Università degli studi di Padova

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Relazione Finale

Evaluation of new Key Performance Indicators for continuous commissioning on commercial centres

Relatore
Prof. Arturo Lorenzoni

Correlatori
Ing. Wilmer Pasut
Ing. Daniele Antonucci

Laureando
Giacomo Fornaro

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Abstract

Buildings are the main energy consumption sector in Europe, accounting for about 40% of the final energy consumption. In particular, wholesale and retail buildings, which account for a 28% of the total non-residential buildings, are characterized by a high energy demand and high CO_2 emissions, and often, by a strong energy inefficiency. Considering the strong socio-cultural impact that these buildings have on the modern society, the Commons*Energy* project aims to transform shopping malls into concrete examples of energy-efficient architectures and systems through a systemic approach made of innovative technologies and easy-to-replicate solutions' sets, as well as methods and tools to support their implementation and assess their environmental impact. The work outlined in this thesis aims to be a support to the creation of a continuous commissioning platform for an overall supervision of the shopping malls, by testing and developing meaningful key performance indicators for the main energy-consuming systems of this typology of buildings.

Contents

Chapter 1

CommON*Energy* Project

1.1 Motivations that brought the project to life

The CommONEnergy project arises from the will to create a reality in which shopping centers will become actual examples of a smart and energy-efficient architecture. In the current time period shopping centers can be defined as symbols of the unbridled consumerism of a society that has always a bigger environmental impact. Proof of this is the high-energy consumption, high CO_2 emissions and energetic inefficiencies typical of these so imposing and diverse buildings.

It is also possible to affirm that this type of buildings represents almost the 30% of the non-residential use ones. In fact, these stores are more and more present in the urban fabric and it is for this reason that it would be desirable to start a conversion from consumption to saving, at least in energetic terms.

Starting from these considerations CommONEnergy has as its objective to find and develop solid strategies and solutions in order to transform these consumerism's giants into energy efficiency models.

1.2 Project Realization

The project involves 23 partners from the industry, research and retail sectors from across Europe (Figure 1.1)[1], with 3 demo cases and 8 reference buildings, all possible thanks to EU financing of it. The EU supports the

[1] http://commonenergyproject.eu/partners.html

project because it is in line with the European climate objectives - such as reducing carbon emissions and energy use, and increasing the share of renewable energy in buildings - as well as because these actions encourage customers to take the good practices home, and the developed solutions can be replicated in buildings (i.e. airports and train stations) creating a new class of workers with technical skills.

Figure 1.1: CommONEnergy Partners

1.3 Case Studies and Technologies

1.3.1 Valladolid, Spain

The Mercado del Val is the first bioclimatic marketplace in Spain. In fact from 2013, Mercado del Val is fully renovated as part of the CommONEnergy project. The planned intervention aimed to recover a late nineteenth century building representative of an architecture and commercial activity from that period, being respectful with its essence, but transforming it into an innovative building that meets the potentialities and commercial needs of the XXI century.

This retrofitted historic building uses several different technologies such as an efficient lighting and system control – optimized glass systems to exploit natural light and automatic blinds to regulate it – natural ventilation strategies – automatic roof skylights coupled with façade openings ensure air quality and comfort as well as saving energy – the iBEMS, and also heat recovery – geothermal heat pumps provide heating in addition to hot and cold water, while the heat rejected by the fridges is recovered to integrate heating and domestic hot water.

1.3.2 Modena, Italy

Located in a residential area close to Modena's center, Canaletto was chosen as part of a requalification strategy, both from a social and functional point of view. In fact In the past couple of years, the neighbourhood experienced a social degradation, which encouraged the city of Modena to define a project requalifying this area.

It boasts multi-functional coating – using thermo-reflective paint reducing thermal loads during warm months – coupling HVAC and refrigeration - thermal insulation and double-glazing window frames to protect from summer irradiation and winter heat loss; in winter, the heat recovered from the food refrigeration system is used to warm partly the building – RES integration, as well as day lighting and artificial lighting solutions – using solar tubes – and the energy management and monitoring system – the iBEMS, enabling an optimal control of all technology systems.

1.3.3 Trondheim, Norway

City Syd is one of the largest shopping centers in central Norway, situated on the outskirts of Trondheim. City Syd joined the project CommONEnergy to test innovative technologies and solutions, implemented between 2013 and 2016 to be effective in 2017.

It is provided of natural ventilation strategies, heat recovery and day lighting and artificial lighting solutions, all monitored by a modern intelligent energy management and monitoring system.

Chapter 2

Key Performance Indicators

2.1 What is a KPI?

A Key Performance Indicator is a measurable value that allows you to evaluate the performance of any activity or process. They are therefore strategic indicators that measure the success of a project by identifying a goal that is quantifiable and measurable. This approach, originally created in the business environment, is easily applicable in the field of energy efficiency of commercial buildings. In this case the goal to be achieved is the reduction in consumption, without compromising the very purpose of consumption, that is the comfort of occupants.

The purpose of these indicators can be different: in addition to providing information on achieving comfort conditions, the indicator may be useful in order to compare the performance with expectations, whether they are based on historical values or based on a design model, or a comparison with other buildings that have similar characteristics and the same type of use. An example is shown in the Figure 2.1 that demonstrates the comparisons for the simplest energy KPI, that is the Energy Use Intensity (EUI), which is the total energy used by the building in a given year divided by the gross square meters (square footage, in this case) of the building [1] .

[1] New Buildings Institute,"Key performance indicators for commercial buildings", 2012

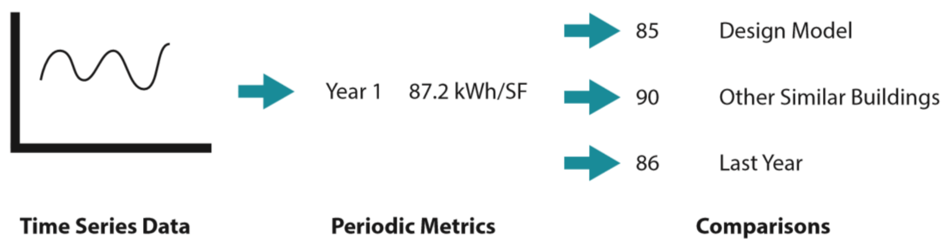


Figure 2.1: Possible uses of a KPI

2.2 Preliminary Requirements

If we want to use this approach to track the performance of a building, we must first identify the parameters that are important to take into account in order to quantify the energy performance of the various systems.

Therefore, it is necessary to set up a continuous monitoring system of the main energy consumptions and the various technical or comfort parameters previously identified during the definition of the KPIs. Once installed and linked to a dedicated server in order to store the values acquired, these data are still unusable strings of values that do not give any useful information.

Thus, a prost-processing procedure is required. The data sent in real time by the sensor system will need to be transformed into useful and easily understandable information - not only for the designer, but also for the operator and occupant of the building - as simple metrics and graphs that characterize the performance of the building, that is, the actual KPIs.

In the near future, there will probably be widespread IoT systems and commonly known and utilized indices, but for the time being we are still in a transition phase. Once the most significant indexes will be identified, and there will be many similar structures to be analyzed with the same parameters, defined in the same way, it will be possible to fully utilize the benchmarking potential of the KPIs.

Given this need to identify standardized procedures for analyzing building performance, specific KPIs for shopping malls have been developed during the project, detailing each one of the energy systems. The work has thus identified the various KPIs that take into account the main energy consumption, together with indoor environmental quality and economic aspects. In this paper, four of these indicators will be tested analyzed in detail:

1. Normalized energy for heating and cooling
2. Normalized consumption of mechanical ventilation
3. Energy efficiency index for refrigeration cabinets
4. Normalized electricity consumption for lights

The first two KPIs will be tested on the Valladolid case study, that provided the data about the consumption of the air conditioning system and the mechanical ventilation system, together with internal temperature and humidty - useful indexes for the evaluation of the thermal comfort - and the concentration of CO_2 - commonly used as an overall proxy for contamination and lack of adequate ventilation.

The 3rd and 4th KPIs will be tested on the Modena case study, that for its part provided technical data about the installed refrigeration system and its consumption, and about the illuminance inside the building and the overall electricity consumption for lighting.

Chapter 3

Normalized Energy for Heating and Cooling

3.1 Definition

In order to know wether a building has an efficient air conditioning system, there are several variables to consider. the easiest procedure is to consider similar buildings for caracteristics and typology of use, and compare the energy consumption per square meter of surface. But if the buildings are in different cimatic zones, it woud be necessary also to consider the buildings' external temperature in order to normalize its consumption.

Another possible use of a KPI is the comparison with historical data of consumption of the same building in order to compare its energy performance after a retrofit operation. However, if the weather of the current year is cooler or hotter than the usual, the energy required to keep the internal comfort would be higher, and so it would seem that the optimization hasn't produced any energy saving. For this reason, in order to fully characterize the savings' effectiveness we have to consider also historical data of external temperature.

Moreover, we have to remember that the aim of a heating and cooling system is to obtain a thermal comfort condition for the occupants of the building. If this condition is not achieved, the energy can be considered wasted and the KPI must be penalized. It would be necessary then to define an index able to quantify the sensation of comfort and add it to the variables that affect the consumption.

