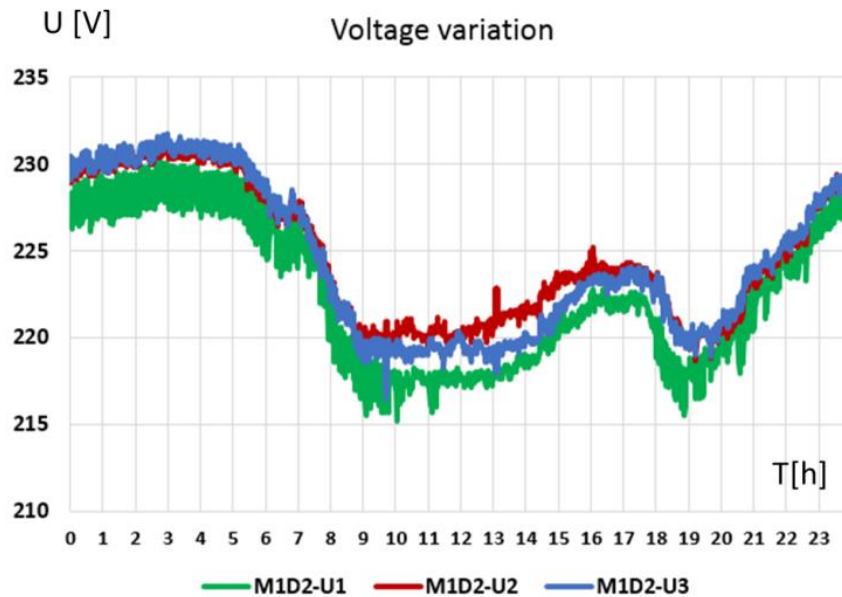


Fig. 3-26 Voltage evolution [99]

The data has been captured with a time step of one minute, investigating a voltage variation on a daily interval. The results show good perspective, remaining in the band of UN +/- 10% within an interval of [207 V, 252 V]. There are two eye-catching voltage levels that can be seen during the selected period. For example, from 8:00AM to 14:00PM, the voltage is constantly low because of minor activity inside the house, while during 18:00PM to 22:00PM, a peak of electrical usage can be detected. Due to internal use of the house, the inhabitants raise the consumption, recording high levels of sampling rate. The data is picked up through smart meters, improving the detection of any malfunction that come into sight.

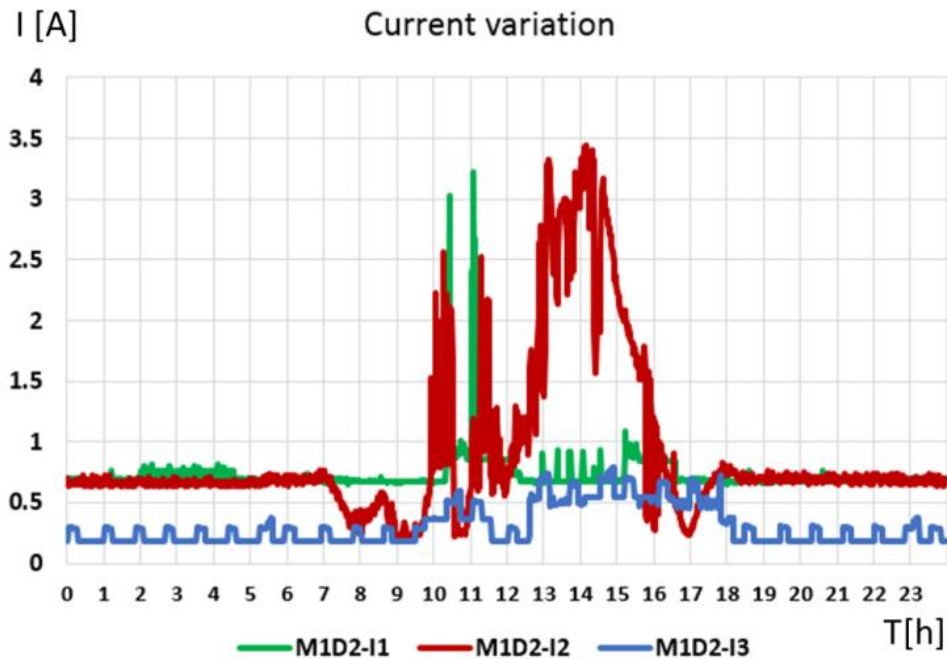


Fig. 3-27 Current evolution on a 24h day log [99]

On the same aspect, Fig. 3-27 displays the current variation within a 24-hour interval with improved data acquisition. One of the most constant consumers in the kitchen is the refrigerator, as seen in Fig.6-19 marked with blue line, noticing that for 24 hours interval no major fluctuations appeared. With red marker line a particular group of loads is outlined, showing changes through the day as primary energy is consumed.

The M1D2-L1 marker, outlined with green line, is a concern for the facility, because of its variation during the testing period. By switching a powerful consumer on, a highly energy consumption will be noticeable into the system. If not kept under strict control a huge impact of energy consumption of the residential building will occur. Another meaningful aspect about the testing facility network is the distribution of the intensity level. Understanding the electrical behavior of each individual consumer, a reduction of energy consumption for the entire structure can be acquired.

Equally important, as presented in Fig. 3-28, the power factor variation was analyzed in order to explain the energy losses from the building. The power factor variation is characterized as the ratio of the real power absorbed by the load to the apparent power flowing in the circuit and is a dimensionless number in the closed interval of  $-1$  to  $1$  [117].

Having a constant value, between  $K=0.9$  and  $1$ , the structure has a diminished reactive power, showing that energy losses are at the lowest possible level. The green marked line of the smart meter sensor, M1D3-PF1 is conserved under perfect values during the 24h testing period.

In the meantime, Fig. 3-29 exemplifies the PV production for one day trial to analyze the necessary power load from the building. There are two interesting hours exemplified, marking 7:00AM and 18:00PM as being critical points, when the inverter uses a higher amount of energy to balance the power loads of the system.



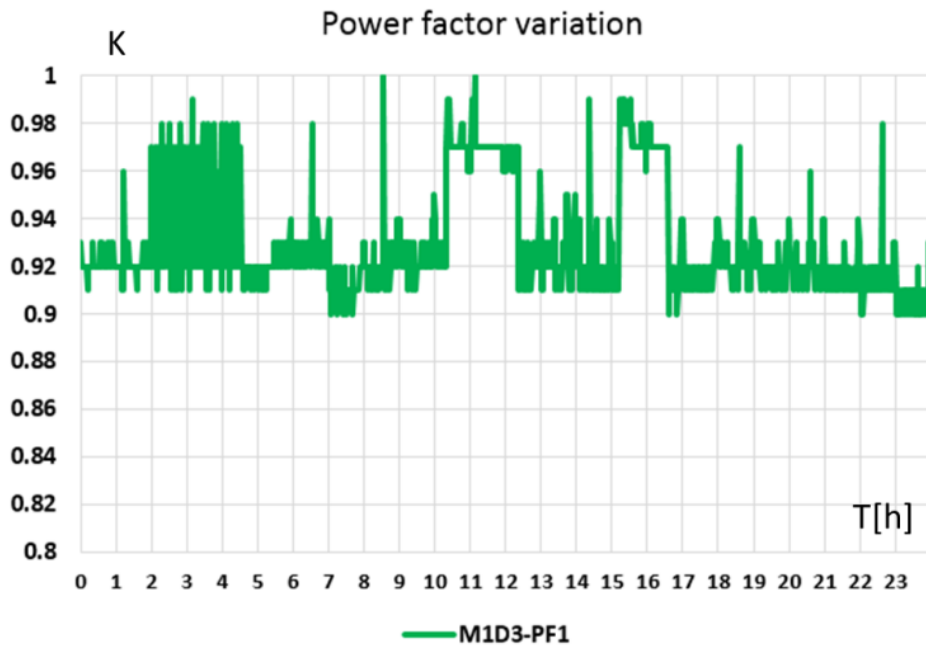


Fig. 3-28 Power factor variation [99]

Also, since testing facility power consumption is above 1, meaning positive, the negative signal demonstrates a presence of power injection. For the selected example, a random day in June was displayed where the PV production was 5.23 kWh, as presented in Fig. 3-29.

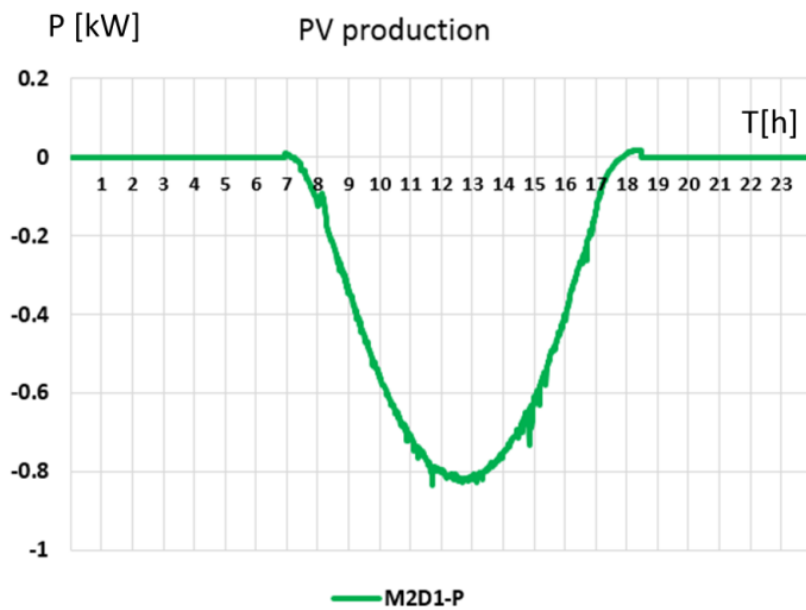


Fig. 3-29 PV Production [99]

### 3.9.2. Results and interpretation of IoT

An example of an IoT device can be seen in Fig. 3-30, where the *Sparrow* node elements are clearly visible. Every block inside the sensor gathers parameter information, especially the indoor air quality specifications.

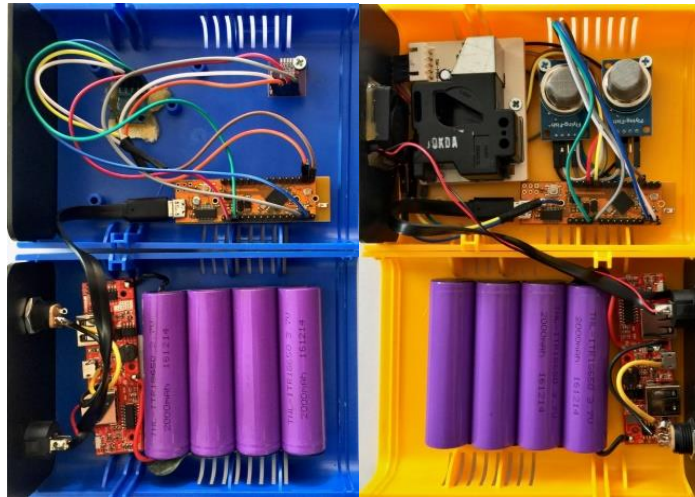


Fig. 3-30 IoT tools [109]

Two dust sensors, S1 and S2, are being represented in Fig. 3-31 showing the edged platform where user can study and investigate the evolution of stored indoor air quality. Furthermore, S2 is a clone sensor that can track down comfort parameters and bring data for detailed analyzation purposes.

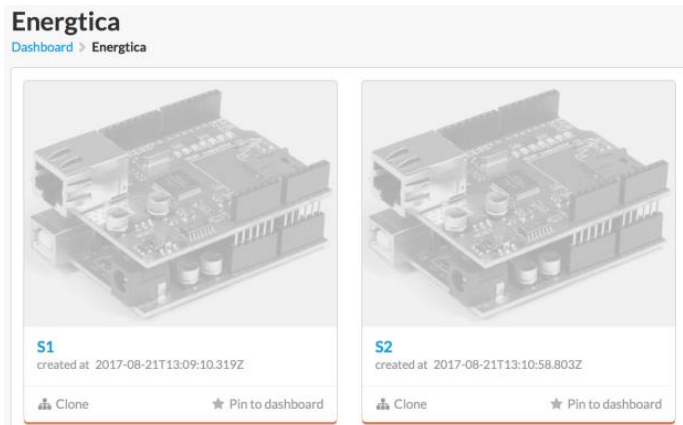


Fig. 3-31 S1 and S2 as dust sensors [109]

In Fig. 3-32, S1 sensor is collecting data on a distinct day of August, recording values such as: 468 of SO<sub>2</sub>, 478 of NO<sub>x</sub> and 143.27 dust particles. The meaning of this collected dust quantity indicates a good air quality limit.

Dashboard > Energica > S1

Sensors 4 sensors

Type	Name	Last value	Actions
	PM02	320.02	
	PM10	143.27	
	NOx	478	
	SO2	468	

Fig. 3-32 Dust sensor S1 - data acquisition [109]

In Fig. 3-33 S1 sensor records a critical value of dust particles at 15:29PM because of weather condition with no impact on the buildings energy consumption or human health. The detailed explanation of Fig.6-25 stands in the evolution of dust particles during the trial period of August, where an average algorithm calculates and displays the estimated values.

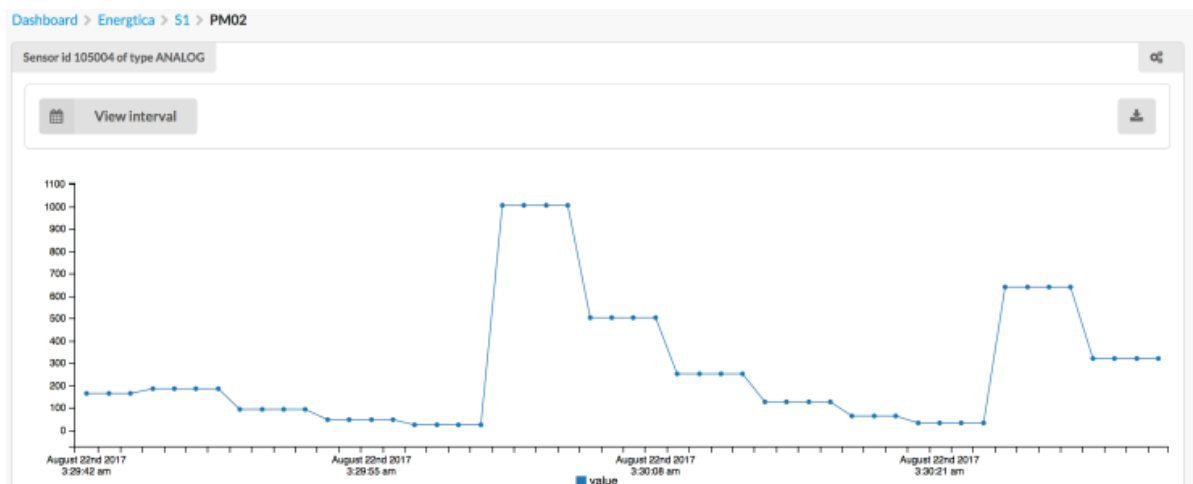


Fig. 3-33 The evolution of parameter gathered on 22th of August [109]

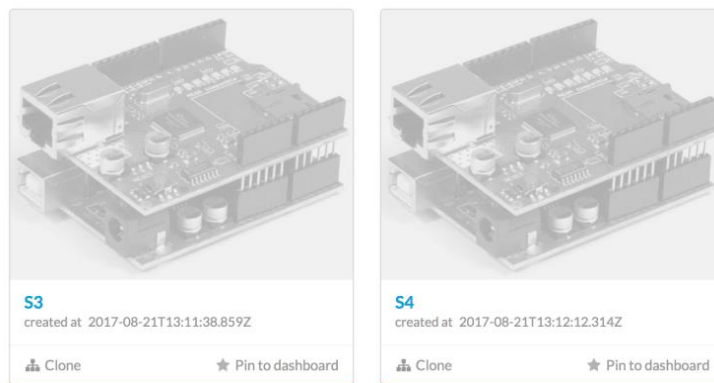


Fig. 3-34 Sensor comfort parameters [109]

As sensor S1 and S2 are responsible for air quality, S3 and S4 are capable of monitoring thermal comfort parameters. The information is gathered once per minute, creating a solid database on the server, via a wireless network exchange. Through a VPN connection, the database can be accessed in two ways: internally and externally. In the below

Fig. 3-34 a reference on the edge platform was created for each sensor, displaying comfort parameters suchlike: ambiental temperature, environmental temperature, humidity and luminosity.

Through a laborious research on the dataset gathered by the sensors it was noticed that S3 and S4 sensors have over 44734 registers displayed in Fig. 3-35. As presented below, results on 22nd of August regarding comfort parameters were: Temperature = 30.16 °C, humidity level = 39.68 % and luminous flux = 5 lm. All the data gathered from the sensors are being uploaded on the edge platform, connected to the cloud, for further use.

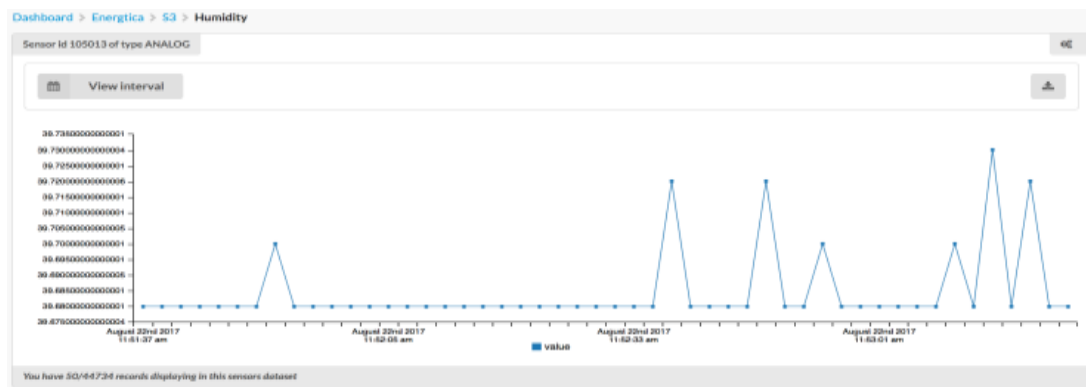


Fig. 3-35 Temperature evolution on a selected day of August [109]

There are many possibilities to interact with the data from the sensors, as well as customizing properties from the edge platform. The WSN is equipped with sensors, indicating comfort parameters. The algorithm for displaying the average temperature and relative humidity provides improved calibration, linearized signals in digital format, in order to stabilize the sensor behavior at high humidity levels as related in Fig. 3-36.

Dashboard > Energica > S3

Sensors 3 sensors

Type	Name	Last value	Actions
	Temperature	30.16	
	Humidity	39.68	
	Light	5	

Fig. 3-36 Data about comfort parameters [109]

The edge platform, as presented in Fig. 3-37, facilitates the connectivity of all the IoT devices in one particular location, for better understand of data flows. Moreover, understanding the signification data taken from the cloud, the user can create simple methods/algorithms to save up and to lower the consumption energy of the testing facility. For example, the client has various alternatives to interact with the edged platform, customizing the necessity of the building, being both cost and time efficient.

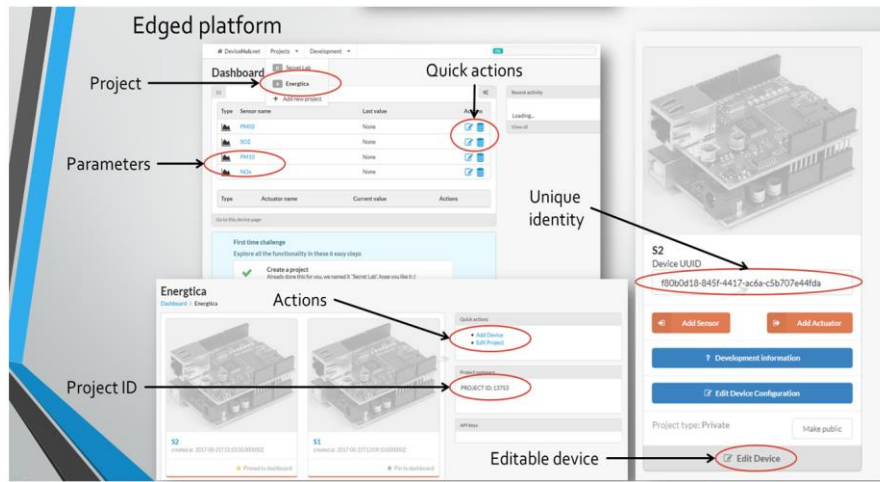


Fig. 3-37 Edge platform

Platform presents multiple applications after the authentication of user into the administrator panel. Dashboard presents a visualization tab for the selected project, where further actions can be done. For an improved working process, additional device (smart meters) can be submitted to the platform having a unique identity (Device UUID). Each electrical and human action have a correspondent into the Edge platform interface. To achieve improved energy consumption of passive house, quick actions bullets are used to integrate the platform on cloud structure.