For these reasons the KPI has been defined as:[1]

$$Q_t^{\text{norm}} = \begin{cases} \frac{Q_t * f_t^{\text{Occ}}}{A * f_t^{\text{HDD}} * I_t^{\text{TC(av)}}} & \text{if heating} \\ \frac{Q_t}{A * f_t^{\text{CDD}} * f_t^{\text{Occ}} * I_t^{\text{TC(av)}}} & \text{if cooling} \end{cases} \quad \left[\frac{kWh}{m^2}\right]$$

Where:

Q_t^{norm}: is the normalized energy for heating and cooling at time t $[kWh/m^2]$;
$f_t^{\text{H}\backslash\text{CDD}}$: is the Heating or Cooling Degree Day factor at time t $[-]$;
f_t^{Occ}: is the Occupancy factor at time t $[-]$;
A: Area of heated/cooled space;
$I_t^{\text{TC(av)}}$: is the average value of the thermal comfort indexes in case of mechanical ventilation. It is calculated as:

$$I_t^{\text{TC(av)}} = \frac{\Sigma_{t=1}^{n} I_t^{\text{TC}}}{n}$$

Where:

$$I_t^{\text{TC}} = \begin{cases} 0.01 & \text{if the whole building is discomfortable at time t} \\ \frac{\Sigma_{i=1}^{\text{N}_t} p_{i,t}^{\text{discomfort}}}{\text{N}_t} & \text{otherwise} \end{cases}$$

N_t: is the number of points where comfort is evaluated;

$$p_{i,t} = \begin{cases} 1 & \text{if the point is within the comfort bounds at time t} \\ 0 & \text{otherwise} \end{cases}$$

The maximum time step t for the data collection is 1 hour. If we have $t < 1\text{h}$ we can define the hourly based KPI as follows, then it is possible to find the daily or monthly value of the indicator by summing the hourly values:

$Q_h^{\text{norm}} = \frac{\Sigma_{t=1}^{\frac{60}{\text{time step}}} Q_t^{\text{norm}}}{\frac{60}{\text{time step}}}$: during the hour h $[kWh/m^2]$;

$Q^{\text{norm}} = \Sigma_{h=1}^{H} Q_h^{\text{norm}}$: during H hours $[kWh/m^2]$.

So the input of the KPI are:

[1] CommON*Energy*,"KPIs and Post Processing Procedure"

- Energy consumption for heating and cooling (including hot water);
- Values of external temperature in the present and in the last 5 years;
- Number of people calculated according to real value (occupancy sensor) or estimated values (number of receipts);
- Area of heated/cooled space;
- Internal temperature and humidity.

3.2 Heating and Cooling Degree Days Factor

As we mentioned above, to quantify the energy savings after an intervention the heating and cooling data need to be corrected in order to be able to compare data from different periods in time of the same site as well as data from other sites.

To do so the heating or cooling degree days (HDD\CDD) are the considered variables, defined as the measure of how much (in degrees) and for how long (in days), the outside air temperature was lower (for HDD) or higher (for CDD) than a specific "base temperature".

There is not a standard base temperature, so it has been decided to use the values reported by the standard[2] for the 3rd category department store buildings, which means $15\,°C$ for the HDD and $26\,°C$ for the CDD.

There is not even a standard way to calculate them. The Eurostat version of the HDD value is[3] :

$$\text{HDD} = \begin{cases} 0 & \text{if } T \geq 15\,°C \\ \Sigma_{i=1}^{d}(18 - T_m) & \text{if } T < \,°C \end{cases}$$

Where:

$T_m = (T_{min} - T_{max})/2$: is the outdoor daily average temperature;
d: is the number of days in which the temperature is lower than $15\,°C$.

[2] EN 15251:2007
[3] https://www.eea.europa.eu/data-and-maps/indicators/heating-degree-days-1

This version of the indicator has a jump discontinuity when daily mean temperature falls below the base temperature. In addition, outside air temperature doesn't remain constant all day long, so it would be possible to obtain a positive value of HDD and CDD in the same day. Mathematically speaking, an infinite number of temperature readings is needed to calculate degree days properly.[4] For this reason, since our data of the external temperature are hourly mean values (as we will see later), we can define the indicators as:

$$\text{HDD} = \begin{cases} 0 & \text{if } T \geq 15\,°C \\ \Sigma_{i=1}^{d}\Sigma_{h=1}^{24}(15 - T_h)/24 & \text{if } T < 15\,°C \end{cases}$$

$$\text{CDD} = \begin{cases} 0 & \text{if } T \leq 26\,°C \\ \Sigma_{i=1}^{d}\Sigma_{h=1}^{24}(T_h - 26)/24 & \text{if } T > 26\,°C \end{cases}$$

Where T_h is the outdoor hourly average temperature in Celsius.

In order to make energy consumption of two different years comparable, the corresponding numbers need to be standardized in terms of the long-term average weather/climate conditions, so historical data of external temperature for at least the last 5 years are required.

The formula for both periods (heating and cooling) is presented below[5]:

$$f^{\text{H}\backslash\text{CDD}} = \begin{cases} \frac{\text{H}\backslash\text{CDD}_{\text{specific}}}{\text{H}\backslash\text{CDD}_{\text{standard}}} & \text{if } \text{H}\backslash\text{CDD}_{\text{standard}} \neq 0 \\ 0.01 & \text{if } \text{H}\backslash\text{CDD}_{\text{standard}} = 0 \end{cases}$$

Where:

$\text{H}\backslash\text{CDD}_{\text{standard}}$: are the long time mean value of month or year;

$\text{H}\backslash\text{CDD}_{\text{specific}}$: are the H\CDD for a specific month or year.

The long time mean value would need 5 years of data, but the publicly-accessible `www.degreedays.net` tool let you generate only up to 3 years of data for free, so it will be used this amount.

According to this definition, when the HDD's historical value of a certain month is zero, the factor will have to be equal to 0.1. Keeping in mind that

[4] https://www.degreedays.net/introduction

[5] Antonucci, 2017

the index is in the denominator, this means that if usually we don't need the heating in a certain month, and for exceptional climatic conditions we would be forced to do it, the energy consumed will be multiplied by a factor of 100. But if we want to compare two different years, the operation would be as follows:

- if the specific HDD of the month is =0, that means that I'm not supposed to be heating so the factor would be 0,01 (that means that the consumption is multiplied by 100).
- if the historical monthly mean is equal to 0, that means that usually it is not necessary to heat in that period, but if the HDD of the day is not zero aswell, you are supposed to consume some energy that wasn't planned. This means that we don't have to consider that energy as normal: for the retrofit that energy is an anomaly so the factor will be 100, decreasing the consumption to one hundredth.

Obviously the same will be for the CDD. So the index will be:

$$f^{\mathrm{H\backslash CDD}} = \begin{cases} \frac{\mathrm{H\backslash CDD_{specific}}}{\mathrm{H\backslash CDD_{standard}}} & \text{if } \mathrm{H\backslash CDD_{standard}} \neq 0 \\ 100 & \text{if } \mathrm{H\backslash CDD_{standard}} = 0 \\ 0.01 & \text{if } \mathrm{H\backslash CDD_{specific}} = 0 \end{cases}$$

This definition also follows the natural trend of the function, that means, if the specific value decreases, the factor will tend to decrease aswell, while if the historical value decreases, the factor will tend to grow.

3.3 Thermal Comfort Index

Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment. Since there are large variations, both physiologically and psychologically from person to person, it is difficult to satisfy everyone in the same space. The environmental conditions required for comfort are not the same for everyone. Extensive laboratory and field data have been collected to provide the necessary statistical data to define conditions that a specified percentage of occupants will find thermally comfortable.

According to the standard[6] there are six primary factors that must be addressed when defining conditions for thermal comfort. A number of other secondary factors affect comfort in some circumstances. The six primary factors are:

- Metabolic rate
- Clothing insulation
- Air temperature
- Radiant temperature
- Air speed
- Humidity

In a monitoring system the common monitored parameters are the air temperature and the humidity ratios, whereas the other parameters useful to design a comfort zone are set according to the intended use of the building and season.

The idea is to have an index to rate thermal comfort that can be integrated with the Heating and Cooling KPI. Its value ranges from 0.01 to 1.00. The value 0.01 represents the condition in which the monitored zone is in a discomfort state for the entire period of analysis (worst-case scenario). On the other hand, the value 1.00 is the situation in which the conditions in the monitored zone are within comfort boundaries for the entire analyzed period (best-case scenario).

3.3.1 Graphic comfort zone method

The proposed KPI is calculated generating a comfort zone based on the graphic method presented in the ASHRAE 55-2010 standard, according to the intended use of the building (influencing the metabolic activity) and the season. The Figure 3.1 is an example of calculation of the index with data collected in an office building[7]. The comfort area is calculated assuming seasonal clothing and metabolic activities according to the standard.

[6] ASHRAE 55-2010
[7] Antonucci, 2017

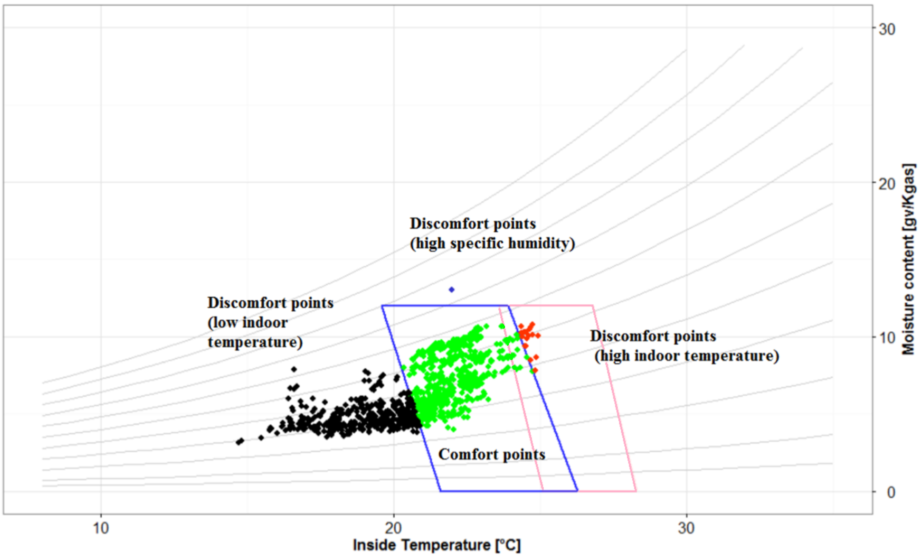


Figure 3.1: Discomfort and comfort points according to the ASHRAE 55-2010. The blue area represents the winter comfort area while the red one represents the summer comfort area.

The calculation of Thermal Comfort Index is made considering the number of points that are inside and the number of points that are outside of the comfort boundaries as follows:

$$I_t^{\mathrm{TC}} = \begin{cases} 0.01 & \text{if all the evaluated points are outside the comfort zone at time } t \\ \frac{\Sigma_{i=1}^{N_t} p_{i,t}^{\mathrm{discomfort}}}{N_t} & \text{otherwise} \end{cases}$$

Where:

N_t: is the number of points where comfort is evaluated;

$$p_{i,t} = \begin{cases} 1 & \text{if the point } i \text{ is within the boundaries at time } t \\ 0 & \text{otherwise} \end{cases}$$

According to the number of the sensors installed in the monitored area the comfort index could be the average value of all data from each sensor installed in the monitored area or the single value from each sensor, if the aim is to visualize the comfort in each monitored point within the area.

However it is permissible to apply this method to spaces where the occupants have activity levels that result in metabolic rates between 1.0 and

1.3 [met] (values for a near sedentary physical activity) and where clothing that is worn provides between 0.5 and 1.0 [clo] of thermal insulation (typical values of clothing worn when the outdoor environment is warm and cool, respectively). But in a supermarket or a shopping mall the metabolic rate is near 1.6, typical value for a person standing or walking[8], so the boundaries must be changed.

3.3.2 PPD - PMV method

The range of operative temperatures of the graphic method are for 80% occupant acceptability. This is based on a 10% dissatisfaction criterion for general (whole body) thermal comfort based on the PMV-PPD index, plus an additional 10% dissatisfaction that may occur on average from local (partial body) thermal discomfort.

The Predicted Mean Vote (PMV) is an index that predicts the mean value of the votes of a large group of people on the 7-point thermal sensation scale (see Table 3.1), based on the heat balance of the human body. Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment.

Vote	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Table 3.1: Seven-point thermal sensation scale

PMV may be calculated for different combinations of metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity and air humidity[9]. In this way, for each hour of data we can find a different value of calculated PMV, function of this 6 parameters.

[8] EN 15251:2007

[9] For the formulas see the EN ISO 7730

The Predicted Mean Vote (PMV) predicts the mean value of the thermal votes of a large group of people exposed to the same environment. But individual votes are scattered around this mean value and it is useful to be able to predict the number of people likely to feel uncomfortably warm or cool.

Once we have the PMV value determined, the PPD is simply defined as a function of it, shown in Figure 3.2.

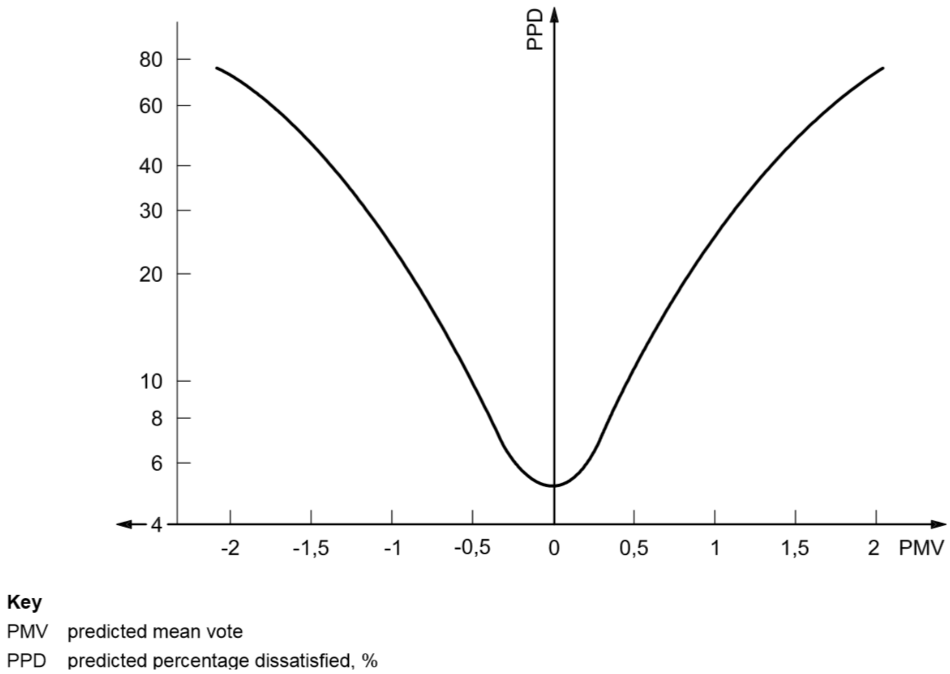


Figure 3.2: PPD as function of PMV.

The PMV-PPD method is the basis for the Graphical Method, but it can be used with values of metabolic rates between 1.0 and 2.0, perfect for our needs. For this reason it has been decided to implement the PMV-PPD index. In the UNI EN ISO 7730 it is possible to find a BASIC program, so we can simply rewrite it using the R language[10]. In this way we obtain a function of 6 variables, which can vary hour by hour, and that gives as result the percentage of dissatisfied people instead of a good-or-bad situation result. Thus, it could result an extra value compared to the graphical method, which

[10] See Listing A.3 for the R script

simply says whether we are inside or outside the comfort boundaries, but it doesn't say anything regarding how distant we are from them. Considering a treshold value of PPD equal to the 10%, this method is comparable to the graphical one, but having a quantitative parameter, although estimated, could give the possibility to make some more considerations.

3.4 Occupancy factor

The number of occupants in a shopping mall is highly variable during the day, and this can affect the internal gains and consequently the energy consumption of the building. According to the availability of monitoring data the occupancy factor could be estimated or measured.

If we don't have the ocupancy sensor, the number of receipts realized during the day can give a gross information about the number of people that daily enter the building.

If we do have an occupancy sensor, generally installed at the top of the entrance, it is possible to know the precise value of the number of people present at any time in the building. This solution has been adopted in the Modena demo case (but not in the Valladolid one, where we will conduct the heating and cooling KPI study, so we have to completely ignore this index).

Another way to obtain this info wold be using Google, as it has a pretty accurate estimate of the number of people present every moment inside every building, using the number of active mobile phones. This information is given only as a qualitative piece of data, that means that it is possible to know in which hour of the day there are more people, and if during the specific hour or day there are more or less people compared to the average amount.

Unfortunatelly Google doesn't give any more detailed information, not even when specifically required (at least by privates).

The occupancy factor is calculated as a ratio between the general occupancy profile of the building and the actual profile as follows [11]:

$$f^{\mathrm{Occ}} = \frac{\mathrm{Occ}_{\mathrm{specific}}}{\mathrm{Occ}_{\mathrm{standard}}}$$

Where:

$\mathrm{Occ}_{\mathrm{specific}}$: occupancy for a specific hour or 15 minutes

[11] Antonucci, 2017

$\text{Occ}_{\text{standard}}$: long time mean value of occupancy

3.5 Data downloading and pre-processing

The heating and cooling consumption's KPI will be tested to the Valladolid case study. In this shopping mall, completelly modernized in 2016, it has installed a heating and cooling system that uses geothermal pumps that also satisfy the needs of hot and cold water. It is also present a system that recovers heat coming from the refrigeration system, that helps to satisfy the heat needs.

As previously said, inside the *Mercado Del Val* there is neither any sensor that gives information on the building's occupancy nor we can get receipts or find other methods to estimate this information, so unfortunatelly the occupancy factor can not be tested.

So the data we need are the area of heated/cooled space (equal to $2280\,m^2$), needed when we want to compare the KPI with the one of other buildings, and the following time variables' quantities:

- electricity consumend by the geothermal pumps;
- values of external temperature in the present and in the last 5 years;
- internal temperature and humidity.

In the next pages will be explained in words the code present in Appendix A. All the following operations are to be considered an explicative exemple of the work of dowloading and pre-processing done in a similar way for all the 4 KPIs considered in this paper.

All the data we will need are inside a serve in which every parameter is carachterized by an id that identifies the file in which it is contained. Every file is generally composed by two columns: one gives the date and time in which the observation has been collected, the second one gives the value of the parameter.

The problem in managing all this small files is that a lot of them have different time steps one from the other, and some of them have double observations or missing pieces of data of one entire day or even a week.

For this reason it has been decided to write a sript in R language that, once we have decided the starting date and the end date of the analisys, could download and organize automatically all the interesting parameters. Thus, first of all a Main file will be created, containing only the time column hour per hour, from the starting day of the analisys untill the last one selected at the start of the program.

Once this is done, the program will download all the data required, organizing them in an hourly format in order to put them together in the Main file matching the time column of each parameter with the time column we just created, letting NA values where needed, that is if pieces of data are missing. In this way we will obtain a dataset complete of all the needed variables, organized according to the acquisition's time.

Heating and cooling energy: The geothermal heating and cooling system is composed of three pumps that work in cascade. Each of them, has a sensor for the heating mode and another one for the cooling one; so we have to download a total of 6 files.

The data given by the sensors are incremental values of energy expressed in MWh, with a time step lower than an hous. Thus, some operations are needed before they can be saved in the Main database:

- delete all the multiple observations inside the same hour;
- replace the incremental value with $\frac{\Delta_{\text{Energy}}}{\Delta_{\text{Time}}}$;
- change from MWh to kWh multiplying by 1000;
- sum the values of the three pumps for the two periods of heating and cooling;

In this way we obtain two separated columns with the hourly values of consumption expressed in kWh, one for the heating and one for the cooling, and we can now add them to the Main.

Specific Heating and Cooling Degree Days: We already said that in order to calculate the HDD and CDD, the external temperature is needed. The sensor gives a value every 15 mins, so the data we need is the mean value of all the observations contained in the same hour of the day. Having to find the HDD of the day (and the same way will be for the CDD), the operation on the data will be:

$$HDD = \begin{cases} (15 - T_{\text{ext}})/24 & \text{if } T_{\text{ext}} < 15\,°C \\ 0 & \text{otherwise} \end{cases}$$

We create a temporary file in which the time doesn't appear, but only the days. In this way it is possible to save the daily values of the HDD summing all the values that match the same day of acquisition in the time's column.

Now we only need to merge the daily file with the Main database to obtain a column containing the same value of daily HDD during the hours of each day of observation.