Another major advantage of using the IoT platform is the easy installation of the software, combined with the solution provided for other system integration. The HVAC system is displayed as a particular system due to the fact that IoT structure activates warnings, in case of malfunctions or hardware error.

To conclude with, the framework of the implemented concept is realized under good efficiency maintenance, cutting down energy losses, improving energy management and lowering power utilization.

### 3.10. Conclusion

Measurements, as well as data acquisition, is realized using a SMX system. Smart meters gather information about the requested parameters to create a specified database. The SMX platform is responsible for the data-extracting procedure, while uploading data on a locally web platform.

Moreover, the interaction between the SMX and the user is made with an HMI which lead to easier data analysis. Additionally, different type of data is gathered using SMX system, being classified, in categories to understand buildings behavior.

The proposed SMX platform examines data to understand the buildings energy consumption, while data gathering procedures are operating with communication protocols founded on networking services. The link protocol between client and broker is highlighted to keep the session unlocked, as far as no disconnection is requested. A low energy consumption is achieved as long as each inside consumer is monitored and identified. Thus, the SMX platform displays details about each consumer and user behavior with regard to energy usage. In addition, as technology evolution is fast, an IoT infrastructure was presented.

Results interpretation of data-collection over the IoT system is presented on the edge platform created. Sensors are able to capture indoor air quality and comfort parameters. Thus, the inhabitant can create simplified routines to save and to lower the usage of electrical energy. The advantage of using the implemented framework is the efficiency maintenance, cutting energy losses and improving energy management while reducing energy consumption. Another result interpretation key point is the physical and electrical acquisition system due to energy usage and consumption rate. Different voltage evolution of energy gathered through sensors are presented Chapter 2, underlining good perspective results that remains in the band of UN +/- 10% despite of the normal electrical peaks found. On the other hand, the current evolution within 24 hours is also exemplified, emphasizing the fluctuation of each consumer inside the building. Equally important, the power factor variation is analyzed to understand energy losses occur in the house. The loss is compensated by the PV system.

The IoT ecosystem collects and posts data on a web platform which contains inputs and weather details, to estimate energy consumption. While running on low energy consumption, environmental parameters are gathered by different types of sensors which are directly influenced by outside weather conditions.

To conclude with, detailed analysis between room positions was made to demonstrate the temperature difference over a daytime period. To sum up, by developing these approaches, testing laboratory was kept under optimal thermal comfort, using minimum energy consumption and the aim of the thesis is considered to be achieved.

The data acquisition system of the experimental house of UPB is able to accept different numerical approaches for estimating energy usage and consumption.

## *CHAPTER IV – Energy prediction based on small amount of information: degree-day and grey-box models*

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Chapter IV presents energy predictions based on degree-day and grey-box methods. These methods are estimating energy consumption of the testing laboratory, while using a very low quantity of data.

## 4.1. Degree-day method

Heating Degree-Day (HDD) is a common procedure for estimating energy consumption of any residential building. Carbon dioxide emissions can also be estimated by using HDD method because of the collected data during a selected period. In case of major building refurbishments, the user can set the energy levels according to the analysis of the system [118].

As the European Environment Agency presented on their website, during 1981 and 2016 trends in heating and cooling degree days is statistically engrossing of 5%. In the below image, on the left side, the Europe trend in heating degree days is presented (Fig. 4-1), covering Romania, as well as the cooling degree days for each European country.

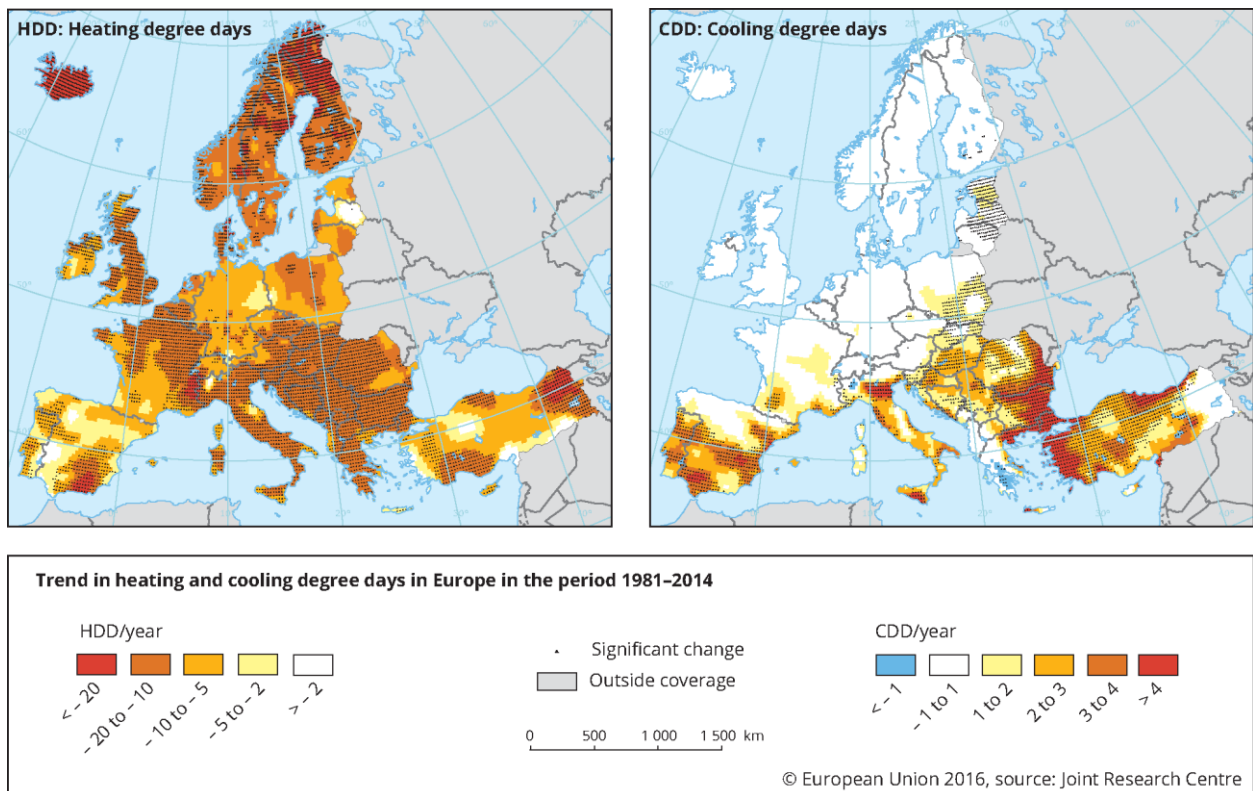


Fig. 4-1 Trend in heating and cooling – EU members [119]

The applications of degree-days can be transformed in building performance analysis if an evaluation of future energy consumption is targeted. For example, the forecast of peak-day gas consumption management in a domestic residence was developed to underline the accuracy estimation of HDD, taking into consideration numerous climate consequence [120].

Energy savings and consumption of residential building are computed by multiplying analogous hour number with outside temperature value. Thus, steady-state models should not be used because of the variation of interior gains and temperature.

Nowadays, computer software can establish specific houses energy consumption, while the biggest disadvantages represents computing time. The degree-day method can bring



estimation of annual loads with, or without, any difficulties (if the internal gains and inside temperature are constant).

In case of changes in free loads and temperature set points of buildings, energy consumption is affected. Taking into account the system improvement, temperature involved in the system can be balanced by using heating degree-day method. As accuracy is one of the main keys of a perfect system functionality, a reference temperature needs to be calculated. The default temperature is equal to the base temperature where building is at equilibrium point. After identifying this step, a difference between outdoor and base temperature needs to be determined. When thermal comfort conditions are fulfilled and system is not working, the building is in balance point [121].

For achieving a good thermal comfort, many users use different heating or cooling systems. Moreover, the testing laboratory from UPB is running the HVAC system, taking into consideration the balance point of the house. The difference between the base and outside temperature, according to HDD methods, is supported by the HVAC system. The degree-days method works if applied on a period of 24 hours. For a better accuracy of the targeted temperature, it is recommended to divide in hourly intervals.

Despite this advantage, several detrimental aspects can be present in the degree-day method:

- the 1<sup>st</sup> problem of using degree-day method is parameter estimation such as overall heat loss coefficient and base temperature (presenting a slight error for the output calculation),
- the 2<sup>nd</sup> issue consists of identifying the buildings energy efficiency approach (the analysis is done only for certain parameters).

Firstly, a hypothesis needs to be done before calculating the output – the residential heating energy consumption. Secondly, any statistical reference can deliver approximate results at the beginning of the analysis. The best fit for the energy appliances relates to the use of internal and external temperatures, constant gains, energy consumption or air infiltration. For example, having an assumption on suggested parameters such as base temperature, average of a day's high and low temperatures, hourly temperature reading, an accurate approximation of the building's energy efficiency can be done.

Simplified methods use mean outdoor input parameters to measure the energy demands. The fluctuation of indoor and outdoor temperatures of degree-day procedure excludes periods when HVAC system is turned off. Duration and magnitude perfectly describe the degree-day technique, while estimating the energy consumption of any building.

For a better understanding of the working principal, the degree-day method is demonstrating the importance of base temperatures and time-period. The temperature has a range from 0 to 20 °C, displaying the base temperature as an average of mean temperatures being equal to 14 °C. The monitoring period has been set up for two consecutive days, measuring inside and outside temperature. The difference between the 1<sup>st</sup> and the 2<sup>nd</sup> day is made by the method used to describe temperatures:

- 1) Day 1 - Mean daily temperature.
- 2) Day 2- Degree-day.

### 4.1.1. Base temperature (balance point)

The base temperature definition lies in the exact point where the building does not need heating or cooling regardless the weather conditions. Every building has its own heat losses, depending on multiple factors. The principal goal of the heating degree day is to bypass those losses and to balance the thermal condition of every building. Starting from insulation, construction materials, windows properties or human behavior, system failures causes lack of prediction accuracy. To exemplify, during the winter period the environment presents a lower temperature than the indoor temperature, indicating the first factor of heat loss. The benefit of having an isolated building, minimizes the heat lost and maximizes the replacement internal load. The most common examples of internal loads are human behavior, lighting system, internal devices or renewable energy sources. The rest of the heat needs to be supplied by the HVAC system running into the building. Taking this into consideration, the aspect of neglecting heating system, at a certain point, the internal heat gains can maintain a normal temperature without using any more energy. Although there will be times when external temperature will be below indoor temperature, the necessity of using the heating appliance to equal buildings balance point will be requested.

The base temperature is set-up at the beginning of calculus, while the degree necessary to turn on the system is hourly determined. Even if the heat gains inflict difficulties on the system by not recognizing the right base temperature, additional adjustments can be done with the HVAC to achieve a comfort inside temperature. To deliver correct explanation of the default temperature, multiple thermal aspects must be taken into consideration as follows:

- thermal capacity,
- heat loss,
- air infiltration rate,
- heat loss coefficient,
- building orientation.

The base temperature,  $T_b$ , is the value of outside temperature for which the total heat loss is equivalent to total heat gain:

$$Q_{gain} = K_{tot}(T_i - T_b) \quad (20)$$

where

$Q_{gain}$  - total heat gains (from sun, lights, occupants, etc.),

$K_{tot}$  - total heat loss coefficient of the building (from sun, lights, occupants, etc) in W/K,

$T_i$  - inside temperature,

$T_b$  - balance temperature.

In particular, the total heat gains and solar radiation must be considered as the average for the selected period, not peak values. The base temperature becomes:

$$T_b = T_i - \frac{Q_{gain}}{K_{tot}} \quad (21)$$

Heating is necessary when inside temperature goes underneath  $T_b$  defining rate of energy consumption as:

$$Q_h = \frac{K_{tot}}{\eta_h} (T_b - T_o(\theta)) \quad (22)$$

where

$\eta_h$  is the efficiency of the heating system.

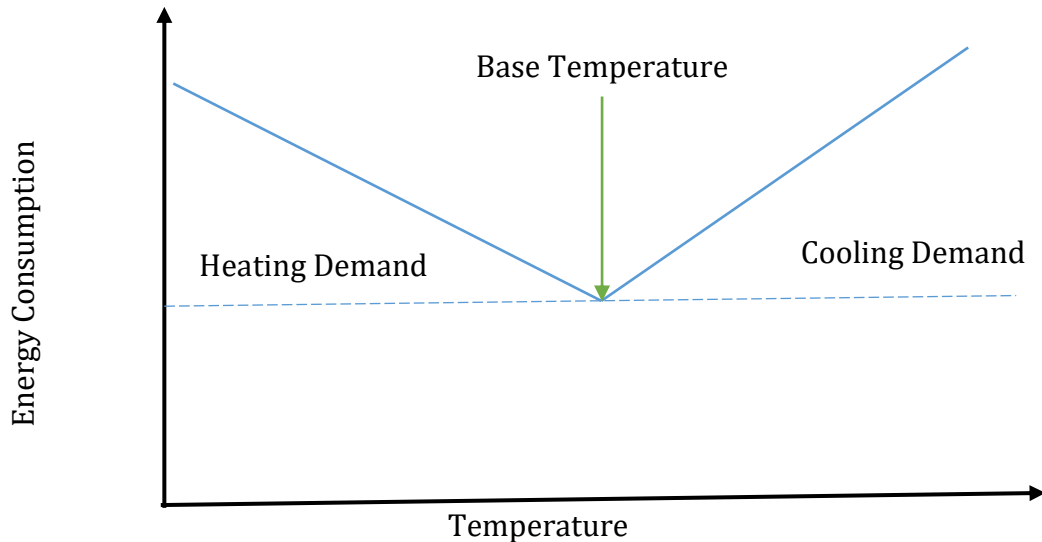


Fig. 4-2 Theoretical relationship between temperature and energy use [122]

As represented in Fig. 4-2, the degree-day procedure is underlying the liaison between energy consumption and temperature where the base temperature marks the balance point of the system. The base temperature can be obtained by monitoring the average temperature values during a specific period. Historical data is needed for lowering the uncertainty of the results although the effect of climate change is playing an important role. In order to solve this type of issues, accurate temperatures predictions on long terms can be the key to success. The direct link between energy and temperature is corresponding to the outside temperature. For example, if the outdoor temperature bypasses the balance point of the building, the energy request increases.

#### 4.1.2. Heating/cooling and degree-day calculation

When using degree-day to calculate the HDD, the proper energy estimation can be analyzed by taking into consideration the most compelling weather input: air temperature. Other variables such as CO<sub>2</sub>, wind speed, air humidity or solar radiation can be adjustment terms for temperature.

The system is supposed to take decision regarding whether to turn on/off the heating or cooling, based on aspects like heat loss, base temperature difference, infiltration rate or ventilation rate. The most problematic factor is the infiltration rate as it is directly proportional to the overall heat loss, counted as the sum of all  $UA$  values for the buildings

components. The variation of infiltration rate for a certain amount of time, improves the necessity of degree-day usage because the forecast of average values:

$$HED = (OHL \cdot DD) * 24 \text{ h/day} \quad (23)$$

where,

HED = heating demand (kWh)

OHL = heat loss coefficient (kW K<sup>-1</sup>)

DD = degree day (K day).

As the above equation explains, the heating energy demand for every system is the multiplication of overall heat loss coefficient with the degree-day of certain period of time. The degree-day is the only parameter that needs to be defined, being equivalent to the specification for heating/cooling at a given temperature for the testing laboratory in UPB.

The HDD and CDD (cooling degree days) are determined using specific formulas:

$$HDD+ = \sum_{i=1}^N (T_b - T_x) \quad (24)$$

while,

$$CDD+ = \sum_{i=1}^N (T_x - T_b) \quad (25)$$

where,

$N$  = number of cooling or heating days of a selected period,

$T_x$  = reference temperature,

$T_b$  = base temperature.

The + sign from each method signifies that only positive differences between the selected temperatures are taken into consideration.

As emphasized in Fig. 4-3, every building has a balance point where the law of conservation energy is applied. The conservation of energy is identified as the solution where the system is in perfect balance, meaning [123]:

$$\begin{aligned} \{Energy\ IN\} - \{Energy\ OUT\} \\ = \{Energy\ accumulated\ within\ the\ system\} \end{aligned} \quad (26)$$

For practical application of this equation, let us consider the system from below figure, where the energy balance is equal to inputs minus outputs. Solar gain,  $Q_s$ , enters the system while heat loss,  $Q_l$ , leaves the system. Assuming the system is homogeneous, the equation (4.56) can be subtracted as:

$$Q_s - Q_l = Q_e + Q_c + Q_i \quad (27)$$

where,

$Q_c$  = heat flow exchange,

$Q_e$  = heating system energy production,

$Q_i$  = internal gains (might be people, devices, lights etc.).

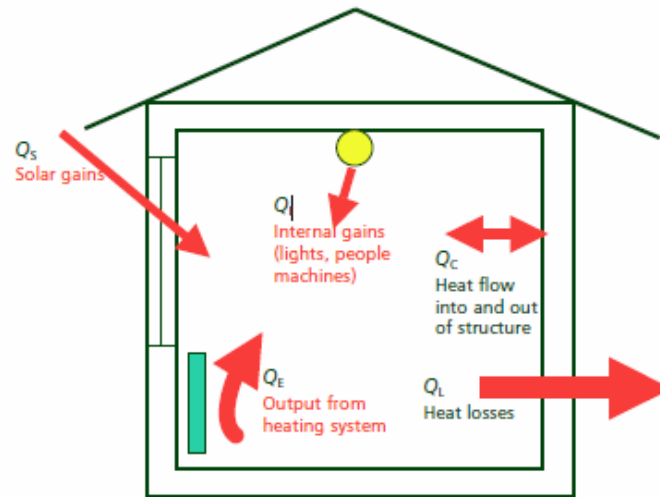


Fig. 4-3 Energy balance of the testing laboratory

Returning to HDD method, “average method” was used to determine degree-days from UPB testing laboratory. For degree-day method examination the selected base temperature is an essential concern. The purpose of HDD is to accumulate points when external temperature falls below base temperature. Cooling degree days does exact the opposite, when external temperature elevates above base temperature. There are two ways of getting base temperature for a building:

- using website: <https://www.degreedays.net/> [124],
- using linear regression analysis [125].

Buildings base temperature is the standard temperature of a structure, below which or above which, requires cooling or heating.

The evaluation of the base temperature is gathered from the PHPP file, and calculated as follows:

$$\begin{aligned} \text{Degree Day} & \hspace{15em} (28) \\ & = \text{Average daily temperature} - \text{Base temperature} \end{aligned}$$

Depending on the heating/cooling degrees, the procedure for estimating the degree days is based on finding the maximum and the minimum temperature occurred on a specific day. Daily temperature records, high and low, are captured by sensors, to determine the average temperature. From average daily temperature, base temperature is subtracted. The resulting value is the specific number of degree day or the amount of degree days that the system needs to function in order to achieve a good thermal comfort.

However, regardless the method used for calculation, the basis consists in having a base temperature which means that a building does not need heating or cooling. According to PHPP file, the base temperature is 20 °C. Considering one random day from the calendar, 1st of May, sensors indicated an average outdoor temperature of 16 °C. Since the outdoor temperature varies, beneath or above base temperature, this might imply warming up to arrive at a balance point.