We saw that also the monthly mean value is needed. Since the website `www.degreedays.net` will provide the historical data as a monthly sum of the daily values, it appears easier for the following operations to have also these specific data in the same format.

However, we can't simply do the sum of all the values inside the same month. In fact, it can happen that some days of data are missing or that we are considering only a portion of a month (for example we have data only for the last 5 days of April), thus, it is necessary to calculate the mean value of the daily data and multiply it by the number of days of every different month. Obviously the less days of data we have, the more the result will be an approximation of the real value.

Standard Heating and Cooling Degree Days: The website `www.degreedays.net` as we said will give us a file with the monthly sum of HDD or CDD of last 3 years. Once the files are manually dowloaded it is possible to load them inside the program.

In this way we have three values for each month, so we just have to calculate the mean value of these three and add this info to the main. We obtain a column in which every hour of the same month shows the same values of standard HDD and CDD.

In Figure 3.3 and Figure 3.4 we can see the trend of HDD and CDD and the historical and specific daily mean value for each month considered

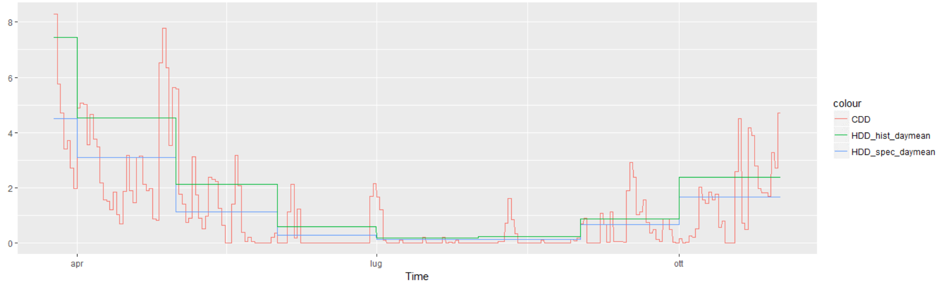


Figure 3.3: HDD and monthly mean values

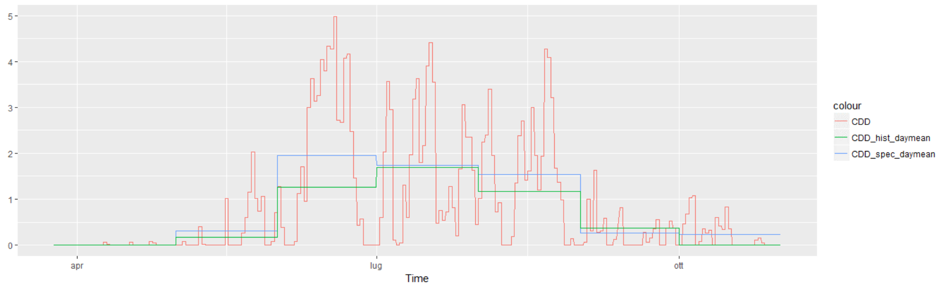


Figure 3.4: CDD and monthly mean values

Internal Temperature and Humidity: Inside the building there are 6 sensors that constantly detect internal temperature and humidity. Also these sensors present a time step lower than 1 hour, so in order to save the data inside the Main we need to take the mean value of all the observations inside the same hour.

We keep the 6 couples of values of the different sensors separated, because each of them can be used to calculate a different value of PMV and PPD.

3.6 Creation of the KPI

Now that we downloaded all the data needed for the creation of the KPI, we start creating all the factors that we decided to keep in account.

3.6.1 $f^{\text{H\textbackslash CDD}}$:

The factor has been defined as:

$$f^{\text{H}\backslash\text{CDD}} = \begin{cases} \frac{\text{H}\backslash\text{CDD}_{\text{specific}}}{\text{H}\backslash\text{CDD}_{\text{standard}}} & \text{if H}\backslash\text{CDD}_{\text{standard}} \neq 0 \\ 100 & \text{if H}\backslash\text{CDD}_{\text{standard}} = 0 \\ 0.01 & \text{if H}\backslash\text{CDD}_{\text{specific}} = 0 \end{cases}$$

The values 100 and 0.01 will result too sharp on the tend of the KPI, so it wes decided to use a maximum value of 10 and a minimum value of 0.1. Thus, we need simply to create the factor as a fraction of the two different quantities, then to fix equal to 10 every value greater than 10 and equal to 0.1 every value lower than that limit.

In Figure 3.5 we can see both the factors. We note that the HDD factor is always <1, that means that it had been a hotter year compared to the standard temperature. The CDD shows us that we had:

- standard July;
- cooler September
- hot June and August
- $CDD \neq 0$ also for April, May and October, to underline that was a hot year.

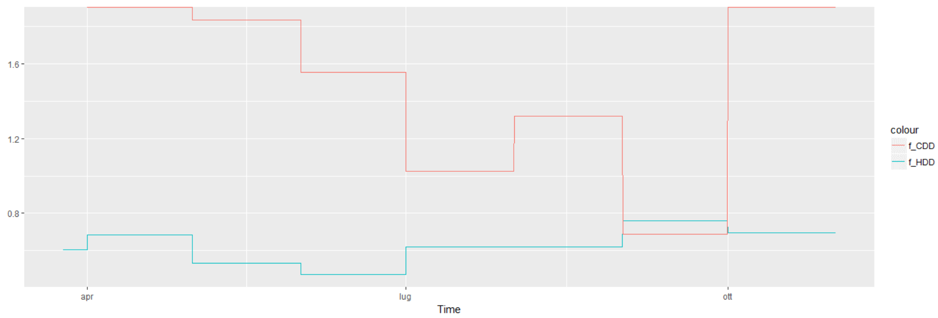


Figure 3.5: HDD and CDD factors

3.6.2 I^{TC}:

It was then decided to utilize the PMV and PPD method. We implemented the function that calculates the two values hour by hour, once the 6 variables are given:

- Air temperature;
- Relative Humidity;
- Metabolic rate;
- Air speed;
- Radiant temperature;
- Clothing insulation;

Among these variables we have only the internal temperature and humidity at the moment, so we have to find a way to calculate or assigning the other ones:

1. *Metabolic rate:* we already said that for the commercial buildings the standard recommend to use a value of $1.6\,met$ equal to about $93\,W/m^2$, so we simply assign this value.

2. *Air speed:* The air speed's value utilized inside the graphical method is $0.2\,m/s$, and since we don't have any better data we can use this constant value too.

3. *Radiant temperature:* also for the radiant temperature we don't have any data. We are forced to completely ignore the local disconfort and to fix the radiant temperature equal to the internal temperature. However we will consider a treshold of PPD$<$10% instead of 20% exactly for this reason, assuming a 10% of discomfort caused by the local discomfort.

4. *Clothing insulation:* In the graphical method the clothing insulation in divided in two slots: $1.0\,clo$ for the cold period and $0.5\,clo$ for the hot period, equal respectively to $0.155\,m^2K/W$ and $0.077\,m^2K/W$. This simplification creates two comfort zones strongly separated, each one that represents 6 months of the year without considering the real external weather conditions.

   An alternative method has been tried: since the amount of clothings' insulation depends on the external temperature, we decided to divide the values of external mean themperature in 4 slots and assign to each one a different value of clothing insulation according to the standard values [12]. In this way the level of clothing insulation is not related to the period of the year: if in June there is a particularly cold day (as we can see in Figure 3.6), the clo value will change consequently. Thus, we can define:

$$Clo = \begin{cases} 1.1 & \text{if } T_m \leq 17 \\ 0.9 & \text{if } 17 < T_m < 21 \\ 0.7 & \text{if } 21 < T_m < 25 \\ 0.5 & \text{if } T_m \geq 25 \end{cases}$$

   Where:

   T_m: external mean temperature between 8 a.m. and 9 p.m.

Now that we have all the 6 variables that we need, we can create the index. We call the function six times, one for each sensor of internal temperature and humidity. We obtain six columns for the PPD and six for the PMV. The index has been defined as:

$$I_t^{\text{TC}} = \begin{cases} 0.01 & \text{if all the evaluated points are outside of comfort zone at time } t \\ \frac{\Sigma_{i=1}^{N_t} p_{i,t}^{\text{discomfort}}}{N_t} & \text{otherwise} \end{cases}$$

[12] ASHRAE 55-2010

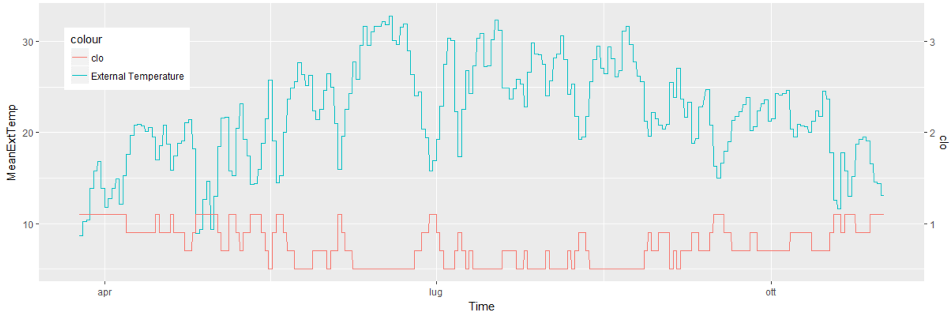


Figure 3.6: Clothing insulation, function of the mean external temperature between 8a.m. and 9p.m.

with p equal to 1 if we are inside the comfort boundaries, 0 otherwise. Also in this case, a value of 0.01 turned out to be too low, that means that multiplying the energy by 100 has a too big effect on the KPI, so we decided to change the lower limit to 0.1.

For the sake of simplicity we assign a value of 1 to the index for each hour of the considered period, then we subtract 1/6 every time one of the 6 zones shows a PPD value greater than 10% (the limit of intervention for buildings of the B category [13]). Lastly, we fix the index equal to 1/10 if all the 6 areas are outside the comfort conditions.

3.6.3 Q^{norm}:

Now we can create the KPI step by step, so we can understand what is the effect of each factor on the KPI.

We create a first index only with the consumptions of heatin and cooling divided by the area of the Valladolid market, that means $2280\,m^2$, named FC and FH in Figure 3.7:

$$f_{\mathrm{H\backslash C}} = Q/A$$

Then we divide both of them by I^{TC} and we obtain (indexes FC1 and FH1 in Figure 3.7):

$$f^{I}_{\mathrm{H\backslash C}} = \frac{Q}{A * I^{\mathrm{TC}}}$$

[13] EN ISO 7730

Now we complete the creation of our KPI adding the $f^{\mathrm{H\backslash CDD}}$ (index FC2 and FH2 in Figure 3.7):

$$Q^{\mathrm{norm}} = f^{II}_{\mathrm{H\backslash C}} = \frac{Q}{A * I^{\mathrm{TC}} * f^{\mathrm{H\backslash CDD}}}$$

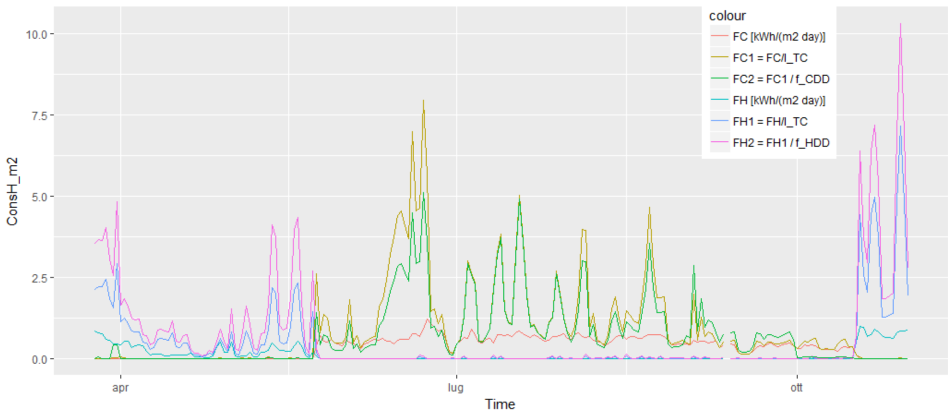


Figure 3.7: Normalized energy for heating and cooling

The Figure 3.7 shows the daily consumption as sum of the hourly values. We can see the daily consumption of both heating and cooling to be lower than $1\,kWh/(m^2day)$ and this info can be used to compare the building's air conditioning system with other ones. FC1 and FH1 show the contribution of the I^{TC} that gives us an idea of which days had the best and worst thermal comfort conditions. The final KPIs contain also the $f^{\mathrm{H\backslash CDD}}$, and as we already saw it gives the information of a hotter heating period by increasing the value of the heating's index, a hotter June and August by decreasing the cooling's index, and a standard July with the path of the two indexes perfectly overlapping.

The KPI defined in this way doesn't give any information about the reason of the discomfort, that means, we don't know if it's too hot or too cold inside the building. In Figure 3.8 we can see that the PMV is positive when i'm supposed to be heating, that is with values of external temperature between $10\,°C$ and $20\,°C$, than decreases when the heating is switched off and decreases even more around $26\,°C$ when the cooling system is switched on. After that we can see a linear correlation between external temperature and PMV between $26\,°C$ and $33\,°C$, suggesting a cooling consumption not correlated to the external temperature.

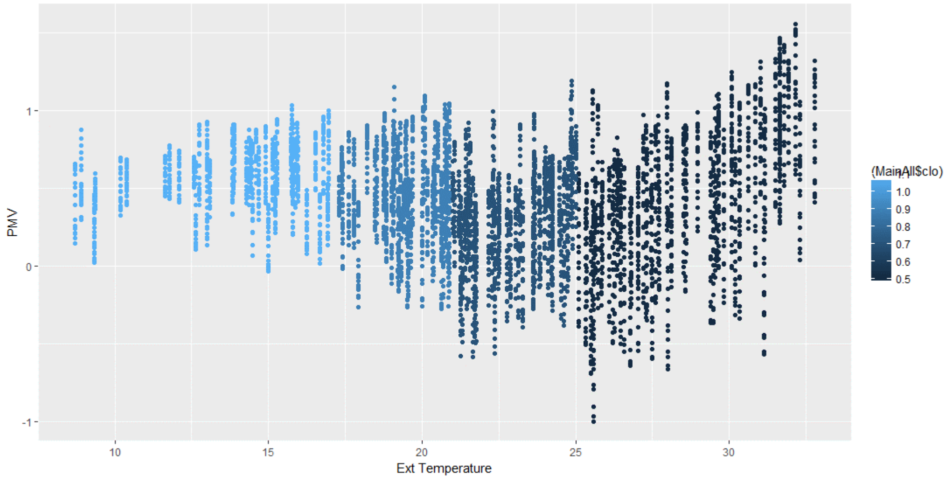


Figure 3.8: PMV evolution compared to the external temperature and different colors according to the clo value.

This KPI can't be used to compare consumption with the previous year, it only gives an idea of the comfort situation. Thus, the presence of the $f^{\mathrm{H\backslash CDD}}$ factor that normalizes the consumption with the standard value of external temperature is not needed.

3.6.4 Possible variations of the KPI:

For the sake of simplicity in this paragraph we will visualize the KPI only with the cooling data, but all the work has been applied also for the heating period.

The KPI as it was defined is and on-off parameter that gives the information of whether there is comfort or not. If we want to compare the consumption of two differend years we need a comfort index less aggressive on the overall value of the KPI.

It has been decided to utilize the mean PPD value as a progressive index of intervention on the parameter:

$$F_1 = \frac{Q}{m^2} * (1 + PPD), \qquad \text{if PPD>10\%}$$

So if we have a predicted percentage of dissatisfied equal to 15%, the consumption of that specific hour will be multiplied by 1.15, otherwise if the PPD is the 50% of the people, the value will be multiplied by 1.5. In this way we obtain an index weighted on the value of the PPD.

The second observation is that we would like to know if there is no comfort because we are not consuming enough or because we are consuming too much. For this reason, if it is too hot inside the building and we are cooling, the index will be increased; but if it is too hot and we are heating, the index will be lowered. This is not a penalization or a promotion of the energy consumed, it is a way to understand how much we should have consumed theorically, to compare the value with other years and understand if the system is going well, separately to the energy management.

What has been decided to do is to add also the sign of the PMV to the equation, to understand if it's too hot or too cold and separate the two periods:

$$F_1 = \begin{cases} \frac{Q}{m^2} * (1 - sgn(PMV) * PPD) & \text{if we are heating} \\ \frac{Q}{m^2} * (1 + sgn(PMV) * PPD) & \text{if we are cooling} \end{cases}$$

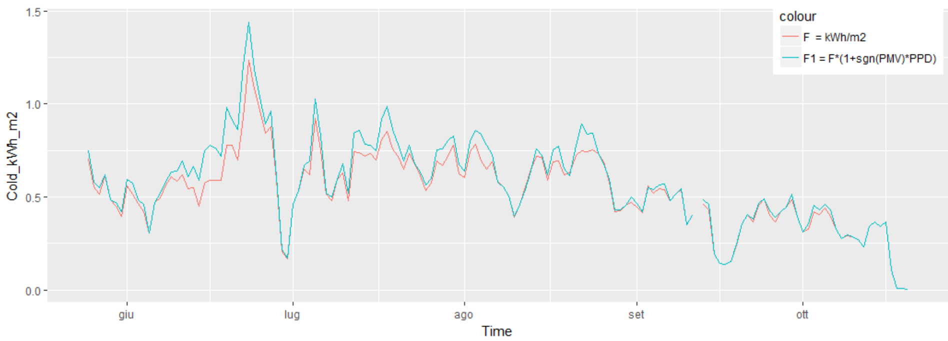


Figure 3.9: KPI created with the PPD index used as a quantitative value and the sign of PMV to understand the reason of the discomfort.

In the Figure 3.9 we can see how the index follows the trend of the consumption without too high peaks. It also shows that the discomford during the cooling period is actually due to a lower consumption compared to the needed amount (as we already knew), and for this reason the index is higher than the consumption.

Now we can add the $f^{\text{H}\backslash\text{CDD}}$:

$$F_2 = F_1 / f^{\text{H}\backslash\text{CDD}}$$

In the Figure 3.10 the final result is that it turns out that while we would have to spend more to get the thermal comfort, if we want to compare the

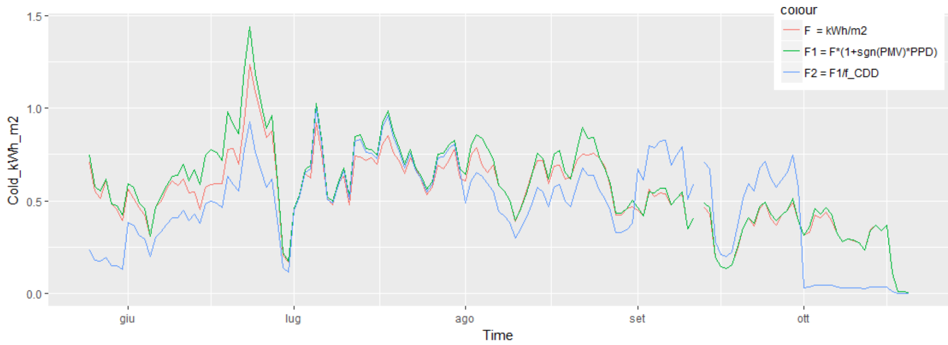


Figure 3.10: Complete alternative KPI.

KPI with the previous years we have to consider a lower consumption for the months of June and August, because as seen before those two months were hotter than expected, so it's not normal to spend so much for cooling.

In September, however, it is the opposite: it has been colder than usual, so usually we spend more on cooling, therefore the index is higher than the energy expense.

October usually does not need cooling, so consumption is divided by 10 as an abnormality.

As we said we had a standard July, in fact here we find an index overlapping the F_1 one.

If we look at the CDD graphic, Figure 3.7, we can see that the mean value for June is higher than the standard one, but the really hot part of the month is the central one, while the first days and the last ones are cold. Actually in those days we can see HDD>0 in Figure 3.6.