The calculation for 1st of May shall be done as follows:

$$4^{\circ}\text{C} * 1 \text{ day} = 4 \text{ HDD} \quad (29)$$

If the 2nd of May outside temperature indicates 3 °C below basic temperature, then we consider:

$$3^{\circ}\text{C} \times 1 \text{ day} = 3 \text{ HDD} \quad (30)$$

If, the 3rd of May the basic temperature is equal to outside temperature, then we examine:

$$0^{\circ}\text{C} \times 1 \text{ day} = 0 \text{ HDD} \quad (31)$$

If, during the 4th of May the outdoor temperature bypass basic temperature, then the system should not be turned on:

$$0^{\circ}\text{C} \times 1 \text{ day} = 0 \text{ HDD} \quad (32)$$

For the 5th of May, a daily mean temperature of 12 °C was established, starting from 00:00AM until 12:00AM and 17°C from 12:00PM until 23:59PM, meaning:

$$(8^{\circ}\text{C} \times 0.5 \text{ days}) + (3^{\circ}\text{C} \times 0.5 \text{ days}) = 5.5 \text{ HDD} \quad (33)$$

To conclude, since outside sensor detected a lower temperature than normal, the HVAC system consumption was higher than usual (due to accumulation of degree-days points). Important to realize is that the accuracy of this type of method is not very high but the rapidity of the analysis provides a result in no time.

Specific annual heat demand for the building is being calculated monthly, showing good response of the system. Fig. 4-4 is presenting the specific losses, gains and heating demand of the testing laboratory marked with different colors. During the warm season, the specific losses are on a minimum trail while the specific solar gains are at maximum potential, implying no specific heat demand for the HVAC system.

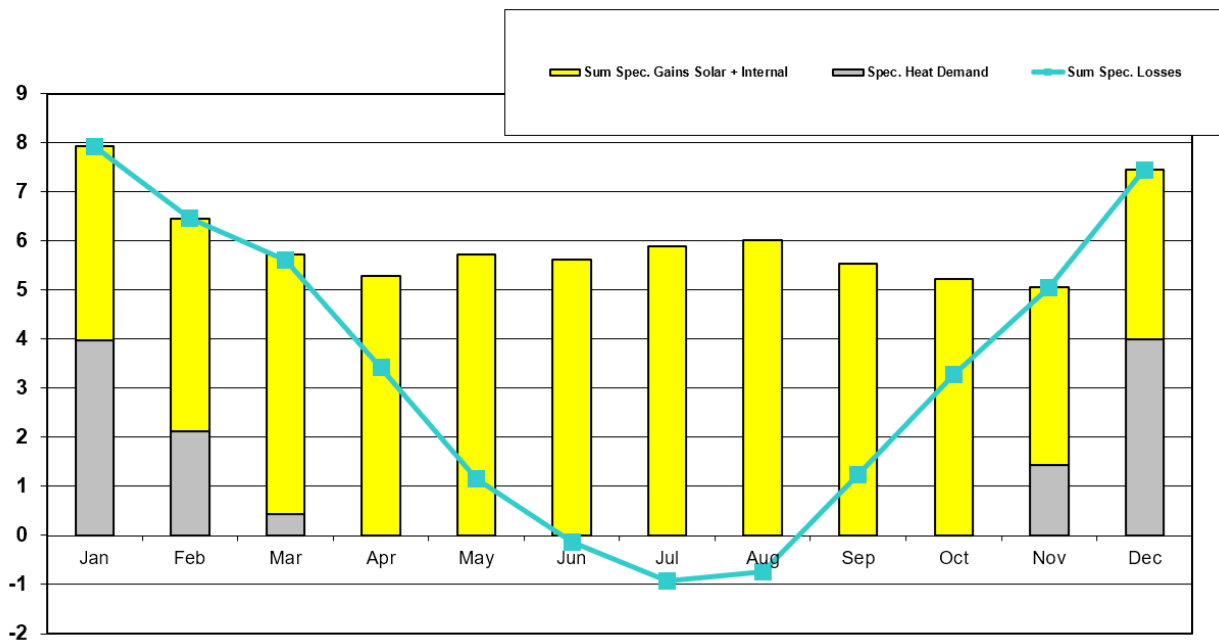


Fig. 4-4 Specific losses, gains, heating demand (kWh/m<sup>2</sup> month - Reference to habitable area)

During winter season, specific heat demand is growing due to weather conditions. Despite this behavior, testing laboratory is running on good reference range intervals because average mean is kept below 12 kWh/m<sup>2</sup>y.

As a result, all parameters are being kept under limited range intervals as displayed in Fig. 4-5, proving that annual heating demand (12 kWh/m<sup>2</sup>y) is exactly as the requirement criteria for a passive house certification.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	
Heating Degree Hours -	16,0	12,8	10,9	6,3	1,7	-0,9	-2,4	-1,9	2,4	6,5	10,2	15,2	77	kKh
Heating Degree Hours -	5,9	5,8	6,4	5,6	3,8	2,6	1,7	1,2	1,2	2,8	3,7	5,0	46	kKh
Losses - Exterior	1028	825	698	403	110	-56	-153	-120	157	421	657	976	4948	kWh
Losses - Ground	80	79	87	76	52	35	24	16	16	38	50	67	621	kWh
Sum Spec. Losses	7,9	6,5	5,6	3,4	1,2	-0,1	-0,9	-0,7	1,2	3,3	5,1	7,5	39,8	kWh/m <sup>2</sup>
Solar Gains - North	7	9	14	18	26	29	29	23	16	11	7	6	194	kWh
Solar Gains - East	69	89	135	163	209	213	225	202	154	120	59	52	1687	kWh
Solar Gains - South	257	312	374	348	348	334	353	400	394	383	229	206	3937	kWh
Solar Gains - West	0	0	0	0	0	0	0	0	0	0	0	0	0	kWh
Solar Gains - Horiz.	0	0	0	0	0	0	0	0	0	0	0	0	0	kWh
Solar Gains - Opaque	0	0	0	0	0	0	0	0	0	0	0	0	0	kWh
Internal Heat Gains	219	198	219	212	219	212	219	219	212	219	212	219	2575	kWh
Sum Spec. Gains Solar	3,9	4,3	5,3	5,3	5,7	5,6	5,9	6,0	5,5	5,2	3,6	3,4	60,0	kWh/m <sup>2</sup>
Utilisation Factor	100%	100%	98%	65%	20%	0%	0%	0%	22%	63%	100%	100%	46%	
Annual Heat Demand	557	298	61	0	0	0	0	0	0	0	201	561	1677	kWh
Spec. Heat Demand	4,0	2,1	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,4	4,0	12,0	kWh/m <sup>2</sup>

Fig. 4-5 Monthly specific heat demand calculation

When using cooling degree-day, buildings energy estimation can be systematized by showing the exact number of day-points needed to minimize the inside temperature. Due to high solar gains, the HVAC system needs to bypass the electrical resistance, injecting fresh ground temperature inside the building. Fig. 4-6 shows the graphical representation of specific losses, loads and cooling demand of the HVAC system, monthly.

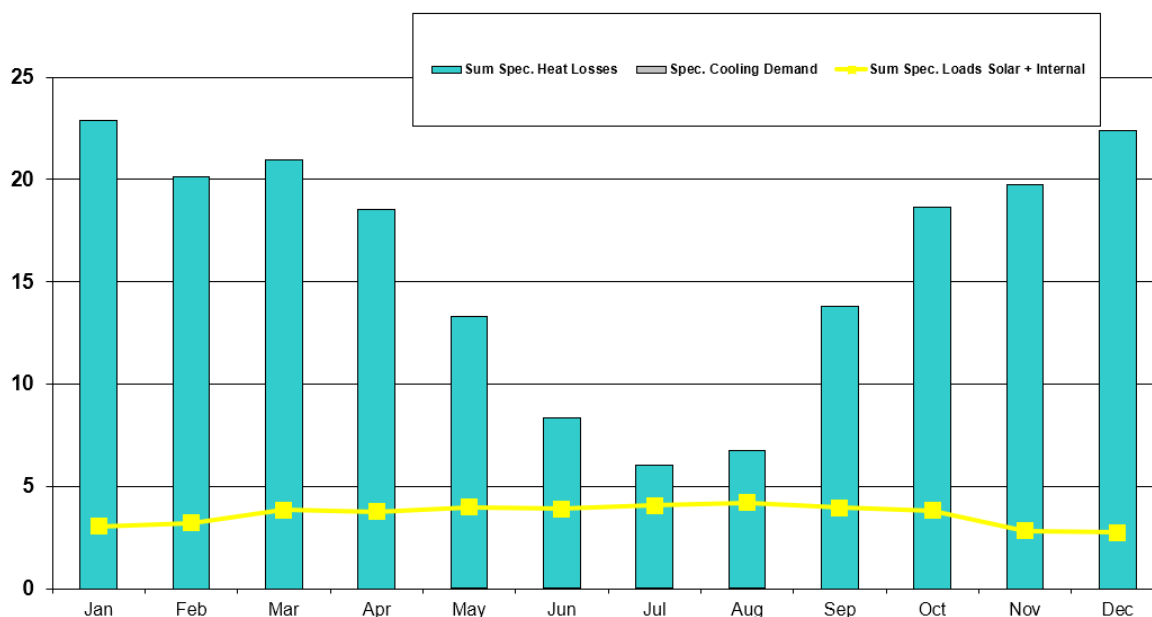


Fig. 4-6 Specific losses, loads and cooling demand (kWh/m<sup>2</sup> month)

As a result, Fig. 4-7 illustrates the necessity of HVAC usage to cool down the house to achieve individual comfort. The HVAC system is organized to implement an indoor temperature of 25 °C during summer period, inside each room of the building.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	
Heating Degree Hours - E	19,7	16,2	14,6	9,9	5,4	2,7	1,3	1,9	6,0	10,3	13,8	18,9	121	kKh
Heating Degree Hours - C	9,7	9,2	10,1	9,2	7,6	6,2	5,5	4,9	4,8	6,5	7,3	8,7	90	kKh
Losses - Exterior	2526	2075	1869	1264	696	351	172	238	775	1316	1771	2422	15474	kWh
Losses - Ground	247	235	259	236	194	159	140	126	123	167	187	222	2296	kWh
Losses Summer Ventilati	425	504	806	1095	968	658	528	580	1029	1126	801	486	9005	kWh
Sum Spec. Heat Losses	22,9	20,1	21,0	18,5	13,3	8,3	6,0	6,7	13,8	18,6	19,7	22,4	191,3	kWh/m <sup>2</sup>
Solar Load North	3	4	6	8	11	12	12	10	7	5	3	2	82	kWh
Solar Load East	32	41	62	75	97	99	104	93	71	55	28	24	782	kWh
Solar Load South	171	207	249	232	232	222	235	266	262	255	152	137	2622	kWh
Solar Load West	0	0	0	0	0	0	0	0	0	0	0	0	0	kWh
Solar Load Horiz.	0	0	0	0	0	0	0	0	0	0	0	0	0	kWh
Solar Load Opaque	0	0	0	0	0	0	0	0	0	0	0	0	0	kWh
Internal Heat Gains	219	198	219	212	219	212	219	219	212	219	212	219	2575	kWh
Sum Spec. Loads Solar +	3,0	3,2	3,8	3,8	4,0	3,9	4,1	4,2	3,9	3,8	2,8	2,7	43,3	kWh/m <sup>2</sup>
Utilisation Factor Losses	13%	16%	18%	20%	30%	47%	68%	62%	29%	20%	14%	12%	23%	
Useful Cooling Energy D	0	0	0	0	0	0	3	1	0	0	0	0	4	kWh

Fig. 4-7 Monthly cooling request calculation

In terms of energy consumption and cost reduction, energy estimation is one of the most important characteristics. With a precise energy estimation, multiple detrimentally issues can be overcome, such as: financial problems, ineffective energy usage or energy savings. Although system simulations help to predict energy use, the accuracy may not be so precise due to software errors. Even though the investigation can be made on a high level, the biggest concern is the time-consuming process. The advantage provided by degree-day method is the simplicity for estimating building's energy consumption when it comes to heating or cooling. It is required only few input data to run a complete analysis to predict energy consumption or, briefly, to identify factors influencing the consumption. Heating degree-day method comes with an improvement in reducing the number of inputs, which is helpful in the estimation of energy consumption.

## 4.2. Grey-box models

### 4.2.1. Introduction

A grey-box model equation is used to describe the dynamic system. The stochastic differential equations (SDE) are the basic equation from where the system draws its inputs:

$$dT_1 = \left( \frac{1}{C_1 R_1} (T_e - T_1) + \frac{1}{C_1 R_2} (T_i - T_1) \right) dt + \sigma_1 d\omega_1 \quad (34)$$

$$Q_{i,k} = \frac{1}{R_2} (T_{i,k} - T_{1,k}) + e_k \quad (35)$$

where,

- $Q_i$  - output is the observed heat flux
- $T_i$  and ambient temperature  $T_e$  - inputs are the indoor air temperature
- $T_1$  - state variable in equation (34), together with the observation equation (35).
- $k$  is the  $k^{\text{th}}$  observed value at time point  $T_k$ .

Parameters are:

- $C_1$  – wall heat capacity
- $R_1$  - thermal resistance from the ambient into the lumped state in the wall
- $R_2$  - thermal resistance from the lumped state to the interior



- $\omega_1$  is assumed to be a Wiener process, which is a continuous time noise process that has the property  $\omega_1, T_k - \omega_1, T_{k1} \sim N(0, (T_{k-1} - T_k)^2)$ . The unit is here  $\sqrt{s}$ . The variance of the system noise is thus  $\sigma_1^2$ .
- the observation noise  $e_k \sim N(0, \sigma^2)$  is presumed to be white noise, hence, normal distributed variance  $\sigma^2$ .

#### 4.2.2. Grey-box identification model

The model used in the system is illustrated with the RC-diagram in Fig. 4-8 . CTSM (Continuous Time Stochastic Modelling) is utilized in estimation parameters with SDE (prediction error) and is available as an R package named CTSM-R. The R software was used to simulate the identification parameters and to transform the analyzed wall into a nodal circuit:

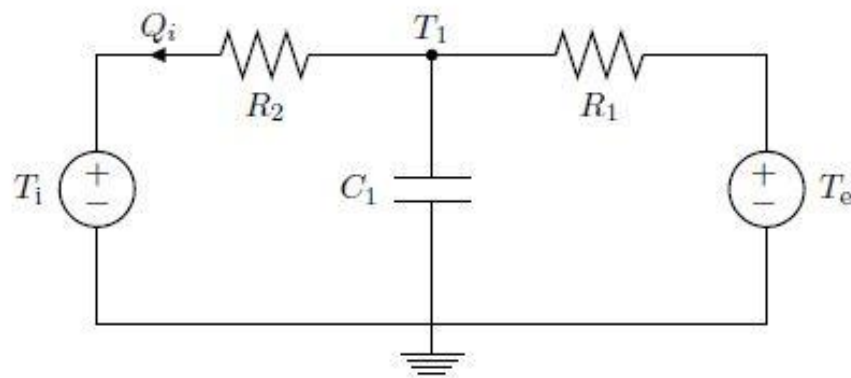


Fig. 4-8 RC diagram

Given these points, a short report was made with concise answers illustrating the plots for the system. The steps of coming up to the displayed parameters started by running the Q script programmed in the R software.

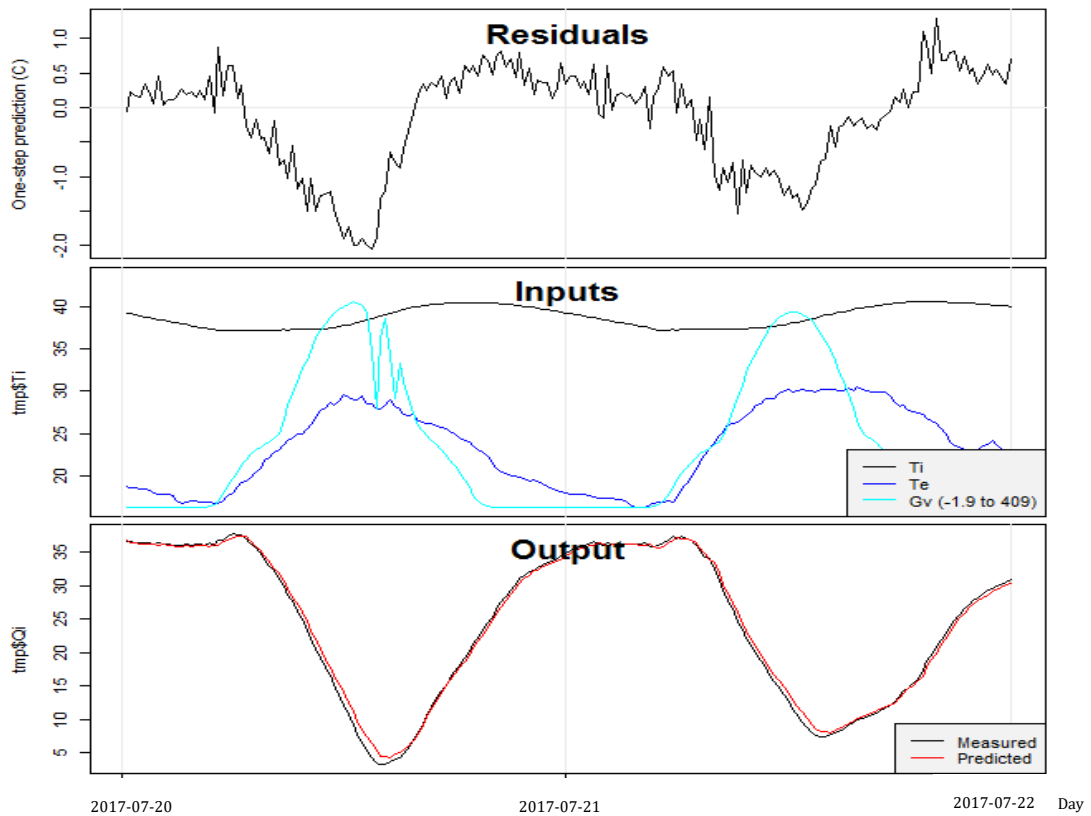


Fig. 4-9 Residuals, inputs and outputs of the system

In Fig. 4-10 is exemplified three important assets for the model. Starting with relieving of inputs system, we identify the inside temperature marked with black line, the environmental temperature outlined with purple line and the solar gains noted with cyan. On the other hand, outputs model are specified in the bottom of the Fig. 4-10, subplot with measured energy flux as black line and the prediction of energy consumption, draw with red line. Thereupon, of the top of Fig. 4-10 the residuals variation is presented.

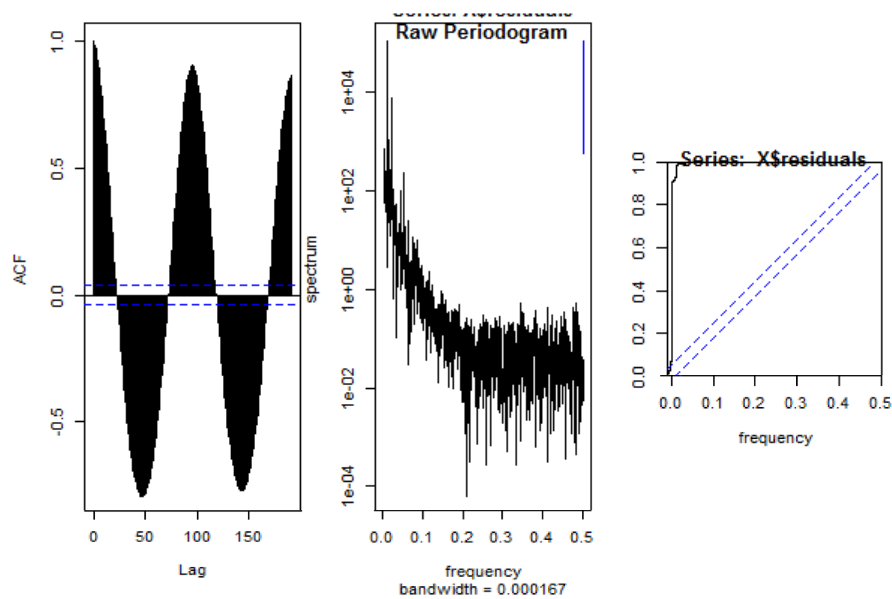


Fig. 4-10 The correlation of residuals and white noise

As presented above, residuals correlation has been calculated using R software while result was plotted in a bandwidth image. In the first place, residuals are correlated, following a precise path, underling the fact that there is no white noise (in our case error). The analyzed spectrum has low values when comparing to a different frequency, which indicates that some parts of our implemented system, even different inputs, have small values. On the other hand, looking at the right side of Fig. 4-10 we can point out the incertitude of residuals that are not in the confidence band, not even 5%, implying that the model is still on working phase. Due to this incertitude the model is classified as not feasible and the perfect fit was not yet discovered.

Moving further on the technical survey, if we examine Fig. 4-11, in terms of results, we can affirm that the system is precise, it follows a good track, but the residuals does not have sustainable values. A good observation would be that there is an enormous influence upon the system that is similar to a solar gain and is influencing the heat flux. By looking at graph and also by checking the elements of equation (34), the “GV” term (solar radiation) is missing completely from the mathematic model. In addition, the solar radiation is impacting directly the house, having a major effect on energy consumption, where  $g$  is a coefficient describing the ratio of the vertical radiation absorbed by the wall.

System enhancement can be made by implementing the solar radiation in the simple grey-box model as follows:

$$dT_1 = \left( \frac{1}{C_1 R_1} (T_e - T_1) + \frac{1}{C_1 R_2} (T_i - T_1) + \frac{g}{C_1} G_v \right) dt + \sigma_1 dw_1 \quad (36)$$

In other words, the system can be summarized as an RC nodal model with 2R (resistance), 1C (capacity), 1Gv (solar gain) and the T (temperatures) from the borders, inside and outside. The flux moves towards the interior temperature with the summation between the outside temperature and solar radiation, as exemplified in Fig. 4-11.

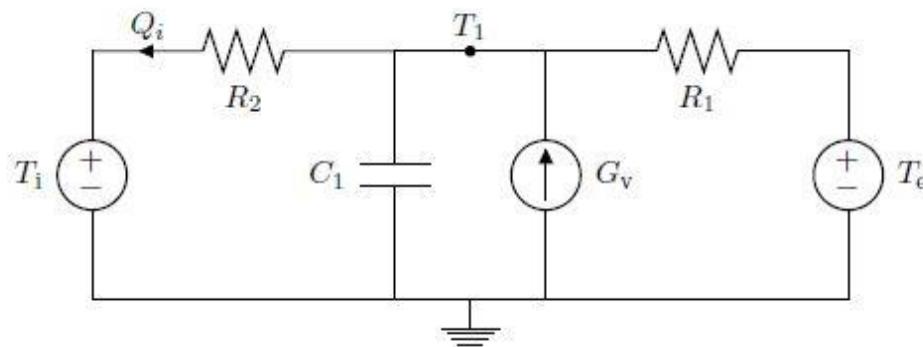


Fig. 4-11 Nodal form with solar radiation

After the calculations has been made, results are presented in Fig. 4-12 where and improvement of the previous version of the system is displayed. As mentioned before, on the top part of the Fig. 4-12 residuals are being plotted, while on the middle section, input parameters are shown. The difference is made by the  $G_v$  term which represents the solar gains of the system. Results presents constant residuals, enhanced inputs and a serisous upgrade of outputs (predication and measured) as mentioned in the bottom of the picture.

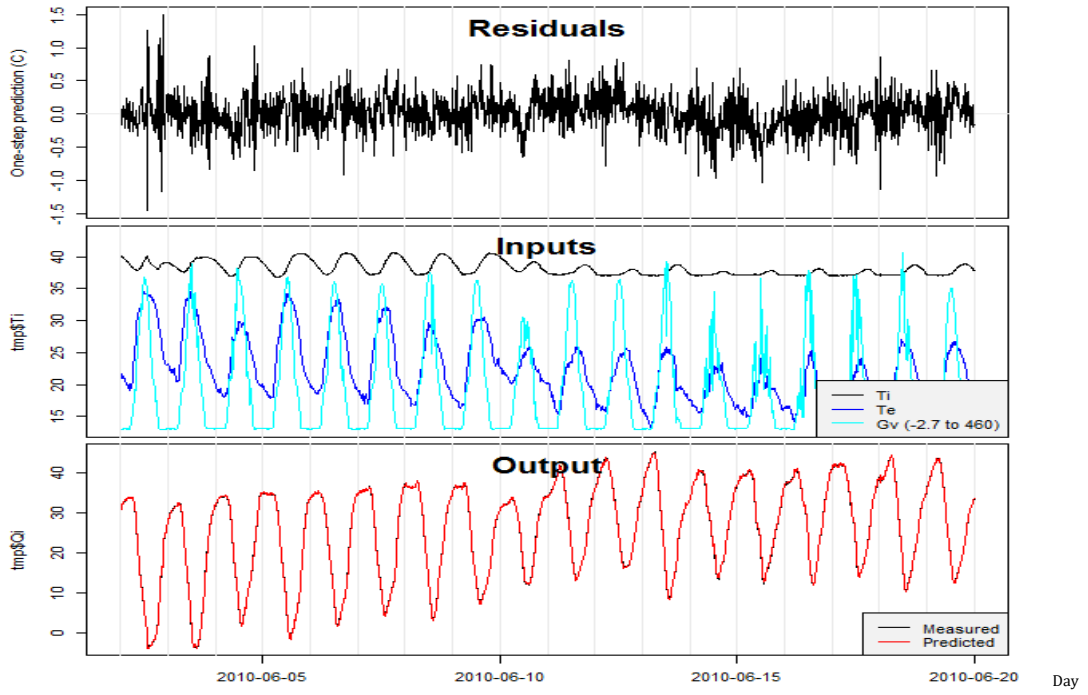


Fig. 4-12 The system with solar radiation implementation

With the intention of achieving better results, solar radiation has been integrated into the system and enhanced a progress in outputs. One of the fastest changes of the system can be seen by looking at high values from Fig. 4-12, pointing that solar radiation is strongly related and directly proportional with the inputs. At the same time, energy flux switches constantly, demonstrating a solid relationship with solar radiation. Taking into consideration results from the above exemplification (model without solar radiation), residuals decreased significantly. Additionally, the system tends to move towards small residual values showing new improvement opportunities.

Last, but not the least, the 3<sup>rd</sup> example of a system was designed. Thus, steady point (T2) and new capacity were brought in accordance with the solar radiation, reminding the fact that capacities are helpful for storing excess energy from the system. Therefore, a new mathematical model was created having the subsequent equations:

$$dT_1 = \left( \frac{1}{C_1 R_1} (T_e - T_1) + \frac{1}{C_1 R_2} (T_2 - T_1) + \frac{g}{C_1} G_v \right) dt + \sigma_1 dw_1 \quad (37)$$

$$dT_2 = \left( \frac{1}{C_2 R_2} (T_1 - T_2) + \frac{1}{C_2 R_3} (T_i - T_2) \right) dt + \sigma_2 dw_2 \quad (38)$$

The analytical structure (7) of new model is different from equation (6) because of the implementation of additional capacitance ( $C_2$ ), resistance ( $R_3$ ) and steady point ( $T_2$ ) as displayed in Fig. 4-13:

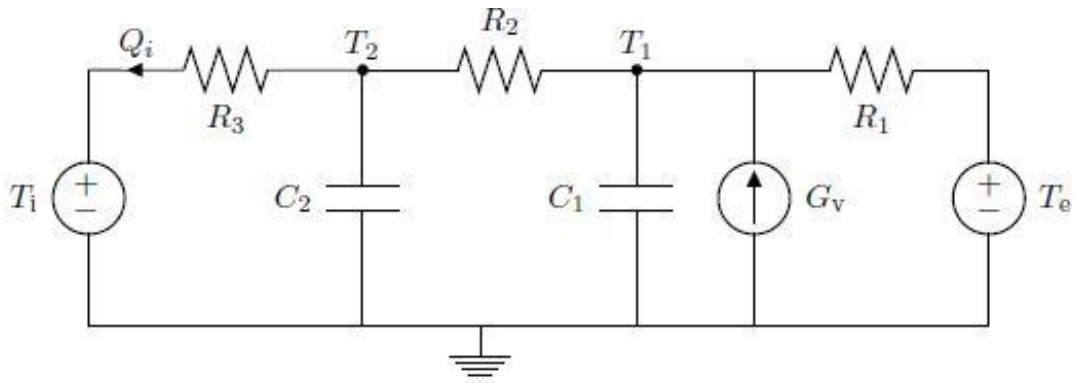


Fig. 4-13 Mathematical model with solar radiation and steady point

The results obtained is an improvement asset to the system, being exemplified in Fig. 4-14, where a substantial residuals difference can be noticed. The residuals are maintained in the confidential bandwidth, with more than 95% of the scenarios showing good enhancement. None of the less, the most important value is the other 5% of the percentage, which is considered to be the systematically error.

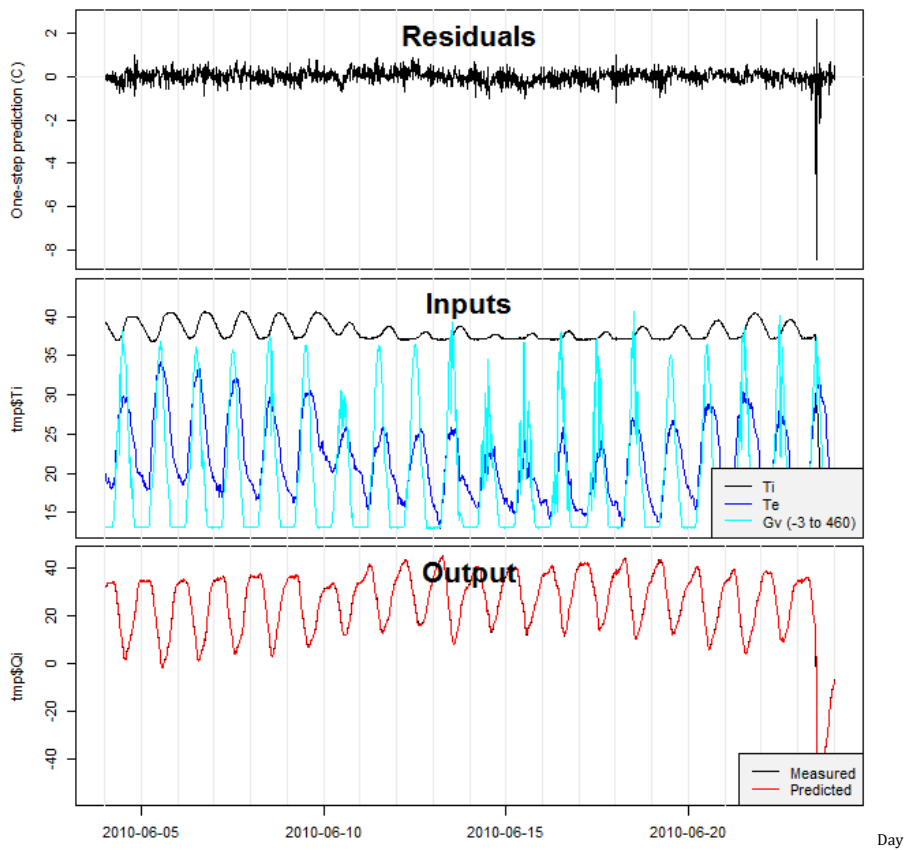


Fig. 4-14 Reports and results for the last model

As Fig. 4-15 presents, inputs are following a favorable trend, being equivalent to solar rays gathered from ambient. Unlike inputs, output parameters have a systematic error at the analysis conclusion. Such mistake takes place once data is missing or as an effect of lack of inputs in the DATA\_Series database, at beginning of the system. Moreover, the time step for

the simulated system was chosen to differ from step to step having as time step: 2, 5, 10, 15, 20 and 30 minutes. Data were gathered in series to comprehend the link between residuals and estimation error prediction.

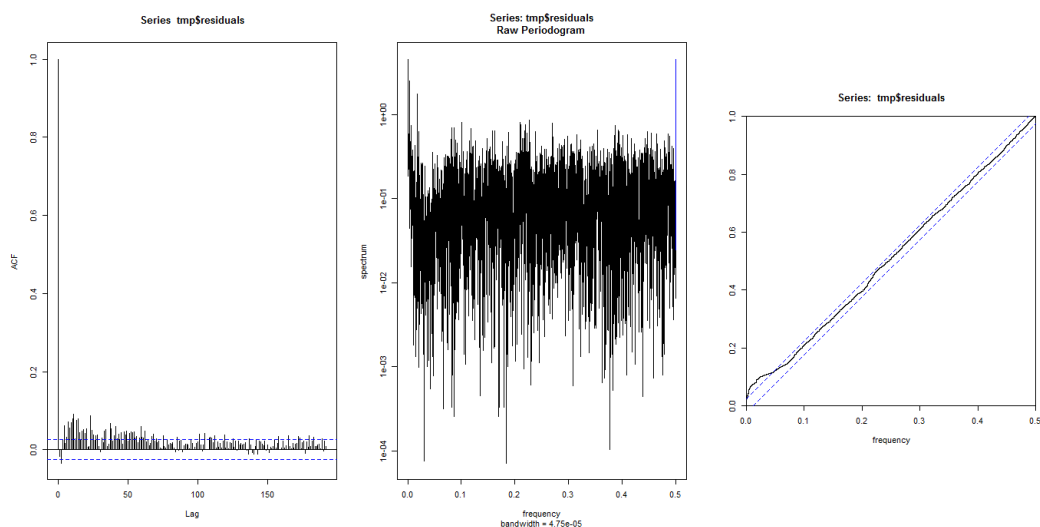


Fig. 4-15 Residuals and results

In closing, the more we reduce time step of the analysis, the more the accuracy is growing, and residuals becomes higher, providing the opportunity to control them easily. The slightest change of inside temperature has a major effect upon residuals, forcing the systems output to change its value. As displayed in Fig. 4-16, residuals present a huge modification at the analysis outcome which was caused by a malfunction of the system. To be noted that residuals are maintained in the band of confidence more than 96%, proving the algorithm efficiency in cause.

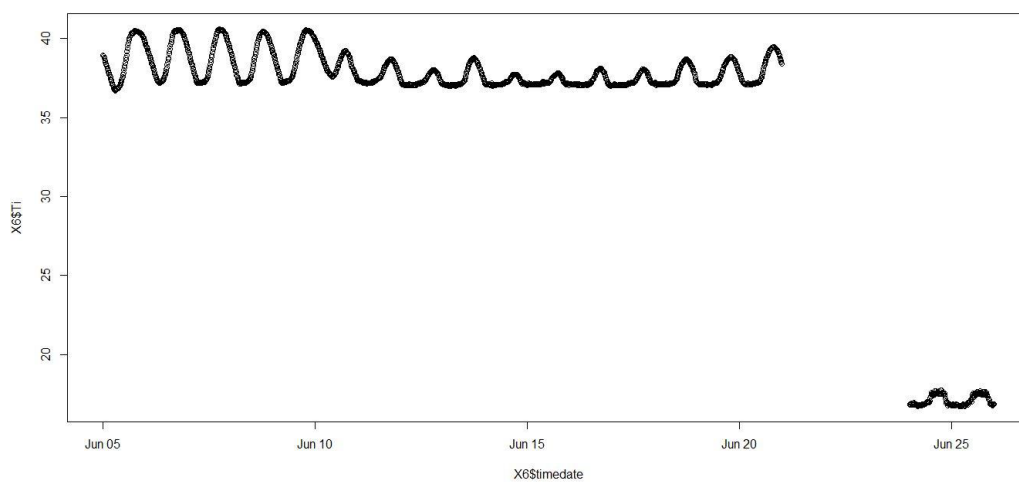


Fig. 4-16 Dropdown in residuals due to temperature change

Moreover, the dropdown seen in Fig. 4-16, cause by the system malfunction residuals are beginning to stabilize at a certain point, on 25<sup>th</sup> of July.

As a conclusion, by seeing the results of residuals, we can acknowledge the fact that this model is an improvement, because residuals are following a constant pattern, being contained in the band of confidence with high precision. The model is sensible to inputs,

especially when initial parameters suffer modification. To cover this issue and improvement is necessary since radiation from sun is strongly related to systems resistances.

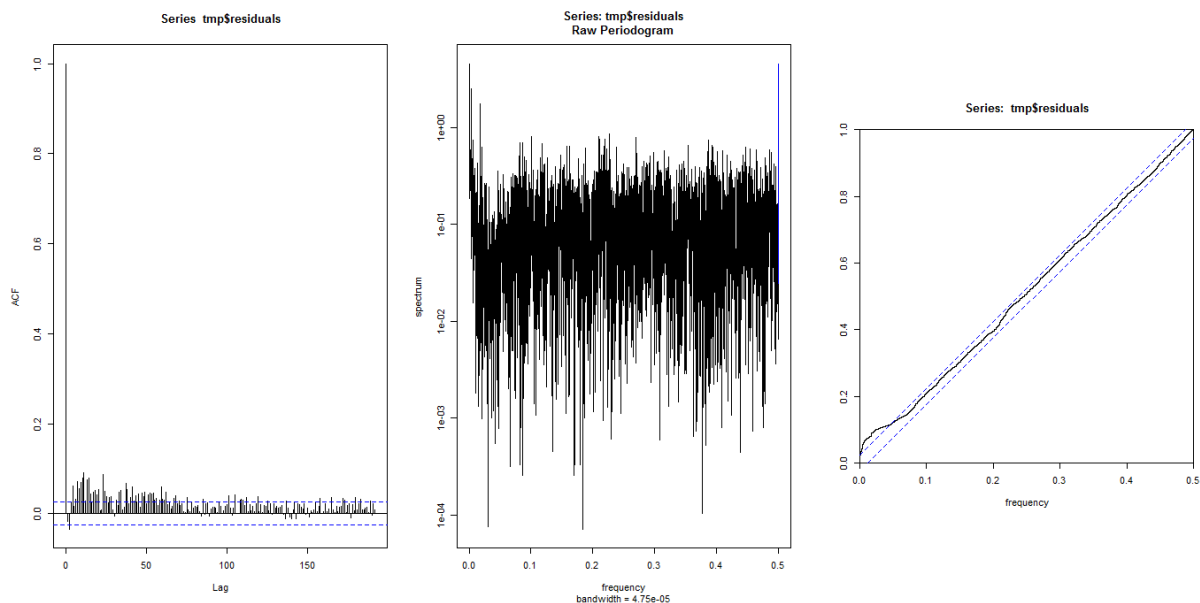


Fig. 4-17 Residuals and results

Model approach number 3<sup>rd</sup> has the best fit for the system analyzed which can further be improved, by taking into consideration larger inputs data, weather aspects or human behavior patterns. The residuals are maintained in the band of confidence with an efficiency of more than 97% as display in Fig. 4-17.

### 4.2.3. Conclusion

Data is gathered from the smart meters and analyzed within the web platform which represents the details for mathematical model described above. Each mathematical model is composed of three main components: input variables, system structure and parameters and output variables. According to basic procedures, output variables are obtained in different ways in conformity with forward or data-driven approach. Multiple features such as precision, sensibility, adaptability, time response or user friendly are beard in mind when choosing a management system.

The degree-day, which estimates energy consumption having historical data, is examined. The balance point of the system is calculated when the causal gains equals losses regardless weather condition and analyze output variables. For this, heating and cooling degree calculation are determined by taking into account weather inputs such as: internal and external air temperature. In short, the system behaves accordingly to outside temperature starting to cool or heat subjective to indoor comfort necessity.

Important to realize the benefit of having control over the HVAC system, as 20% of energy usage can be overcome with a clean behavior. For this reason, state-space model and intelligent algorithm prove to be modern approaches used by engineers in buildings project. First, thermal network method is submitted, consisting in finding systems parameters such as

resistance value or total capacitance value. Therefore, each facility element is transformed into a RC network while an incident matrix is proving how to assemble multiple thermal circuits.

Last but not the least, intelligent prediction methods are emphasized in thesis, indicating beneficial impact of artificial neural network in control approaches. State-space models utilize state parameters to characterize a mathematical model through differential equations of 1<sup>st</sup> order. Thus, controlling those state-parameters with artificial neural network generates less energy consumption for the consumer.

Given these points, numerical approaches for estimating energy consumption indicate the necessity of having control over the HVAC system and consequently over the entire testing facility behavior. Thus, usage and energy control via fuzzy logic method can reduce energy consumption, pursuing the aim of my thesis. In addition, this technique can lead to desire thermal comfort using less energy than previously assumption.