For this reason we decided to test another kind of $f^{\mathrm{H\backslash CDD}}$: instead of taking the mean value of specific and standard H\CDD, we can take the daily specific value and compare it with the standard monthly mean (that means red and green function in Figure 3.7):

$$f^{\mathrm{H\backslash CDD}}_{\mathrm{daily}} = \frac{\mathrm{H\backslash CDD}_{\text{specific day}}}{\mathrm{H\backslash CDD}_{\text{standard month}}}$$

We create the KPI in the same way:

$$F_3 = \frac{Q}{m^2} * \frac{(1 \pm sgn(PMV) * PPD)}{f^{\mathrm{H\backslash CDD}}_{\mathrm{daily}}}$$

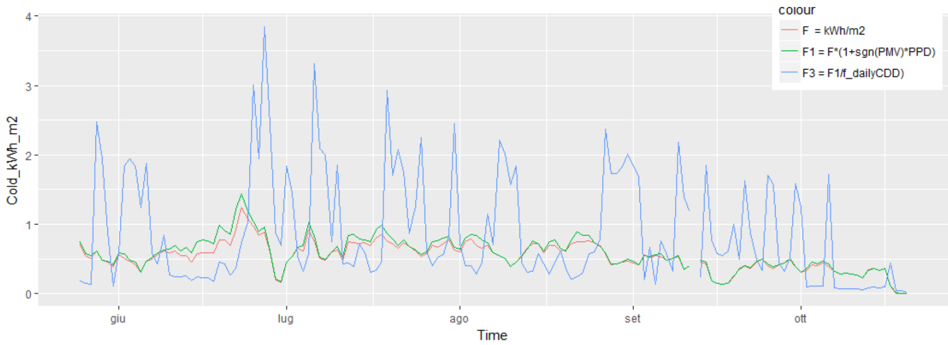


Figure 3.11: Complete alternative KPI with daily $f^{\mathrm{H\backslash CDD}}$.

The KPI, as we can see in Figure 3.7, appears really sensitive to the daily variation of the CDD. However it gives some more information: when the index gives a peak, that means that we are consuming energy for cooling, but outside the temperature is cold, so you are not supposed to be cooling. In fact we can see that most of the peaks are found in periods where consumption is decreasing, in other words the thermal inertia of the building creates the necessity of cooling even if outside it's not hot anymore.

This information gives the possibility to think of some better solutions, like implementing a better natural ventilation during those periods.

Chapter 4

Normalized Consumption of Mechanical Ventilation

4.1 Definition

Air quality is an important parameter that has to be evaluated due to its implication with health and impacts on productivity. The most commonly assessed parameter is the level of carbon dioxide, commonly used as an overall proxy for contamination and lack of adequate ventilation. The average CO_2 concentration in air is about $700\, mg/m^3$ (390 ppmv). Usually, CO_2 concentrations in indoor-residential air are higher and depend on the number of occupants inside the same area that continuously require oxygen and produce it as a byproduct of the respiratory system. Consequently, a substantial increase in CO_2 results in a corresponding decrease in oxygen concentration in the air itself and hence a risk to human health.

European countries suggests different national threshold levels. For example, three different levels of concentration for CO_2 are recommended in Germany: less than $1800\, mg/m^3$ (1000 ppmv) are considered to be unacceptable, between $1800\, mg/m^3$ (1000 ppmv) and $3600 mg/m^3$ (2000 ppmv) as high and those over $3600\, mg/m^3$ (2000 ppmv) as unacceptable[1].

Based on that, an index of air quality based on CO2 evaluation is developed[2]:

[1] G. Settimo et al.
[2] Antonucci, 2017

$$E_{\text{Fan,t}}^{\text{norm}} = \frac{E_{\text{Fan}}}{m^2} * I_t^{CO_2(\text{av})}$$

Where:

$E_{\text{Fan,t}}^{\text{norm}}$: is the energy consumption of fans normalized during the time step t $[kWh/m^2]$;

$I_t^{CO_2(\text{av})}$: Average value of CO_2 level indexes in the monitored ventilated space at the time t

This KPI is independent from the typology of mechanical ventilation system installed in the shopping centre, and it can show mechanical system faults (high values of CO_2 together with high consumption of fans).

This indicator will be tested with the Valladolid's data, so the CO_2 index is created as the average of six indicators, one for each monitored area; for each area we will have an indicator equal to:

$$I_t^{CO_2(\text{av})} = \begin{cases} 1 & \text{if the amount of } CO_2 \text{ is lower than the threshold} \\ \frac{CO_2}{CO_2^{\text{threshold}}} & \text{otherwise} \end{cases}$$

4.2 Creation of the KPI

The most commonly used limit value in European countries is 1000 ppm, but in the considered building the air quality is great, so we used a threshold of 600 to get a better view of the indicator.

First of all we create the KPI as defined. In Figure 4.1 is shown the ventilation consumption divided by the area and the KPI.

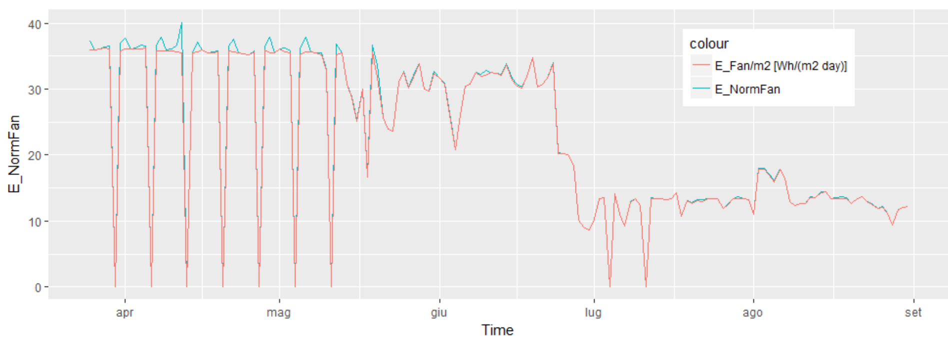


Figure 4.1: Normalized Consumption of Mechanical Ventilation

Howerer we can see a strange trend during April: the energy goes to zero for one entire day. In Figure 4.2 we can see that the day with no consumption is Thursday (in italian, giovedì). This explains also the small negative peak of the KPI between a thursday and the next one: those ones are sundays, in which the consumption remains the same but the market opens only half day.

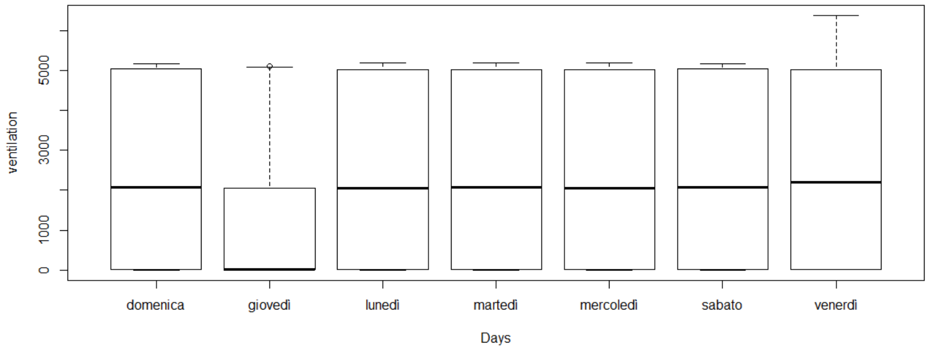


Figure 4.2: Boxplot showing the consumption of the ventilation system during the days of the week

The problem of this KPI is that if the consumption during those days is zero it is impossible to know whether there is a good concentration of CO_2 or not.

The solution that we decided to adopt is: every time the indicator I^{CO_2} is greater than 1 and the consumption is less than the monthly average, instead of the specific consumption of that hour we use the monthly mean value of consumption to calculate the KPI:

$$E^{\text{norm}}_{\text{Fan},1} = \begin{cases} \frac{E_{\text{Fan}}}{m^2} * I^{CO_2(\text{av})} & \text{if } E_{\text{Fan}} > E^{\text{MM}}_{\text{Fan}} \\ \frac{E^{\text{MM}}_{\text{Fan}}}{m^2} * I^{CO_2(\text{av})} & \text{otherwise} \end{cases}$$

where $E^{\text{MM}}_{\text{Fan}}$ is the monthly mean of consumption's values different to zero. We use this value because there is no correlation between the amount of CO2 and the consumption, as we can see in Figure 4.3.

This way, as we can see in the Figure 4.4, the factor gets higher during the negative peaks, in case the concentration of CO_2 is greater than the threshold.

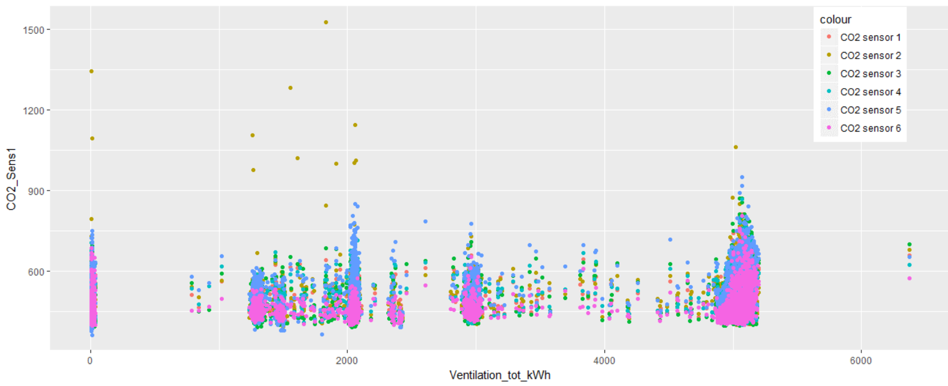


Figure 4.3: There is no correlation between vantilation's consumption and the concentration of CO_2

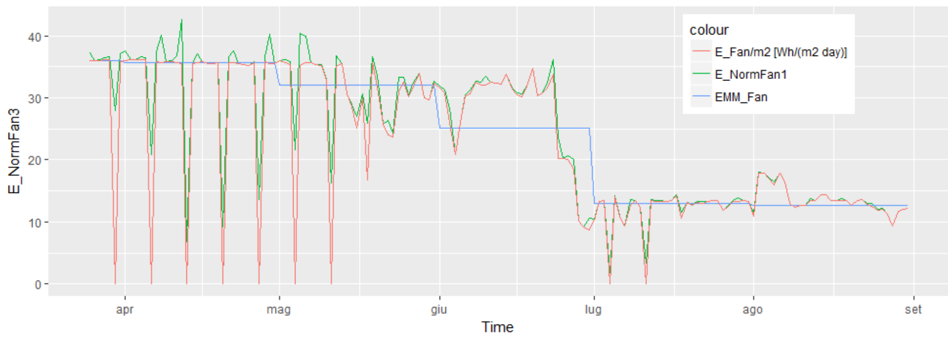


Figure 4.4: KPI using the $E_{\text{Fan}}^{\text{MM}}$ values

During that Thursdays the energy is still lower than the monthly average, which means that we have high values of CO_2 for a few hours per day compared to the operating hours of ventilation. This means that other values of consumption may be too high aswell.