## *CHAPTER V – Energy monitoring and control*

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Towards chapter V energy monitoring and control are being highlighted withing the thesis goal. Small introduction about energy control and energy generated inside the Passive House are presented as a solution for controlling and optimizing the buildings energy consumption.

To attain good thermal comfort inside the house, fuzzy logic technique is used. The proposed target is measured by percentages of logic assumptions.

MATLAB software was used to simulated and validate the process in accordance with a policy management system.

## 5.1. Introduction

In this chapter energy control and monitoring are presented, as a solution for optimizing buildings energy consumption. Energy monitoring involves capturing the overall power consumption of testing laboratory or recording the consumption of each device from the building. Nowadays, monitoring energy can be acquired through several means such as:[126]

- thermostats,
- system feedback,
- smart meters,
- administrative data,
- statistical models' surveys,
- specific sensors.

Energy monitoring is helpful if control is required. The importance of using fuzzy logic in automatic control is related to the fact that the user does not need much system knowledge and the controlled usage is determined by linguistic rules. The system doesn't need to be reduced to develop a working fuzzy logic controller while the conditions are robust, because of variability in inputs [127][128].

Thermal comfort depends on many factors. Multiple algorithms and software tools have been released in order to respond to human necessity for indoor comfort. Such exemplification is illustrated in the following chapter where a fuzzy controller matches the inhabitants needs from UPB testing laboratory. The occupants are no longer preoccupied by interior temperature since the HVAC and energy management system are working simultaneously. To understand the advantage of such implementation, a fuzzy controller is developed running on strict rules. Policies using if-then-else rules are written, giving the possibility to reduce energy consumption trough this manner. Fuzzy algorithm analyzes input parameters, filters, and outputs the requested energy amount necessary for achieving good thermal condition.

Within the fuzzy logic system, input sets are being uploaded in a verification software, where the accuracy of outputs and achieving stable inside temperature are monitored. Thus, implementing the following control algorithm, pursue the thesis goal of energy consumption reduction.

## 5.2. Thermal comfort in buildings using fuzzy logic

The fuzzy logic technique is an approach of attaining a reliable thermal comfort. This method implies controlling the energy system by heating and cooling the building. Whether to start, or to shut down the HVAC system depends on policies and human behavior. Fuzzy logic suggests two realistic mechanisms to identify whether energy is saved or lost.

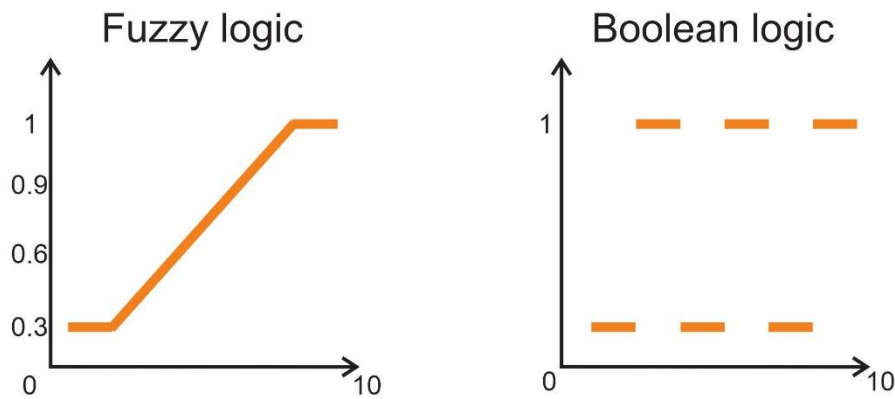


Fig. 5-1 Fuzzy mechanism

The first mechanism is recognized as being part of the Boolean logic system, meaning that any object can be described by either “True” or “False” value. The interpretation values define static values such as 1 or 0; 1 – is assigned to “True” value while 0 – is allocated to the “False” value, as presented in Fig. 5-1.

On the other hand, second mechanism receives values between a specific reference range. The controller analyzes data gathered from sensors and correlates them with values from 0 to 1. Hence, when receiving 0.7 grade of value, it’s not completely true, but partially true, while False or mainly false, is pointing to 0.3 grades of value.

Most compelling evidence is that residential sector started to implement fuzzy logic technology, showing a tremendous success in energy proficiency of the testing laboratory [129][130][131][132]. Taking into consideration that user demands are to diminish energy consumption, fuzzy logic came with a solution for modeling heat and cooling loads [133].

Any system equipped with fuzzy logic, can take crucial decisions, improving energy effectiveness and energy savings. The implementation of a fuzzy logic system into the testing laboratory proved higher efficiency when modeled with HVAC system [134][135].

The software implemented into the testing laboratory is a (SBC) Smart Building Controller, able to reduce buildings energy consumption. The monitoring infrastructure collects surrounding inputs and creates a database for further analysis. In the light of achieving a good temperature level, SBC enables the possibility to modify policies, to control the HVAC equipment. Additionally, the SBC software has a couple of benefits, including the electrical resistance management or real time feedback. Each system feedback is useful for predicting energy consumption, due to a detailed information about database. Hence, the user can interact with the system by configuring each part of the SBC software. This configuration can be implemented with strict rules, such as: IF, THEN, ELSE codes, as seen in Fig. 5-2.

The optimization of energy consumption is developed with less complications when using fuzzy logic technique as it can be transformed and realized using artificial neural network [136].

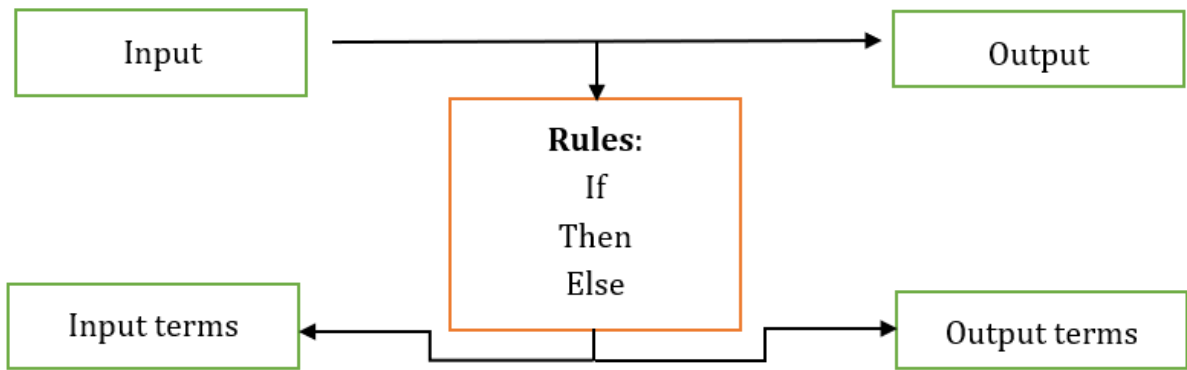


Fig. 5-2 Specific example of using ANN with fuzzy logic

Even if fuzzy logic concept started to be developed in 1960 by Lofti Zadeh, nowadays it's covering a wide area of appliances including artificial intelligence. The future of applied technology "fuzzy-logic" is wildly use in software programming, microcontrollers or temperature system development [65].

Fuzzy control is based on applied engineering methods, following strict standards without taking into consideration values such as true or false. A fuzzy logic system consists of taking non-linear INPUT data and transforming to scalar OUTPUT data as in Fig. 5-3.

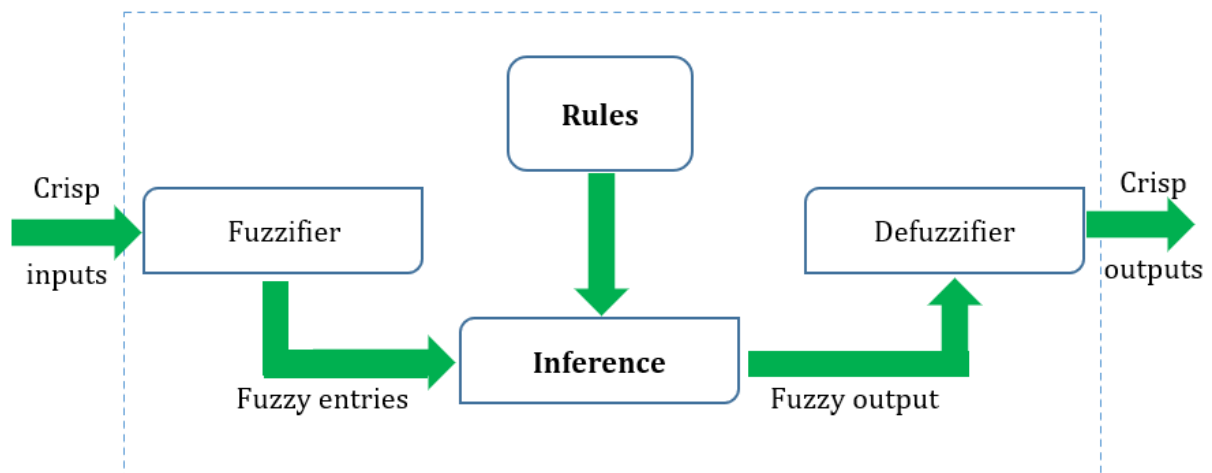


Fig. 5-3 Structure of fuzzy implementation

The structure of fuzzy algorithm from Fig. 5-3 image, details the basic method of analyzing input data and providing requested output. The fuzzifier receives the input data gathered from sensors and transforms it into dependency grades, starting from 0 to 1. After transformation takes place, a fuzzy input set is being created and prepared for the upcoming process. The afterwards process is the inference step, where the acquired set is put under a set of regulation which are created by the user to generate fuzzy output sets. The inference level has every input evaluated by each rule, generating output sets based on feedback. The final process relies on the transformation of fuzzy output set into input set to the "defuzzifier", which accepts the data and models them into numerical values, thus non-fuzzy.

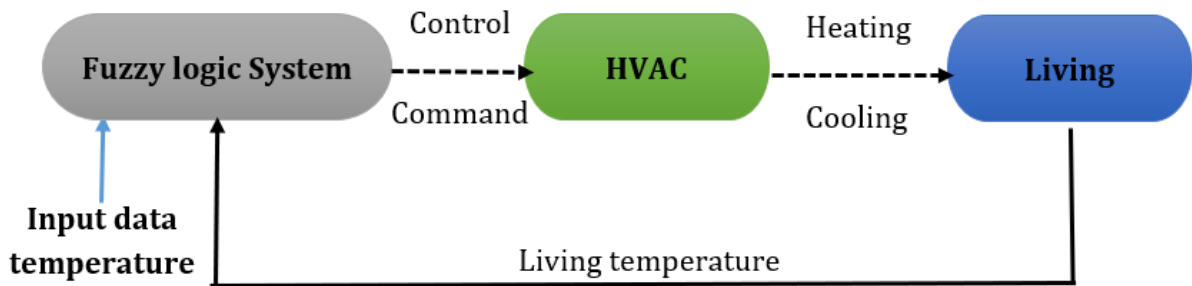


Fig. 5-4 Fuzzy system appliance

Fig. 5-4 presents an approach of UPB testing laboratory fuzzy system. The diagram starts from the left part, as it gathers set of inputs data (degrees) from the environment. After the fuzzification takes places, the HVAC system, depending on the commands he receives from the algorithm, knows what action to take. The HVAC system can heat or cool, the inside temperature, influencing the buildings energy consumption, but not before confronting with initial value of indoor temperature.

Returning to the dependency set, input data is submitted to a specific set of rules and classified as being either HOT or COLD. The classification is made relying on a dependency level as presented in Table 5-1.

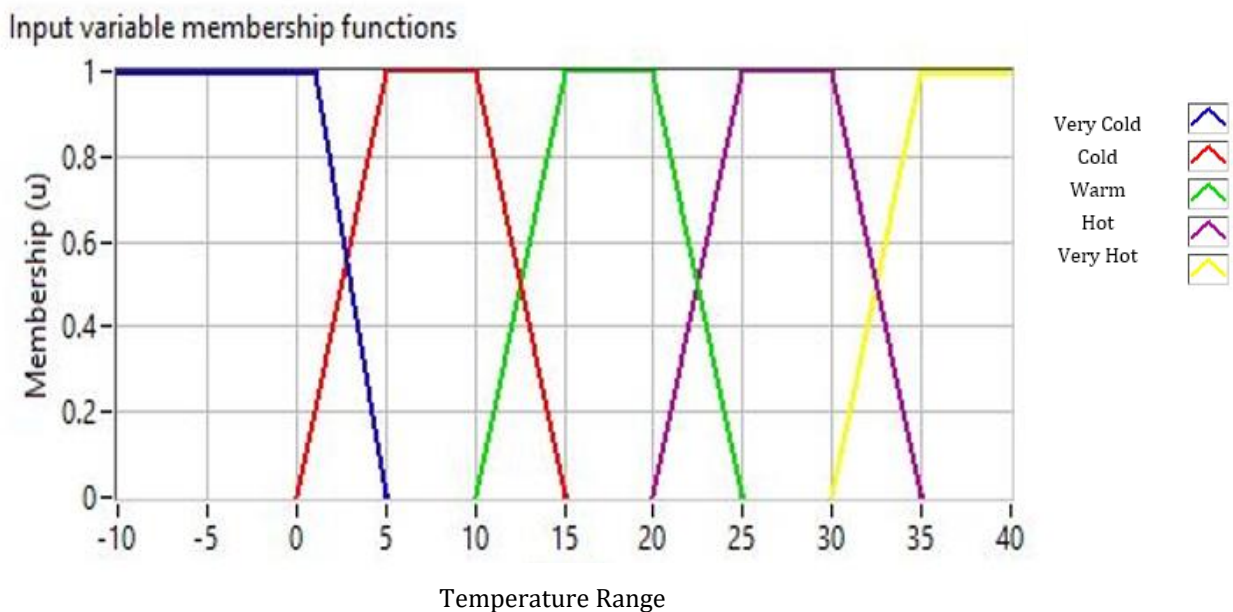


Fig. 5-5 Membership level of fuzzy logic algorithm

If external sensor detects 18 °C beneath room temperature, the HVAC will receive a dependency level of 0.95 HOT and 0.05 COLD, meaning the system must turn on.

Table 5-1 Fuzzy logic input reference for temperature

Temperature	Very Cold	Cold	Warm	Hot	Very Hot
<b>Very Cold</b>	Don't change	Heat up	Heat up	Heat up	Heat up
<b>Cold</b>	Cool down	Don't change	Heat up	Heat up	Heat up
<b>Warm</b>	Cool down	Cool down	Don't change	Heat up	Heat up
<b>Hot</b>	Cool down	Cool down	Cool down	Don't change	Heat up
<b>Very Hot</b>	Cool down	Cool down	Cool down	Cool down	Don't change

To simplify the equation, the dependency levels can be kept as a matrix form, improving accuracy and triggering HVAC system. Table 5-1 is defining the matrix from where the system chooses what to trigger, dragging signal from rows to columns.

### 5.3. Fuzzy algorithm

For a better explanation of the membership level, a set of fuzzy inputs has been uploaded into the LABVIEW software, as presented in Fig. 5-6 to observe output results from the HVAC system. The dependency levels are described as fuzzy function, that can transform fuzzy values into non-fuzzy values (numerical values). In a fuzzy logic system, the most substantial variable is the output. As long as the control output is stable and doesn't fluctuate, a good thermal condition is obtained. The software includes a three-tab panels where input, rules and testing system are selected. Firstly, the input was assessed to temperature variable which is represented by outdoor temperature.

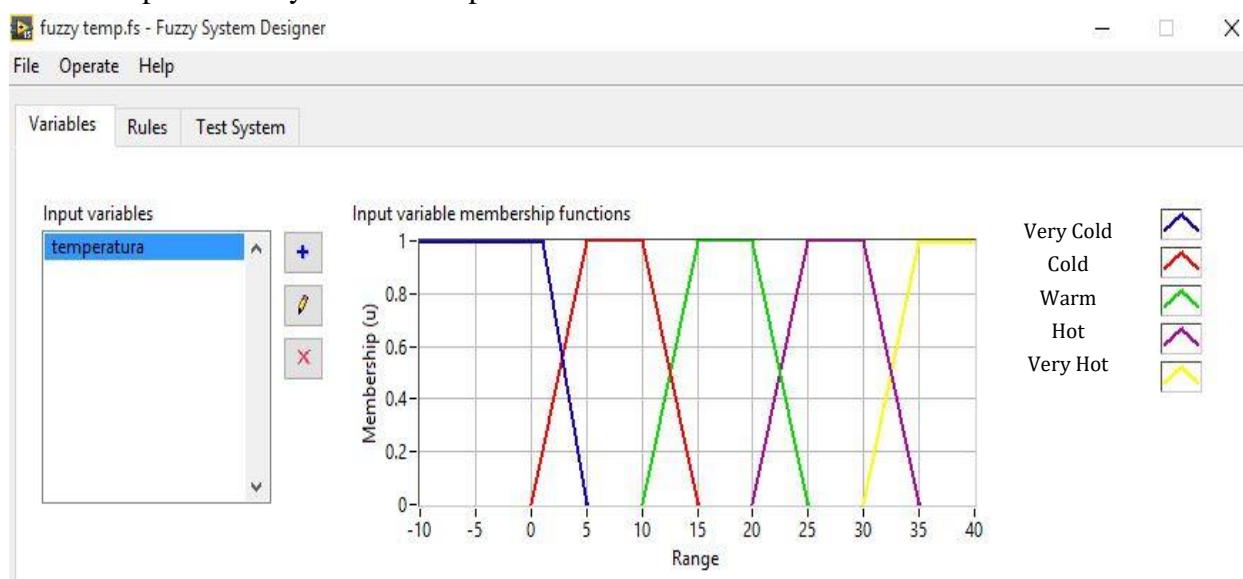


Fig. 5-6 Fuzzy membership functions

The fuzzy system software-designer from LABVIEW allows users to examine when, and in what manner, the HVAC system will be triggered. User can select the Defuzzification method concerning multiple inputs with a suggested consequent. Second step consists of the construction of the logical conditions for each time-step of the system, as displayed in Fig. 5-7.

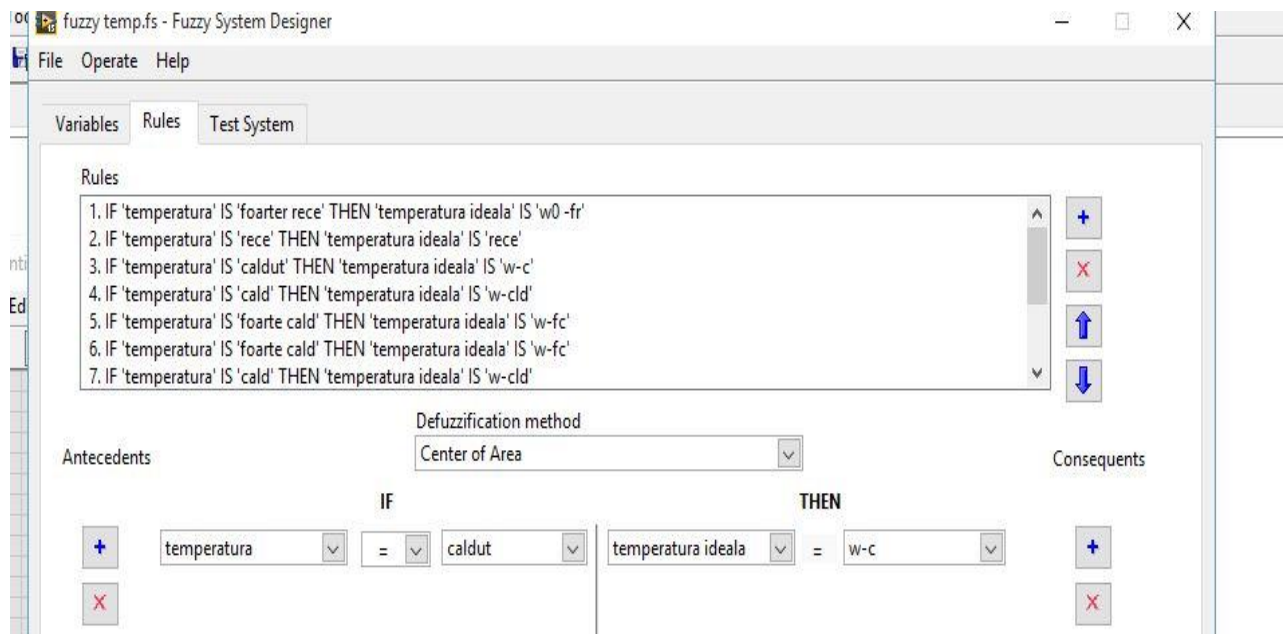


Fig. 5-7 Implementation of fuzzy rules

One of the advantages of using this technique is the easy implementation of any logical condition such as: CASE, IF-THEN, IF-THEN-ELSE, FOR. As Fig. 5-7 presents, the rules are built strategically to understand the next execution and their simplicity of implementation into the system. On the lower part of the image, multiple inputs can be selected and subjected to a specific rule. The action is mentioned on the right part where the HVAC system is triggered.



Third step described in Fig. 5-8, is the plotting of bonding between input/output relationship. Readout of input variable is shown in left side while the outputting is mentioned on the top of the image. Interested to note that the output variable can be modified depending on the thermal comfort and the interference set up.

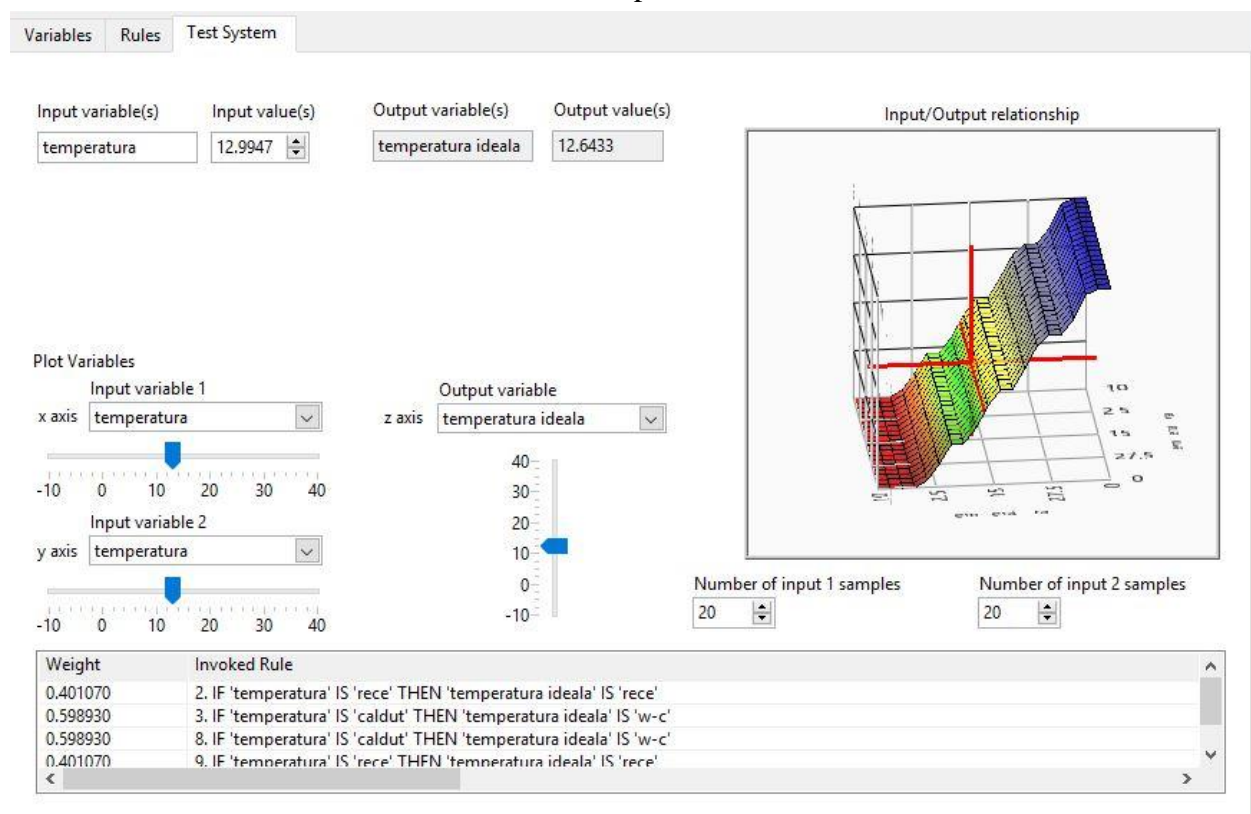


Fig. 5-8 Fuzzy logic testing system

As literature presents, fuzzy logic method has been tested in strong relationship with artificial intelligence, resulting in achieving good thermal comfort with optimized energy consumption [137]. Taking into consideration that temperature is classified as the most compelling element of thermal condition, by attaining it, involves keeping inside temperature between 20 °C and 28 °C [137]–[139].

To achieve and to preserve a favorable degree of comfort, the implementation of a policy that commands the ventilation flow rate was developed. The policy was created depending on two inputs, outdoor temperature and ground temperature exemplified in Fig. 5-8. In addition, policy was set up with two regulations, one to identify and one to validate outside temperature. Outside temperature is directly impacting energy consumption of the house, which leads triggering the HVAC system and energy usage.

These rules are applied during daytime and nighttime, once per minute, calculating an average with inside temperature, as illustrated in Fig. 5-9. When dropping below or above 20 °C of the average outside temperature, the fuzzy-logic algorithm changes the flow rate and increases the fan capacity, to equilibrate with the inside temperature. Moreover, due to strict guideline, the rate flow raises with 20 % when temperature is below 20 °C and reduces to 7 % when temperature is above the reference.



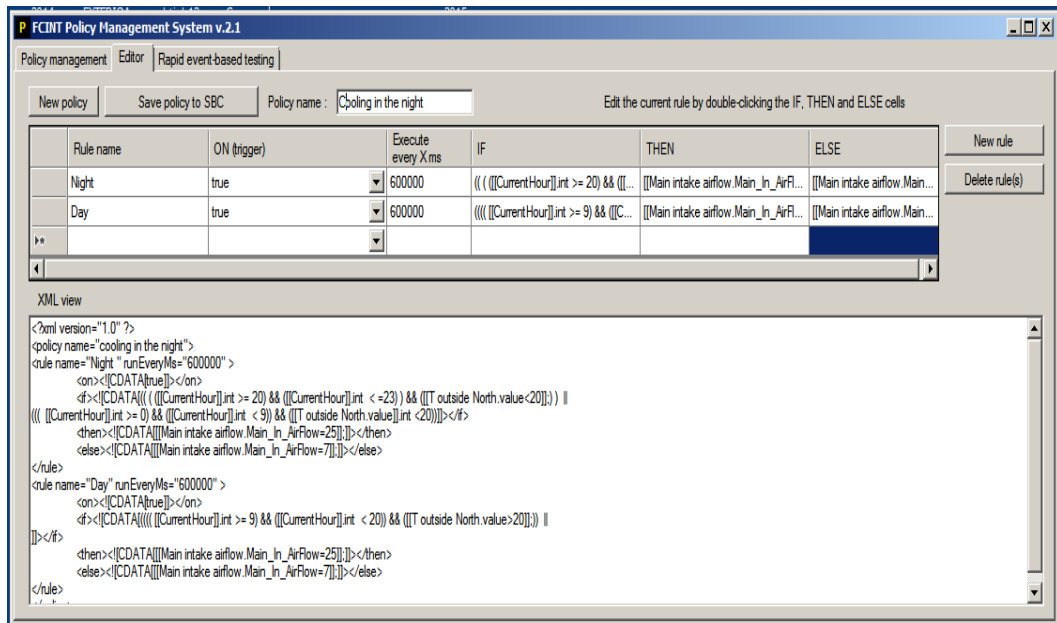


Fig. 5-9 Policy line code

As displayed in Fig. 5-9, the policy management has multiple tabs which can be customized without difficulty. In order to personalize the algorithm, XML code must be written under the Editor tab. The Rapid Event tab can set up collecting time-step data, preciseness of activating HVAC equipment and interpretation of power spent, within the house necessities.

## 5.4 Results and interpretation

With a view on the energy consumption, data is plotted for 6 months (as presented in Fig. 5-10):

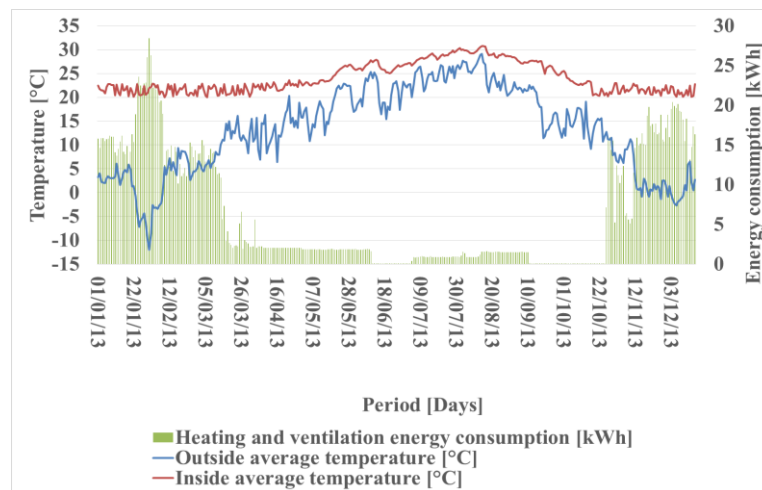


Fig. 5-10 Variation of heating and ventilation energy consumption [90]

During summer period, temperatures are elevated and the request from HVAC system to ventilate inside rooms was high, but with minimum energy consumption. The variation of indoor temperature between 18.73 °C and 30.96 °C is exemplified with 166.08 kWh energy demanded for ventilation. Furthermore, the average temperature for selected period was

26.46 °C taking into consideration solar radiation input. Displaying a value of 406.53 W/m<sup>2</sup>, the mean solar radiation had a big impact on the indoor temperature who was kept under 27 °C, due to exchange air-cooling with ground temperature. For instance, Fig. 5-11 relates the variation of outdoor temperature during the daytime (from 08:00 AM until 20:00 PM). Each colored line exemplifies a specific zone of the house, while solar radiation is represented as a scale on the graph, as Fig. 5-11 displays:

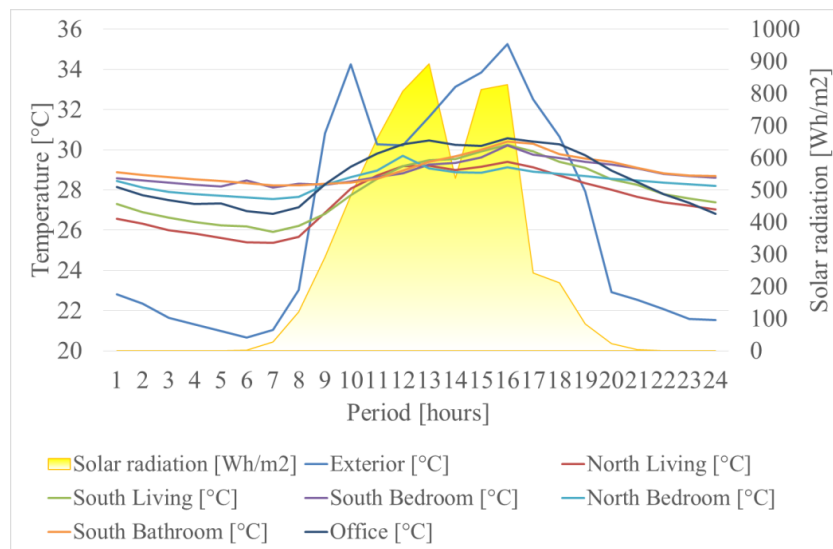


Fig. 5-11 Evolution of indoor and outdoor temperature

Equally important is the exemplification of temperature evolution within a selected day, underlining the inactivity of airflow rate, while inside temperature is constant.

The working procedure of the system relies on a Canadian Well method, as presented in Chapter II within the testing facility HVAC system. Outside air is dragged into U-shape pipelines, while exchanging temperature with ground temperature, and injecting into the “air to air heat recovery unit”. From this point, the cold air is introduced inside building and ventilated constantly to maintain a stable thermal behavior.

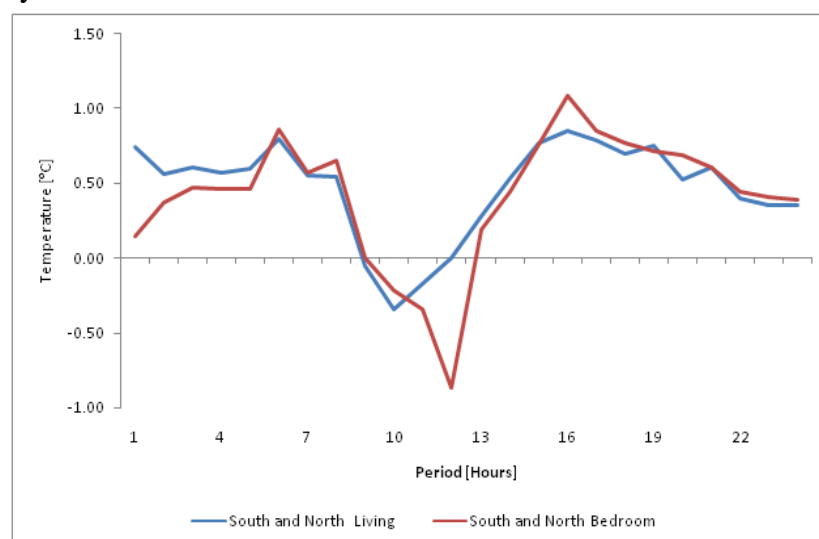


Fig. 5-12 Temperatures variation between N and South [109]

A comparison between the rooms positioning was made. As Fig. 5-12 shows, the orientation of the house impacts the energy consumption directly, having a variation between North and South.

By using Canadian Well and heat recovery technique, heating and cooling request lowered up to 90 % in comparison with regular buildings, and lowered by 75 % compared to new buildings [140][85].

To conclude with, by developing and testing the fuzzy logic technique, inside temperature of the testing laboratory has been kept under good thermal level, with maximum energy savings. The system has been implemented in LabView software and tested on the laboratory to manage production of energy in an effective way.

## 5.2. Conclusion

As shown above, thermal condition improvement is considerably achieved through fuzzy logic control and policy management. Experimental results are exemplified in this chapter, along with other experimental results. Even if human behavior presents a reliable solution for reducing energy consumption, a greater result is obtained while running intelligent control systems.

If-then-else scripts are developed within policy management system which can adjust the HVAC system to save energy. Inputs are passing through a “fuzzifier” filter, applied to certain rules and then outputted into a “defuzzifier” filter. Crisp outputs are being displayed to a web platform created for monitoring interior parameters.

As the fuzzy control is based on following precise commands, real data are being transmitted to the platform for constant evaluation of energy usage. An example of how system reacts to temperature fluctuation is being presented in Table 5-1, where a dependency matrix tells the system when to trigger on or off. Given these points, several sets of fuzzy inputs have been uploaded to a computer, to exemplify the dependency matrix and the observation of output results.

As long as control outputs are stable and don't vary often, good thermal condition is acquired with minimum energy consumption. The occupants can anytime examine the HVAC status and changes brought to the system. A reliable comfort degree was successfully met by implementing policy editor that controls buildings ventilation flow rate. These set of rules are working on day-night routine, calculating average inside temperature, in order for the system to start working or not.

As has been noted, temperature and ventilation control are improving air quality rate and reducing energy consumption for UPB testing laboratory. The system implemented in UPB building permits measurements and acquisition of real-time data, later used in estimating energy consumption, and controlling buildings temperature.

## *CHAPTER VI – Conclusions and perspectives*

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Chapter VI concludes thesis goal to optimize residential buildings energy efficiency by using artificial intelligence techniques. Energy consumption depends on three different things: buildings energy efficiency, systems energy efficiency and how the energy is being exploited (human behavior and control algorithms which corresponds to nowadays needs.

This contribution includes development and implementation on a real house of a fuzzy controller.

Furthermore, this chapter emphasize the thesis perspectives about an introduction in human behavior and a detailed weather algorithm implementation.

## 6.1. Introduction

Artificial intelligence approaches have been proven to optimize the energy efficiency of residential building to accomplish thesis goals, especially for the testing laboratory from UPB. The knowledge about different degree levels, times scale, inputs collection or output computing time have been presented as a solution to reduce energy consumption in residential buildings.

As mentioned above, the experimental house from UPB was the building where testing have been made. The proposed algorithm demonstrates the utility of a HVAC systems, especially with efficient insulation and air tightness. Energy savings are efficient when walls are well insulated and triple glazed windows are oriented south. The efficiency of HVAC system can be increased by using the Canadian well, to take advantage of constant ground temperature.

To sustain this technology, a substantial monitoring system was put into operation to enhance systems efficiency, as well as to collect information about indicated parameters. Furthermore, the monitoring system is prepared with software and hardware resources, giving the opportunity to organize the system with energy consumption policies. Thus, optimized conditions for measuring and collecting data are available within the monitoring system, proving that energy consumption depends on three distinct level:

- Buildings energy efficiency
- Systems energy efficiency
- Energy usage (human behavior and control algorithms)

## 6.2. Thesis goal

The main thesis objective was to reduce energy consumption using artificial intelligence and control algorithms, with the aim of responding nowadays human necessities.

For this, measurement and data system acquisition have been utilized. Smart meters and a SMX platform were responsible for data-collection. Such operations are charging evidence on a locally web-platform, having real time information about requested parameters.

An HMI was used to interact with the SMX platform and to understand the buildings behavior. Moreover, an IoT ecosystem was built to collect data through internet, having parameters and weather details as inputs in order to estimate energy consumption.

The data acquisition structure is able to admit different numerical approaches and methods for estimating energy usage and consumption, such as:

- Classical PID,
- Modern State-space,
- Intelligent (fuzzy controller).

A classical proportional, integrator and differential controller adjusts the error through multiplication of deviation between the set-point and the measurement, with a constant. Moreover, the integrator corrects the control signal, by integrating the error while differential operation rectifies the low frequency flaws collected by integrator.

On the next part, a modern state-space optimization models differential equation of any dynamic systems at any given time, as a function of its current state. Also, the system is changing due to acceleration and position. Additionally, calculus of how energy changes through analysis of relationship between its states and derivatives of arbitrary dynamic system can be done.

An intelligent fuzzy control system has been developed and implemented in order to achieve thermal comfort inside residential buildings. Fuzzy logic algorithms are formed of specific rules representing an approach to human behavior, especially while interacting with testing laboratory.

### 6.3. Thesis contribution

To achieve good thermal condition, user desired thermal comfort, fuzzy logic control and policy management plays a crucial role. Such role presents a reliable solution in reducing energy consumption, especially when running intelligent control systems. Algorithm controls are made of if-then-else rules, capable of adjusting HVAC system to reduce power usage. Inputs are passing through specific filters, outputting data on a web platform, temperature, and a constant evaluation of energy usage.

Taking into consideration the above facts, several sets of fuzzy inputs have been uploaded into the system to exemplify the dependency matrix and the observation of output results in a MATLAB software. Minimum energy consumption is acquired using fuzzy control while obtaining good and constant inside thermal condition. A customized level of comfort can be obtained due to policy editor implementation, that controls the buildings ventilation flow rate. Thus, controlling temperature and ventilation an improvement of comfort and energy savings within UPBs testing laboratory can be acquired.

Heat and mass transfer are used to model thermal behavior of building, while degree-day method estimate energy consumption based on historical data. For creating the weather algorithm, heating and cooling degree calculation are determined. The following weather inputs were taken into consideration: internal and external air temperature. Briefly, the system behaves consequently to outside temperature.

Mathematical models are used to describe any running system to obtain specific output. Every mathematical model composition is made of three elements: input variables, system function, and output variables. On a basic process, output variables are obtained in different ways in conformity with forward or data-driven approach, as well as state-space models.