Defining I^{CO_2} as $= 1$ when the CO_2 level is below the threshold may avoid the possibility of seeing system inefficiencies: If the CO_2 level is good, it is probably not necessary for the ventilation to remain at the maximum power. So let's try to define I^{CO_2} without distinction:

$$I^{CO_2} = \frac{CO_2}{CO_2^{\text{threshold}}} \quad , \quad \text{for every value of the } CO_2 \text{ concentration}$$

Note that we can do so because our threshol is 600 ppm, lower than the real one that would be around 1000.

As a result the indicator is almost always lower than the actual daily consumption, as we see in Figure 4.5.

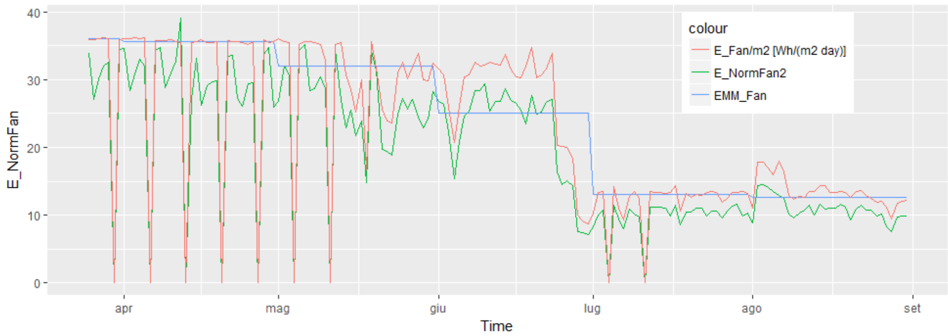


Figure 4.5: KPI using the new definition of I^{CO_2}

If we put in the same graph the two different definitions of I^{CO_2}, it is possible to note another problem: frequently the first version of the index (I1_mean in Figure 4.6) is greather than 1 while the second version is not. That means that the mean value of the concentration of CO_2 is good, but there are some areas in which the value is over the threshold.

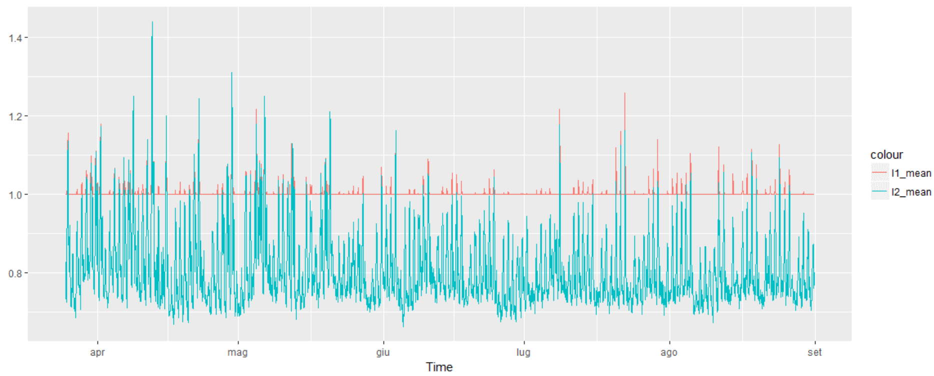


Figure 4.6: Comparing the two definitions of I^{CO_2}

The ventilation has to guarantee the comfort in each one of the areas of the monitored building. It is not enough that the mean value is good. For this reason it has been decided to change another time the definition: instead of the mean value of the 6 areas we take the maximum value:

$$I^{CO_2}_{\max} = \frac{CO_2^{\max}}{CO_2^{\text{threshold}}}$$

The final result (E_NormFan3 in Figure 4.7) should therefore indicate the daily ventilation energy that would actually be used to maintain the desired air quality across the monitored area.

Figure 4.7: The final KPI of ventilation's consumption

Chapter 5

Energy Efficiency Index for Refrigeration Cabinets

5.1 Definition

The refrigeration is always one of the biggest causes of consumption in a shopping mall or a supermarket. Thus, it is important to understand whether our refrigeration system is consuming the right amount of energy, even if there is not any comfort index related to this consumption.

This KPI will be tested on the Modena's data, and since we don't have any data about flow rates or temperatures of the refrigerating fluid, it is impossible for us to estimate parameters like the classic coefficient of performance (COP) of each machine.

Actually, the only information we have is the overall consumption of the system and some technical data about the different types of refrigerated display cabinets (RDC). Given that most of the buildings have only these kind of info, it is important to find a way to estimate the performance of a RDC system without phisically calculate it.

In order to classify the cabinets among themselves, the following Energy Efficiency Index (EEI) has been defined[1]:

$$EEI = \frac{\left(\frac{\text{TEC}}{\text{TDA}}\right)_{\text{measured}}}{\left(\frac{\text{TEC}}{\text{TDA}}\right)_{\text{reference}}} * 100$$

Where:

[1] Antonucci, 2017

TEC = REC + DEC [kWh/day]: is the Total Energy Consumption, sum of the Refrigeration Electrical energy Consumption and the Direct Electrical energy Consumption;

TDA : is the Total Display Area, that is the sum of the vertical and horizontal projected areas of visible foodstuff[2]

$\left(\frac{\text{TEC}}{\text{TDA}}\right)=$ Eff: is defined in the standard as an efficiency index, to be compared with the reference value calculated under laboratory's conditions. It will be noted that the lower the value, the more efficient is the cabinet. It will thus be considered more as a standardised consumption than as an efficiency rating.

The reference data corresponds to arbitrary values determined statistically after gathering sales data from major manufacturers on the European market. This data allows the establishing of an energy label using the classic lettering already used by the well known labels for electrical appliances such as washing machines or refrigerators[3].

5.2 Laboratory Conditions' TEC

If we want to measure the reference TEC value in a laboratory, first of all we need to fix some different climate classes. Eight sets of test conditions are defined at the international level. The set that most closely resembles the conditions of a store in Europe is the number 3, whose data are defined in Table 5.1.

Test chamber climate	Dry bulb temp. ($°C$)	Relative humidity	Dew point ($°C$)	Absolute hum. (g_w/kg_a)
Climate 3	25	60	16.7	12

Table 5.1: "Climate 3" test conditions according to ISO standard 23953:2005.

[2]according to EN ISO 23953-2:2005+A1:2012
[3]S.Marinhas, 2012

The refrigerator must be tested using some packets (M-Packages) whose temperature is constantly monitored. Therefore, the norm defines some temperature classes as shown in Table 5.2, according to the different temperatures reached by the various packages. In particular, three limits are taken into account, as shown in Figure 5.1:

- θ_{ah}: *upper* limit of the *highest* temperature reached by the *hottest* package
- θ_b: *lower* limit of the *lowest* temperature reached by the *coldest* package
- θ_{al}: *lower* limit of the *lowest* temperature reached by the *hottest* package

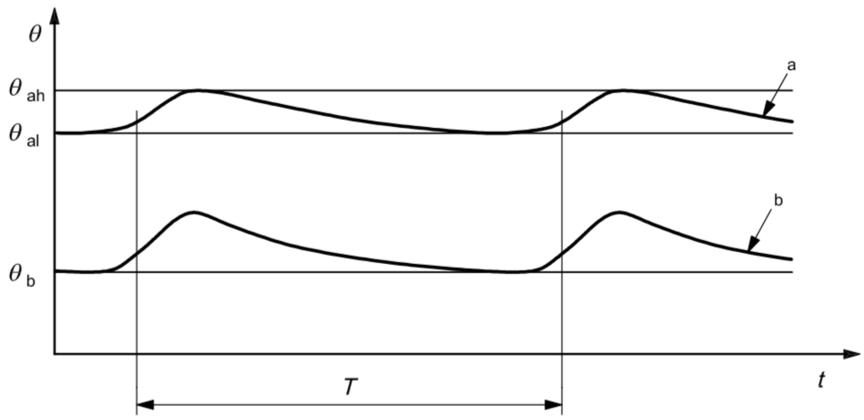


Figure 5.1: Temperature curves of M-packages

T: test period
a: temperature curve of warmest M-package
b: temperature curve of coldest M-package

	L1	L2	L3	M1	M2	H1	H2
$\theta_{ah}(°C)$	-15	-12	-12	+5	+7	+10	+10
$\theta_b(°C)$	-	-	-	-1	-1	+1	-1
$\theta_{al}(°C)$	-18	-18	-15	-	-	-	-

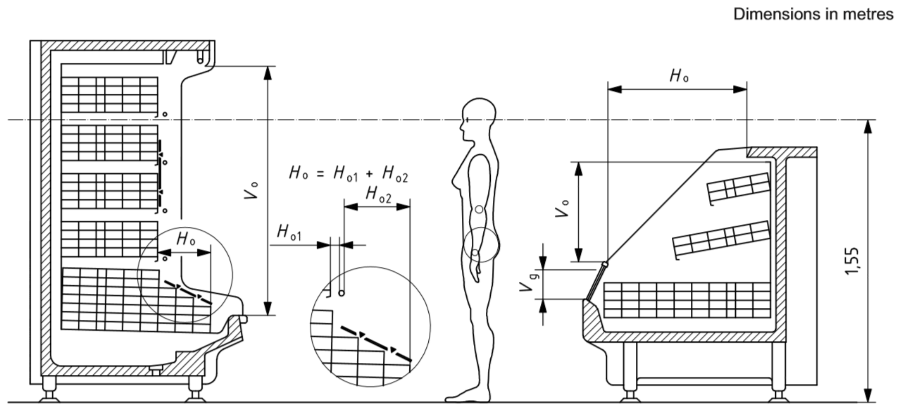
Table 5.2: The temperature categories according to ISO standard 23953:2005.