To validate the system, couple of estimation approaches that use several parameters were brought to predict energy consumption and to lower buildings energy usage. A grey-box modeling estimates parameter by establishing a bond between inputs and outputs. A rigorous analysis was made using R software, based on weather influence over the inputs. Solar radiation utilization, proven to be helpful into the mathematical model, leading to less energy consumption. The system exemplification is made using data readout, while a mathematical model clarifies the correlation between output and residuals. As mentioned above, R software

was used to plot the results in a bandwidth image explaining the incertitude of residuals and their belonging to allowed bandwidth.

Result interpretation of both physical and electrical data leads to an improvement on the energy usage and consumption rate, while different voltage evolution underlines constant results in the bad of UN with +/- 10%, as exemplified In Chapter V [90]. Moreover, the energy losses from the building are compensated by the energy produced by the PV system, helping in the reduction of overall energy consumption. The results shown through the IoT system can be used to create policies/routines to save or to lower the energy building, reducing energy consumption.

In closing, by developing these approaches, UPB testing laboratory was kept under optimal thermal comfort, using minimum energy consumption and the aim of the thesis is considered to be achieved.

## 6.4. Thesis outlook

The algorithms proposed to predict the energy consumption for residential buildings are adequate and constitute the first step in designing and controlling the heating and cooling of the system. A perspective future work can extend the algorithm by taking into consideration the human behavior aspect.

It is appropriate to understand both human and building behavior to understand the energy usage and to find configurations to reduce its utilization. An algorithm can be created to simulate a pattern for every inhabitant, as well as every device which may lead to energy loss. Although, human behavior is not considered to be the main factor, more than 20% can be saved by understating the daily routine of each individual.

Another future activity should be focused on improving the weather algorithm by adding multiple input parameters in correlation with the desired output. A rigorous study on the effectiveness of weather parameters will be useful in order to take advantage of every aspect of buildings behavior. Therefore, improved algorithm can lead to better results on reducing energy consumption for residential buildings.





## Legend of electrical equipment:



















	Simple switch with tipper contact, buried mounting, including the dose of apparatus
	Double switch with tipper contact, buried mounting, including the dose of apparatus
	End switch, buried assembly, including device dose
	Simple button with rollback, buried mounting, including the dose of the device
	Twilight sensor that has the possibility to adjust the trigger threshold according to the light intensity IP54
	Simple socket with protective contact, buried mounting, including the dose of apparatus
	Double socket with protective contact, buried mounting, including the dose of apparatus
	Triphasic socket with no work and protective contact, buried mounting, including the dose of apparatus
	Connection point for outdoor lighting
	Electrical panel, apparent/buried installation
	L2 - tubular fluorescent luminaire, apparently mounted, fully equipped, airtight, one-phase, TYPE FIPAD, IP65
	L17 - light body with economical bulb, apparently mounted, fully equipped, airtight, with a phase, type apply on the wall
	L20 - fluorescent tubular luminaire, apparently mounted, fully equipped, airtight, with a phase, type apply to the wall, IP44
	L22 - luminaire with economic bulb, apparently mounted, ceiling type, airtight, one-phase, with a 20W lamp, IP20
	L22 - luminaire with economic bulb, apparently mounted, ceiling type, airtight, one-phase, with 2 lamps of 20W, IP44
	L27 - luminaire with economic bulbs, equipped bagpipe, ceiling type, airtight, one-phase, 2 lamps of 20W, IP20
	L29 - luminaire with economic bulbs, equipped bagpipe, ceiling type, airtight, one-phase, with 3 lamps of 20W, IP20
	L42 - tubular fluorescent luminaire, fully equipped, apparently mounted, fully equipped, airtight, one-phase, with a 18W lamp plus simple socket with protective
	Separation part mounted in a special wire provided with door opening with special keys, mounted at h=0.3m from the ground

Fig. 7-2 Ground floor elements

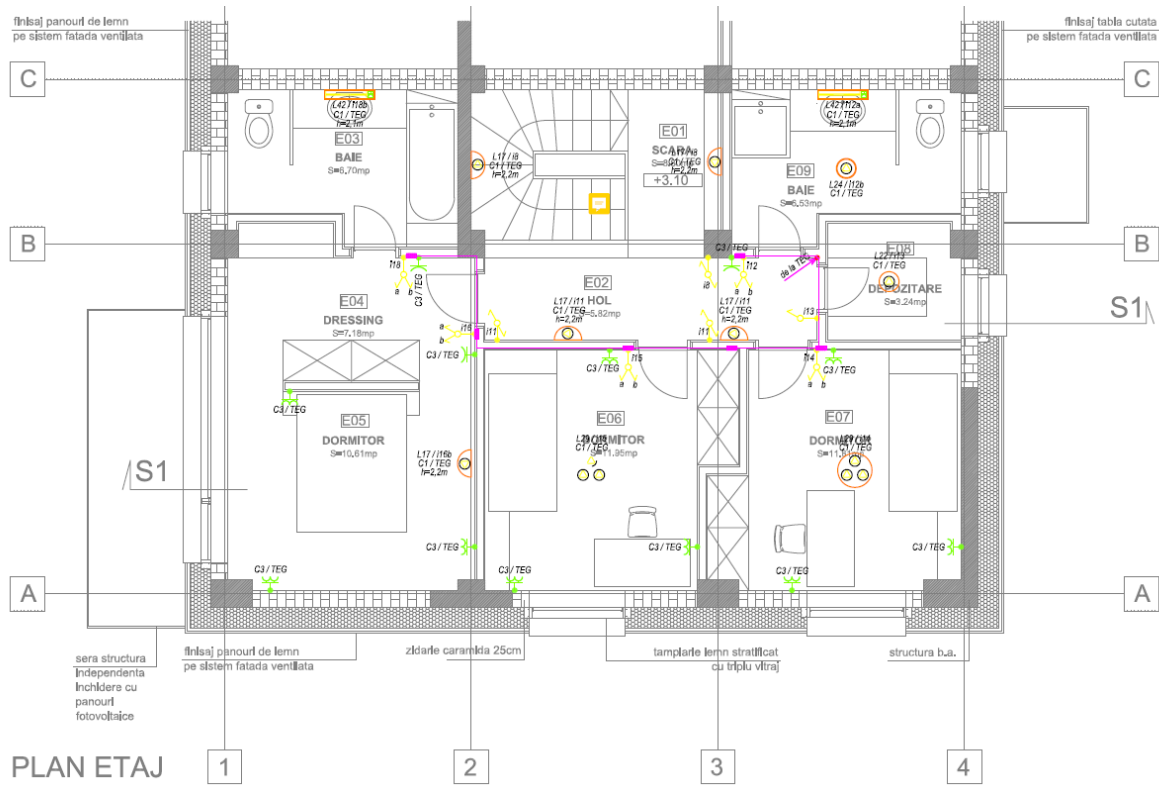


Fig. 7-3 1st floor of the testing facility

PHPP2007\_UPB\_PHL\_East house\_feb2011 - Compatibility Mode

File Home Insert Page Layout Formulas Data Review View Help

Clipboard Font Alignment Number Styles

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### BRIEF INSTRUCTIONS

Place your mouse here to see the PHPP help. If no help appears when the mouse passes over cell B5, you can activate it by going into the Worksheet Menu Bar/Tools/Options/View, and under "Comments", select "Comment Indicator Only".

#### Passive House Verification: Meaning of Field Formats

Example	Field Format	Meaning
78,8	Courier, blue, bold on yellow background	Input Field: Please enter the required value here
6619	Arial, black, standard on white background	Calculation field, please do not change
78,8	Courier New, purple, bold on white background	Field with references to another sheet - should not be changed.
125,0	Arial, black, large & bold on green background	Important result

#### Passive House Planning: Worksheet Directory

Worksheet Name	Function	Brief Description	Required for the certification?
Verification	Building Data: Summary of Results	Building description, selection of the calculation method, summary of results	yes
Areas	Areas Summary	Building Element Areas, Thermal Bridges, Treated Floor Area. Use exterior dimension references!	yes
U-List	U-Value Summary	List of calculation results from the U-Values worksheet, Building Element Database	yes
U-Values	Calculation of Standard Building Element U-Values	Heat transmission coefficient calculations in accordance with DIN EN ISO 6946.	yes
Ground	Calculation of Reduction Factors Against Ground	More precise calculation of heat losses through the ground	if applicable
Windows	U <sub>w</sub> -Value Determination	Input of geometry, orientation, frame lengths, frame widths, U <sub>f</sub> and U <sub>w</sub> -values of the frame, and the thermal bridge heat loss coefficients of the connections. From these inputs, determine U <sub>w</sub> and total radiation.	yes
WinType	Characteristic Values of Glazings and Frames	Lists of glazings and window frames with all necessary characteristics	yes
Shading	Determination of Shading Factors and Influence of Window Orientation	Input of shading parameters, e.g. balcony, neighbouring building, window reveal and calculating the shading factors	yes
Ventilation	Air Flow Rates, Exhaust/Supply Air Balancing, Pressurization Test Results	Sizing the ventilation system from extract and supply air requirements, infiltration air change rate and actual efficiency of heat recovery. Input of pressurization test results.	yes
Annual Heat Demand	Annual Heat Demand / Annual Method	Calculation of the annual space heat demand according to the energy balance method following EN 13790: Transmission + Ventilation - η (Solar Gains + Internal Gains)	yes
Monthly Method	Monthly Method Following EN 13790	Calculation procedure for the monthly method following EN 13790. Make appropriate selection in the Verification worksheet, if calculations should be performed following this procedure	if selected

Fig. 7-4 PHPP worksheet directory about the testing facility

## 7.2. In\_Situ\_Wall MATLAB code

```
# Plot the data first.
D1 <- read.csv("data1.csv", sep=";", header=TRUE, as.is=TRUE)
D2 <- read.csv("data2.csv", sep=";", header=TRUE, as.is=TRUE)

plot(D2$Text,D2$Tint,type="l",main="T_ext = f(T_int)",ylab="Interior
Temperature",xlab="Exterior Temperature",col="red")

plot(D1$Text,D1$HF,type="l",main="T_ext = f(HeatFlux)",xlab="Exterior
Temperature",ylab="Heat Flux",col="red")
plot(D1$Tint,D1$HF,type="l",main="T_int = f(HeatFlux)",xlab="Exterior
Temperature",ylab="Heat Flux",col="red")

#####
# cum ar fi  $Y_t = \alpha * X_t + \epsilon_t$ 
#  $\epsilon = N(0, \sigma^2)$ 
alfa<-2.4
# st deviance = square root of variance
sigma<-0.5
N<-1500
L<-20.4
A<-2.4
D1$Text
lamda<-DATA_serie1$HF/L*(DATA_serie1$Text-DATA_serie1$Tint)
R<-L/(lamda*A)
x<-cos(seq(D1$Text,D1$Tint,len=1))
#simulate the model !!!!!!!
y<-alfa*x+rnorm(N,0,sigma)
#rnorm(n,mean=0,sd=1)
#n = nr of observations , mean= vector of means , sd = vector of standard deviation
#plot the model
par(mfrow=c(1,2))
plot(x,type="l",col="red")
plot(y,type="l",col="green")
## plot s vs y
plot(x,y,type = "p",col="blue")

##estimation of parameters with matrix calculations !
# setam X - matrix
X<-matrix(D1$Text,ncol=1)
Y<-matrix(D1$Tint,ncol=1)
```

```

# solve() - folosit pentru X / Y ) sau (X^-1)*Y !
#t(x) = transpusa de X
# % * % - ptr inmultirea matricilor !!
theta=solve(t(X)%**X,t(X)%**Y)
theta

## another solution is to use lm() - easier
D<-data.frame(x=x,y=y)
fit<-lm(y~0+x,data=D)
#write results
summary(fit)
#-----
#Kalman filter
#-----
# X(n)=A * X(n-1) + B * u (t) + w(n-1)
# y(n) = C * x (n) + D * u(n)
#-----
f<-0;
A=matrix(c(1,-1),ncol=1)
B=t(matrix(c(DATA_serie1$Text[1],DATA_serie1$Tint[1]),ncol=2))
C<-
D<-0;
ek<- Rk * qk
e<- -A %**% fi + b
q<- G*e
G<-1/R
C<-solve(t(A)*q+f)fi)

```

### 7.3. Policy exemplification code

```

<?xml version="1.0" ?>
<policy name="Simple heating">
  <rule name="ON"
runEveryMs="60000" >
    <on><![CDATA[true]]></on>
    <if><![CDATA[[[T
livingroom.value]].double < 20]]></if>
    <then><![CDATA[[[HVAC
Electric
Heater.Electric_Heater=1]];]]></then>
    <else><![CDATA[]]></else>
  </rule>
  <rule name="OFF"
runEveryMs="60000" >
    <on><![CDATA[true]]></on>
    <if><![CDATA[[[T
livingroom.value]].double>22]]></if>
    <then><![CDATA[[[HVAC
Electric
Heater.Electric_Heater=0]];]]></then>
    <else><![CDATA[]]></else>
  </rule>
</policy>

<?xml version="1.0" ?>
<policy name="Heating Policy 2014-2015">
  <rule name="Stop condition"
runEveryMs="20000" >
    <on><![CDATA[true]]></on>
    <if><![CDATA[[[Livingroom.
Temperature]].double >= 45.0 &&
[[Livingroom.Temperature]].double <= 46.0) ||
([[CurrentHour]].int>=17 && [[CurrentHour]].int<=23) ||
([[CurrentHour]].int>=0 && [[CurrentHour]].int<=8)]]></if>
    <then><![CDATA[[[DeactivateSchedule("HVAC
RELAY")]];
[[HVAC Electric Heater.Electric_Heater=0]];]]></then>
    <else><![CDATA[]]></else>
  </rule>
  <rule name="If cold" runEveryMs="20000" >
    <on><![CDATA[true]]></on>
    <if><![CDATA[[[Livingroom.Temperature]]
.double <= 40.0 && ([[CurrentHour]].int>=8 &&
[[CurrentHour]].int<17)]]></if>
    <then><![CDATA[[[ActivateSchedule("HVAC
RELAY")]];]]></then>
    <else><![CDATA[]]></else>
  </rule>
</policy>

<?xml version="1.0" ?>
<policy name="Air Heating time 2015">
  <rule name="Heating ON"
runEveryMs="10000" >
    <on><![CDATA[true]]></on>
    <if><![CDATA[(((
([[CurrentMinute]].int >= 1) &&
([[CurrentMinute]].int < 15) ) && ([[HVAC Electric
Heater.Electric_Heater]].int == 0) )) ||
((( [[CurrentMinute]].int >= 30) &&
([[CurrentMinute]].int < 45)) && ([[HVAC Electric
Heater.Electric_Heater]].int == 0)]]></if>
    <then><![CDATA[[[HVAC Electric
Heater.Electric_Heater=1]];]]></then>

```

```

        <else><![CDATA[]]></else>
    </rule>
    <rule name="Heating OFF"
runEveryMs="10000" >
        <on><![CDATA[true]]></on>
        <if><![CDATA[(((
[[CurrentMinute]].int >= 0) &&
([[CurrentMinute]].int < 5)) && ([[HVAC Electric
Heater.Electric_Heater]].int == 1 )) ||
        ((( [[CurrentMinute]].int >= 15) &&
([[CurrentMinute]].int < 30)) && ([[HVAC Electric
Heater.Electric_Heater]].int == 1)) || (((
[[CurrentMinute]].int >= 45) &&
([[CurrentMinute]].int < 59)) && ([[HVAC Electric
Heater.Electric_Heater]].int == 1)) )]]></if>
        <then><![CDATA[[[HVAC Electric
Heater.Electric_Heater=0];]]></then>
        <else><![CDATA[]]></else>
    </rule>
</policy>

```

## 7.4. Content of Modules from Chapter III

### 7.4.1.Modules.txt

```
#
#Number of modules (can be greater than the actual number of modules)
#
iNoOfModules=10                               Maximum number of modules
#Module 1 MQTT client 1
M1-Name=MQTTClient1                            Name of the module, given by the
user
M1-ClassName=modules.MQTTClient               Module type, from exiting
(implemented) classes
M1-AttributesFile=MQTTClient1.txt             The specific file with attributes for
this module
#Module 2 MongoDB client 1
M2-Name=MongoDBClient1                        Name of the module, given by
the user
M2-ClassName=modules.MongoDBClient           Module type, from exiting
(implemented) classes
M2-AttributesFile=MongoDBClient1.txt         The specific file with attributes
for this module
#Module 3 Meter Virtual 1
M3-Name=MeterVirtual1
M3-ClassName=modules.MeterVirtual
M3-AttributesFile=MeterVirtual1.txt
```

### 7.4.2.MeterVirtual - modules

```
#                               Sign for comments
pDataSet = DataSet1             This shows on which Dataset will be stored the
variables
sPrefix = SMX/LD01/             This shows which is the collection (LD01) and
the database (SMX)
#                               Sign for comments
lPeriod = 1000 ms               Period for refreshing the data values, which is 1
second (1000 ms.)
#
U1 = 235.21                     Initial value of voltage U1
U2 = 235.21                     Initial value of voltage U2
U3 = 235.21                     Initial value of voltage U3
#
I1 = 5.34                       Initial value of current I1
I2 = 5.34                       Initial value of current I2
I3 = 5.34                       Initial value of current I3
```

#		
PF1 = 0.97		Initial value of power factor PF1
PF2 = 0.97		Initial value of power factor PF2
PF3 = 0.97		Initial value of power factor PF3
#		
PF = 0.97		Initial value of average power factor
f = 49.97		Initial value of frequency Hz
#		
Ap = 12345.678		Initial value of active energy plus index Ap (or
A+)		
Am = 23456.678		Initial value of active energy minus index Am (or
A-)		
Rp = 34567.678		Initial value of reactive energy plus index Rp (or
R+)		
Rm = 45678.678		Initial value of reactive energy minus index Rm
(or R-)		
#		
RndPrc = 0.1		randomization level (value 0.1 = 10% of initial
value)		
#		
#	No of digits after decimal point	
#		
DecU = 2		Number of decimals after point, giving the
resolution for voltage U		
DecI = 2		Number of decimals after point, giving the
resolution for current I		
DecPF = 2		Number of decimals after point, giving the
resolution for power factor		
Decf = 2		Number of decimals after point, giving the
resolution for frequency f		
DecPQ = 2		Number of decimals after point, giving the
resolution for P and Q		
DecAR = 3		Number of decimals after point, giving the
resolution for indexes A&R		
#		

### 7.4.3.Meter IEC6205621 - Module

#		
pDataSet = DataSet1		This shows on which Dataset will be stored the variables of the
meter		
sPrefix = SMX/LD02/		This shows which is the collection (LD02) and the database (SMX)
#		



```

lPeriod = 10000          Period for refreshing the data values, which is 10 second (10000
ms.)
#
#   Serial Port
#
sPortName = /dev/ttyUSB0 The port for communication with the meter, in this case through USB
iPortSpeed = 300         The speed for communication with the meter, in this case 300 baud
sPortParam = 7E1         The parameters for communication, in this case 7bits, even, 1 parity
#
iReadTimeout = 20000     The timeout period for a message, in milliseconds, in this case 20 sec.
iInterCharTimeout = 100 The timeout period inter characters, in milliseconds, in this case 0.1 s.
iCheckEcho = 1           If there is echo when transmitting (need cancelation on receive).
#
sAddress =               If an address is needed. In this case, no address is considered
#
sDateSep = .            Expected separators inside the "Date-stamp". This may vary on
meters
    sTimeSep = :        Expected separators inside the Time stamp. This
may vary on meters

```

#### 7.4.4. Mongo database client - module

```

#
pDataSet = DataSet1      The Dataset used for communication with MongoDB
sReadPrefix = SMX/       The prefix of data to be read in MongoDB
sWritePrefix = SMX/      The prefix of data to be written in MongoDB
sIntPrefix = SMX/        The internal prefix in SMXCore real-time data
#
sURI = mongodb://localhost The MongoDB path
sDatabase = SMX          The database name in MongoDB
sCollection = LD01       The database collection name in MongoDB
#
lPeriod = 10000          The period between 2 automatic queries of data from/to MongoDB
#
pReadAssociation=ReadAssoc1.txt Read Association file between Dataset and
MongoDB
pWriteAssociation=WriteAssoc1.txt Write Association file between Dataset and
MongoDB
#
sIDName = _id
sFind = /                Expected separators need to be found for being replaced
sRepl = .                Separators found before will be replaced with this one
#

```

The association files are presented below:

## “REadAssoc1.txt”:

```
# Format
# MongoDB path = Internal attribute
#
# Real-Time Values
#
# Clock
LD01/0-0-1-0-0-255/-2 = LD01/Rec2-Date
# Voltage
LD01/1-1-32-7-0-255/-2 = LD01/Rec2-U1
LD01/1-1-52-7-0-255/-2 = LD01/Rec2-U2
LD01/1-1-72-7-0-255/-2 = LD01/Rec2-U3
# Current
LD01/1-1-31-7-0-255/-2 = LD01/Rec2-I1
LD01/1-1-51-7-0-255/-2 = LD01/Rec2-I2
LD01/1-1-71-7-0-255/-2 = LD01/Rec2-I3
# Power Factor
LD01/1-1-33-7-0-255/-2 = LD01/Rec2-PF1
LD01/1-1-53-7-0-255/-2 = LD01/Rec2-PF2
LD01/1-1-73-7-0-255/-2 = LD01/Rec2-PF3
#
LD01/1-1-13-7-0-255/-2 = LD01/Rec2-PF
# Frequency
LD01/1-1-14-7-0-255/-2 = LD01/Rec2-f
# Active Power
LD01/1-1-36-7-0-255/-2 = LD01/Rec2-P1
LD01/1-1-56-7-0-255/-2 = LD01/Rec2-P2
LD01/1-1-76-7-0-255/-2 = LD01/Rec2-P3
#
LD01/1-1-16-7-0-255/-2 = LD01/Rec2-P
# Reactive Power
LD01/1-1-151-7-0-255/-2 = LD01/Rec2-Q1
LD01/1-1-171-7-0-255/-2 = LD01/Rec2-Q2
LD01/1-1-191-7-0-255/-2 = LD01/Rec2-Q3
#
LD01/1-1-151-7-0-255/-2 = LD01/Rec2-Q
# Active Energy
LD01/1-1-1-8-0-255/-2 = LD01/Rec2-Ap
LD01/1-1-2-8-0-255/-2 = LD01/Rec2-Am
# Reactive Energy
LD01/1-1-3-8-0-255/-2 = LD01/Rec2-Rp
LD01/1-1-4-8-0-255/-2 = LD01/Rec2-Rm
```

## 7.4.5.MQTTClient - Modules

```
#
pDataSet = DataSet1           The Dataset used for communication with MQTT
sPubPrefix = G3M40000001/SMX/ The prefix of data to be published with MQTT
sSubPrefix = G3M40000001/SMX/ The prefix of data to subscribe with MQTT
sIntPrefix = SMX/             The prefix of internal data within the DataSet
#
sBroker = tcp://localhost:1883 The address of the Mosquitto MQTT broker
sUserName =                   The username for connecting to MQTT broker
sUserPass =                   The password of the user for connecting to MQTT broker
sClientID = ID                The ID for connecting to MQTT broker, not implemented yet
#
lPeriod = 10000               The period for publishing through the MQTT
broker
#
pPubAssociation = PubAssoc1.txt The publish association
pSubAssociation = SubAssoc1.txt The subscribe association
#
iPubQos = 1                   The publish Quality of service
iSubQos = 1                   The subscribe Quality of service
#
```

In the pre-deployed version, the “*PubAssoc1.txt*” file has the following content:

```
# Format
# Internal attribute = MQTT topic
#
# Real-Time Values
#
# Clock
#
LD01/Date = LD01/0-0-1-0-0-255/-2
# Voltage
LD01/U1 = LD01/1-1-32-7-0-255/-2
LD01/U2 = LD01/1-1-52-7-0-255/-2
LD01/U3 = LD01/1-1-72-7-0-255/-2
# Current
LD01/I1 = LD01/1-1-31-7-0-255/-2
LD01/I2 = LD01/1-1-51-7-0-255/-2
LD01/I3 = LD01/1-1-71-7-0-255/-2
# Power Factor
LD01/PF1 = LD01/1-1-33-7-0-255/-2
LD01/PF2 = LD01/1-1-53-7-0-255/-2
LD01/PF3 = LD01/1-1-73-7-0-255/-2
```

```

#
LD01/PF = LD01/1-1-13-7-0-255/-2
#   Frequency
LD01/f = LD01/1-1-14-7-0-255/-2
#   Active Power
LD01/P1 = LD01/1-1-36-7-0-255/-2
LD01/P2 = LD01/1-1-56-7-0-255/-2
LD01/P3 = LD01/1-1-76-7-0-255/-2
#
LD01/P = LD01/1-1-16-7-0-255/-2
#   Reactive Power
LD01/Q1 = LD01/1-1-151-7-0-255/-2
LD01/Q2 = LD01/1-1-171-7-0-255/-2
LD01/Q3 = LD01/1-1-191-7-0-255/-2
#
LD01/Q = LD01/1-1-151-7-0-255/-2
#   Active Energy
LD01/Ap = LD01/1-1-1-8-0-255/-2
LD01/Am = LD01/1-1-2-8-0-255/-2
#   Reactive Energy
LD01/Rp = LD01/1-1-3-8-0-255/-2
LD01/Rm = LD01/1-1-4-8-0-255/-2

```

#### 7.4.6.File Storage - Module

```

#
pDataSet = DataSet1
sPrefix = SMX/
#
lPeriod = 10000
#
:

```

##### StoreAssoc1.txt:

```

#   Format
# Internal attribute = Storage header
#   Clock
LD01/Date = LD01/0-0-1-0-0-255/-2
#   Voltage
LD01/U1 = LD01/1-1-32-7-0-255/-2
LD01/U2 = LD01/1-1-52-7-0-255/-2
LD01/U3 = LD01/1-1-72-7-0-255/-2
#   Current
LD01/I1 = LD01/1-1-31-7-0-255/-2

```

```

LD01/I2 = LD01/1-1-51-7-0-255/-2
LD01/I3 = LD01/1-1-71-7-0-255/-2
#   Power Factor
LD01/PF1 = LD01/1-1-33-7-0-255/-2
LD01/PF2 = LD01/1-1-53-7-0-255/-2
LD01/PF3 = LD01/1-1-73-7-0-255/-2
#
LD01/PF = LD01/1-1-13-7-0-255/-2
#   Frequency
LD01/f = LD01/1-1-14-7-0-255/-2
#   Active Power
LD01/P1 = LD01/1-1-36-7-0-255/-2
LD01/P2 = LD01/1-1-56-7-0-255/-2
LD01/P3 = LD01/1-1-76-7-0-255/-2
#
LD01/P = LD01/1-1-16-7-0-255/-2
#   Reactive Power
LD01/Q1 = LD01/1-1-151-7-0-255/-2
LD01/Q2 = LD01/1-1-171-7-0-255/-2
LD01/Q3 = LD01/1-1-191-7-0-255/-2
#
LD01/Q = LD01/1-1-151-7-0-255/-2
#   Active Energy
LD01/Ap = LD01/1-1-1-8-0-255/-2
LD01/Am = LD01/1-1-2-8-0-255/-2
#   Reactive Energy
LD01/Rp = LD01/1-1-3-8-0-255/-2
LD01/Rm = LD01/1-1-4-8-0-255/-2
sFileName = ./Log/Log1
sFileExt = .txt
#
pStoreAssociation = StoreAssoc1.txt
#
sSeparator = \t
#
iCompress = 1
iMove = 1
#

```

### 7.4.7.Metere DLMS Client - module

```

#
pDataSet = DataSet1           The Dataset used for communication with a DLMS meter
sPrefix = SMX/LD03/          This shows which is the collection \(LD03\) and the database \(SMX\)
#

```

```

lPeriod = 1000          Period for refreshing the data values, which is 1 second (1000 ms.)
#
#   Gurux parameters
#
sCmdLineArgs = /m=lgz /sp=COM13 /b=9600 /s=DLMS /a=Low
/pw=00000000
sLogFile = Gurux-data/Log1          Path for the Gurux log file
sPath = Gurux-data/Manufacturer    Path for the Gurux description files for each
manufacturer
iBlockRead = 1          The meter is read in blocks of OBIS codes (more than one at a time, if =1)
#
sObj1File = Gurux-data/Objects10.xml  File with OBIS codes read from meter in
1st message
sObj2File = Gurux-data/Objects20.xml  File with OBIS codes read from meter in
2nd message
sObj3File = Gurux-data/Objects30.xml  File with OBIS codes read from meter in
3rd message
#
#

```

Content of “SMXCore.bat” can be found by typing the following command (for windows user, open CMD and type the command:

```

cd ./App1
java -jar ../SMXcore.jar Modules.txt
pause

```

## 7.5. Weather data algorithm and implementation

```
% clear all
clc %clear console
% Load weaher data
M = csvread('ROU_Bucharest.074810_IWEC.csv');
from = 25*24; %start time
period = [1:31*24]'; %simulation period
Time = 3600*period.
% Day = M(from+period,3); Hour = M(from+period,4);
Temp = M(from+period,7); %Dry bulb temperarure [°C]
PhiDirN = M(from+period,15); %Direct horizontal solar radiation [Wh/m2]
PhiDiff = M(from+period,16); %Diffuse solar radiation [Wh/m2]
RadNDir = M(from+period,15); %Direct normal solar radiation [Wh/m2]
RadHDif = M(from+period,16); %Diffuse horizontal solar radiation [Wh/m2]
WDir = M(from+period,21); %Wind direcrion: N=00; E=90°; S=180°; W=270°
WSpeed = M(from+period,22); %wind speed [m/s]
month = M(from+period,2); %
day = M(from+period,3); %
hour = M(from+period,4); %
minute = M(from+period,5); %
B = 90; Z = 0; L = 45; albedo = 0.2;
[PhiDir, PhiDif, PhiRef] = fSolRadTiltSurf(month, day, hour, minute, ...
    RadNDir, RadHDif, B, Z, L, albedo);
plot(Time/(24*3600), PhiDir,'b'), hold on %direct on surface
plot(Time/(24*3600), RadNDir,'g') % direct on normal to sun
plot(Time/(24*3600), PhiDif,'r') % diffusif on surface
plot(Time/(24*3600), RadHDif,'k') % diffusif on horizontal surface
plot(Time/(24*3600), PhiRef,'m') % reflected on surface
legend('\Phi_d_i_r', '\Phi_N_d_i_r', '\Phi_D_i_f', '\Phi_N_D_i_f')
clear M
```

Implementation of the algorithm:

```
% 5 walls: concrete (4 layers) + insulation (2 layers)
% glass (1 node)
% ventilation
% Inputs: outdoor temperature, solar radiation, HVAC heat flow rate
% Feedback(FB) / control : 1) HVAC 2) envelope: ventilation + solar
clc, clear all
pkg load control
Kp = 1000;
% Data
% *****
Sc = 5*3*3; Si = Sc; Sg = 3*3; %surface [m2]: concrete, insulation, glass
```

```

Va = 3*3*3; %air volume[m3]
rhoa = 1.2; ca = 1000; %indoor air density; heat capacity
Vpa = 2*Va/3600; %infiltration and ventilation air: volume/hour
% c: concrete; i: insulation; g:glass
lamc = 2;lami = 0.04; lamg = 1.2; %[W/m K]
rhoccc = 2.5e6; rhoici = 2e6; rhogcg = 2e6; %[J/K m3]
wc = 0.2; wi = 0.08; wg = 0.01; %[m]
epswLW = 0.9; %long wave wall emmisivity
epswSW = 0.8; %short wave wall emmisivity
epsgLW = 0.9; %long wave glass emmisivity
taugSW = 0.8; %short wave glass transmittance
alphagSW = 0.2; %short wave glass absortivity
% convection coefficients
hi = 4; ho = 10; %[W/m2 K]
% MODEL
% *****
nth = 8; nq = 12; % # of temperature node, # of flow nodes
Tm = 20 + 273; %mean temp for radiative exchange
sigma = 5.67e-8; %[W/m2 K4]
Fwg = 1/6; %view factor wall - glass
% G conductance matrix
G = zeros(nq,nq);
G(1,1)=ho*Sc; G(2,2)=lamc/(wc/2)*Sc; G(3,3) = G(2,2);
G(4,4)=lami/(wi/2)*Si; G(5,5) = G(4,4); G(6,6) = hi*Sc;
G7a = epswLW/(1-epswLW)*Si*4*sigma*Tm^3;
G7b = Fwg*Si*4*sigma*Tm^3;
G7c = epsgLW/(1-epsgLW)*Sg*sigma*Tm^3;
G(7,7) = 1/(1/G7a + 1/G7b + 1/G7c);
G(8,8) = 1/(1/(ho*Sg) + wg/(2*lamg*Sg)); G(9,9)=lamg/(wg/2)*Sg;
G(10,10) = hi*Sg;
G(11,11)=Vpa*rhoa*ca;
G(12,12) = Kp; %amplification of controller
% C capacity matrix
C = zeros(nth);
C(5,5) = Sc*wc*rhoccc;
C(6,6) = Si*wi*rhoici;
C(7,7) = Sg*wg*rhogcg;
C(8,8)=Va*rhoa*ca;
% A adjancy matrix
A = zeros(nq,nth);
A(1,1)=1;
A(2,1)=-1; A(2,5)=1;
A(3,2)=1; A(3,5)=-1;
A(4,2)=-1; A(4,6)=1;
A(5,3)=1; A(5,6)=-1;
A(6,3)=-1; A(6,8)=1;
A(7,3)=-1; A(7,4)=1;
A(8,7)=1;
A(9,4)=1; A(9,7)=-1;
A(10,4)=-1; A(10,8)=1;
A(11,8)=1;

```



```

A(12,8)=1;
%State-space representation
%State-space model
nnodes = size(C,1); %n° total nodes
nC = rank(C); %n° nodes with capacity
n0 = nnodes - nC; %n° of nodes with zero capacity
K = -A'*G*A;
K11 = K(1:n0,1:n0);
K12 = K(1:n0,n0+1:end);
K21 = K(n0+1:end,1:n0);
K22 = K(n0+1:end,n0+1:end);
Kb = A'*G;
Kb1 = Kb(1:n0,:);
Kb2 = Kb(n0+1:end,:);
CC = C(n0+1:end,n0+1:end);
As = inv(CC)*(-K21*inv(K11)*K12 + K22);
Bs = inv(CC)*[-K21*inv(K11)*Kb1+Kb2 -K21*inv(K11) eye(nnodes-n0,nnodes-n0)];
%Select relevant inputs and outputs
Bs = Bs(:, [[1 8 11 12] nq+[1 3 7 8]]); %inputs: [To To To Phiw Phii Phig Qh]
Cs = zeros(1,nC);Cs(nC)=1; %output

% SIMULATION
% *****
% Read data
BUCHAREST_ReadWeatherFilesSolRad; %read weather files
n = size(Time,1);
th = zeros(nth,n);
Qh = zeros(n,1);
TintSP = 20*ones(n,1);
% Inputs
u = [Temp Temp Temp TintSP ...
     epswSW*Sc*PhiDif taugSW*epswSW*Sg*PhiTot alphagSW*Sg*PhiTot ...
     Qh];
% Integrate using lsim (linear systems)
x0 = zeros(nth,n);
sys = ss(As,Bs,Cs);
[y, t, x] = lsim(sys, u, Time);
subplot(2,1,1)
plot(Time/3600,y,'g', Time/3600, Temp,'b'),
xlabel('Time [h]'), ylabel('T [C]')
Qh = Kp*(TintSP - y); Qh(1)=0;
subplot(212), plot(Time/3600,Qh,'r')
% Integrate at each time step 0:dt:dt
% needs to itterate
dt = 3600/1; % simulation step 1h/dt = 3600s / dt
th = zeros(size(As,2),n);
for k = 1:n-1
    x0 = th(:,k);
    x = lsode (@(x, t) ssm(x, t, As, Bs, u(k,:))', x0, 0:dt:dt);
    th(:,k+1) = x(2,:);
    Qhvac(k+1) = Kp*(TintSP(k+1) - th(4,k+1));

```

end

```
subplot(211), hold on, plot(Time/3600, th(4,:), 'r'), hold off  
subplot(212), hold on, plot(Time/3600, Qhvac), hold off  
xlabel('Time [h]'), ylabel('Q_h_v_a_c [W]')
```

Euler and Von Neumann stability method for heating equation are implemented as:  
[CG2]

```
68 for k = 1:n-1  
69     th(:,k+1) = (eye(nth) + dt*A)*th(:,k) + dt*B*u(:,k);  
70     thi(:,k+1) = inv((eye(nth) - dt*A))*(thi(:,k) + dt*B*u(:,k));  
71 end
```

While the integration is using library functions such as:

```
114 x0 = zeros(nth,n);  
115 sys = ss(A,B,C);  
116 [y, t, x] = lsim(sys, u', Time);
```

Moving forward to the stability condition:

The condition of stability is  $\min(\lambda_i \Delta t) < -1.9789$ .

```
88 lambda = eig(A);  
89 min(min(lambda))*dt; %needs to be in [-2 0]
```

This condition is respected if the number of steps per hour is  $dh > 1.98$ ; if  $dh < 1.98$ , the system is numerically unstable. Compare with the results for the explicit method.

Change the value of  $dh = 2$

```
61 dh = 1.969; %if dh = 1.98, stable if dh = 1.97, instable
```

to  $dh = 1.98$ ,  $dh = 1.97$ ,  $dh = 1.96$  and  $dh = 1.95$

For  $dh = 1.969$ , compare the results given by forward Euler method with those given by

lsi. Outputting

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## FOLIO ADMINISTRATIF

### THESE DE L'UNIVERSITE DE LYON OPEREE AU SEIN DE L'INSA LYON

NOM : NEGREA

DATE de SOUTENANCE :

(Avec précision du nom de jeune fille, le cas échéant)

Prénoms: LIVIU ANDREI

TITRE: Optimization of energy efficiency for residential buildings by using artificial intelligence

NATURE : Doctorat  
2020LYSEI090

Numéro d'ordre :

Ecole doctorale : MEGA - Mécanique, Energétique, Génie civil et Acoustique

Spécialité : Thermique et Energétique

RESUME :

La consommation d'énergie est devenue l'un des principaux problèmes d'urbanisation et de crise énergétique, car l'épuisement des combustibles fossiles et le réchauffement climatique mettent en péril l'utilisation de l'énergie des plantes. Dans cette thèse, une méthode d'économie d'énergie a été adoptée afin de réduire la consommation d'énergie dans le secteur résidentiel et les maisons passives.

Un modèle mathématique basé sur des mesures expérimentales a été développé pour simuler le comportement d'un laboratoire d'essai de l'UPB. Le protocole a été réalisé à la suite d'actions telles que : la construction de bases de données sur les paramètres, la collecte de données météorologiques, l'apport de flux auxiliaires tout en considérant le comportement humain.

L'algorithme de contrôle-commande du système est capable de maintenir une température constante à l'intérieur du bâtiment avec une consommation minimale d'énergie. Les mesures et l'acquisition de données ont été configurées à deux niveaux différents : les données météorologiques et les données sur les bâtiments. La collection de données est faite sur un serveur qui a été mis en œuvre dans l'installation de test en cours d'exécution d'un algorithme complexe qui peut fournir les prédictions sur la consommation d'énergie pendant 30 jours à l'avance.

La thèse rapporte plusieurs méthodes numériques pour estimer la consommation d'énergie qui est encore utilisée avec l'algorithme de contrôle. L'estimation des paramètres R-C avec la prévision du flux de chaleur a été faite en utilisant la méthode nodal, basée sur des éléments physiques, des données d'entrée et des informations météorologiques. La prévision de la consommation d'énergie à l'aide de la modélisation de l'espace d'État montre des résultats améliorés tandis que la collecte de données IoT a été téléchargée sur une carte à base de système de tarte aux framboises.

Tous ces résultats ont été stables montrant des progrès impressionnants dans la prévision de la consommation d'énergie.

MOTS-CLÉS : prévision énergétique, consommation d'énergie, IoT, algorithme de contrôle, comportement humain

Laboratoire (s) de recherche : Centre d'Energétique et de Thermique de Lyon (CETHIL)

Directeur de thèse : Prof. Dr. Ing BADEA Adrian et Prof. Dr. Ing GHIAUS Christian

Président de jury :

Composition du jury :