Once it is determined that the refrigerator remains within the temperature limits set for its temperature class, it is possible to measure the amount of energy used for the refrigeration (REC) and the amount used for the auxiliary components (DEC). Then, summing the two quantities we will know the reference's total energy consumption of the fridge.

5.3 TDA

The total display area is different from model to model, so it would be advisable to phisically measure it but since we don't have this possibilty we will estimate it referring to the standard's examples

As shown in the Figure 5.2, it is necessary to take into account the vertical and horizontal lengths of all M-pakages that face the external radiation, taking into account the presence and typology of glasses.



	L_{oh} = 2,500	H_o = 0,291
T_{gh} = 100 %	L_{gh} = 2,500	H_g = 0
	L_{ov} = 2,500	V_o = 1,367
T_{gv} = 100 %	L_{gv} = 2,500	V_g = 0

TDA = $(H_o \times L_{oh}) + (H_g \times T_{gh} \times L_{gh}) + (V_o \times L_{ov}) + (V_g \times T_{gv} \times L_{gv})$	4,145

	L_{oh} = 2,500	H_o = 0,761
T_{gh} = 100 %	L_{gh} = 2,500	H_g = 0
	L_{ov} = 2,500	V_o = 0,546
T_{gv} = 81 %	L_{gv} = 2,400	V_g = 0,175

TDA = $(H_o \times L_{oh}) + (H_g \times T_{gh} \times L_{gh}) + (V_o \times L_{ov}) + (V_g \times T_{gv} \times L_{gv})$	3,608

Figure 5.2: Example of the calculation of the TDA

In these examples of TDA calculation we can see that each vertical and horizontal length is multiplied by the length of the refrigerator and by the light transmission T (as defined by the standard, see Table 5.3). Then, all the areas are added together.

Type of glazed surface	T_g
Single anti-reflection glass	98%
Single glass	90%
Double glass or two single glasses	81%
Triple glass without coating	73%

Table 5.3: Light transmission factor T for different types of glasses

5.4 Reference TEC

The data provided subdivides Modena coop's RDCs in seven different types with different characteristics (Figure 5.3).

Type	n°	Installed Length [m]	Height [m]	Typology	Open - Closed	Temperature Class	Climate Class [-]
1	2	5	1.38	Vertical	Open	M1	3
2	2	3.2	2.6	Vertical	Open	H1	3
3	6	14	1.8	Vertical	Closed	M1	3
4	9	23.75	2	Vertical	Closed	M2	3
5	4	9.4	1.25	Serve-Over	Open	M1	3
6	4	7.5	1.25	Serve-Over	Open	M2	3
7	4	14	2	Vertical	Closed	L1	3

Figure 5.3: Technical data provided by the coop

From the typology (vertical or serve over), height, temperature class and the fact that they are open or closed we can trace to the most similar type defined in the standard and calculate an approximate display area.

Once the total display area of each type is found, the best reference efficiency value (Eff_{ref}) can be found aswell thanks to the standard values shown in (Figure 5.4), considering the typology, the climate class, and the temperature class.

Then, with this second data we can find the total reference energy consumption as:

$$\text{TEC}_{\text{ref}} = \text{Eff}_{\text{ref}} * \text{TDA}$$

We find that the total energy value consumed in a day by the standard refrigerators is around 910 kWh/day (Figure 5.5)

Type of cabinet		Temperature category	TEC/TDA reference value
	RHC1	3H	6.2
		3M2	6.7
		3M1	7.2
	RHF1	3L3	21.0
	RHC3,	3H	5.5
		3M2	5.8
	RHC4	3M1	6.2
	RHF3,	3L1	15.0
		3L2	14.0
	RHF4	3L3	13.0
	RHC5,	3H	4.3
		3M2	4.7
	RHC6	3M1	5.0
	RHF5,	3L1	12.0
		3L2	11.2
	RHF6	3L3	10.4
	RVC1,	3H	10.1
		3M2	12.3
	RVC2	3M1	13.4
		3M0	14.5
	RVC3	3H	13.8
		3M2	16.0
	RVF1	3L3	29.0
	RVF4	3L1	28.5
	RVC4	3H	6.1
		3M2	7.4
		3M1	8.0
		3M0	8.7
	RYF3	3L2	30.0
		3L3	29.0
	RYF4	3L2	28.5
		3L3	27.6

Figure 5.4: Eff_{ref} reference values

Type	TDA	Eff = TEC/TDA ref	TEC = Eff * TDA
1	7.2	7.2	51.84
2	4.8	10.1	48.48
3	15.50178	8	124.01424
4	26.2976625	7.4	194.6027025
5	6.6975	7.2	48.222
6	5.34375	6.7	35.803125
7	14.308	28.5	407.778
			910.7400675

Figure 5.5: Calculated reference TEC

5.5 Creation of the KPI

By remembering the definition of the KPI, if we have both the total energy consumptions - the measured and the reference one - we can now put aside the Eff values by cutting the TDAs:

$$\mathrm{EEI} = \frac{\left(\frac{\mathrm{TEC}}{\mathrm{TDA}}\right)_{\mathrm{measured}}}{\left(\frac{\mathrm{TEC}}{\mathrm{TDA}}\right)_{\mathrm{reference}}} * 100 = \frac{\mathrm{TEC}_{\mathrm{measured}}}{\mathrm{TEC}_{\mathrm{reference}}} * 100$$

Thus, the only thing that we have to do now is to divide the real consumption's data by 910 kWh/day. The result is shown in (Figure 5.6)

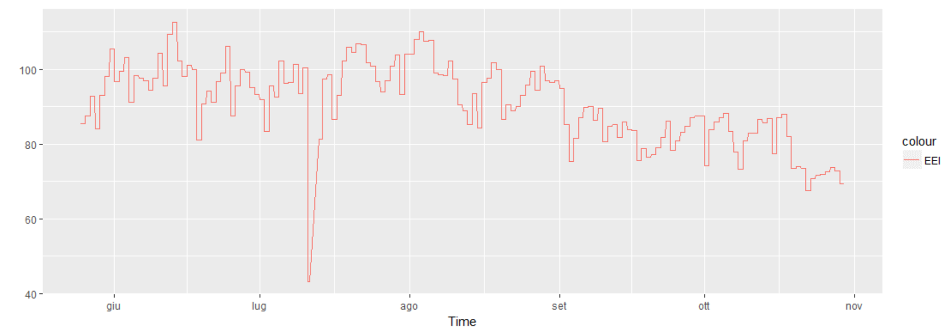


Figure 5.6: Energy Efficiency Index

It is clear that, as we could imagine, there is a correlation between the KPI and the temperature. In fact, the index gets better and better moving towards the cold part of the year.

By adding to the chart the average internal temperature, we notice a trend that seems strongly correlated (Figure 5.7). The linear regression between the two variables gives an R^2 of 66% (Figure 5.8).

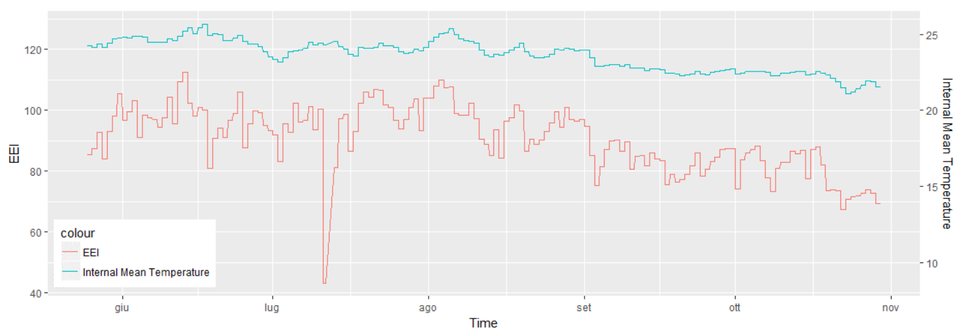


Figure 5.7: EEI and internal mean temperature

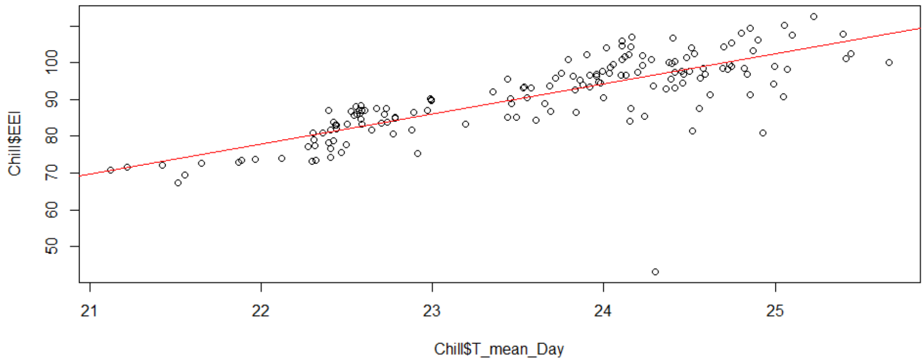


Figure 5.8: Correlation between EEI and internal temperature

We remember that the climate class 3 was defined with a test temperature equal to 25 °C. At that temperature the KPI is around 100, that means that the total energy consumption is equal to the reference value.

Thus, even if we had to make some hypothesis about the total display area and the right typology that comes closest to the real one, the KPI seems to work correctly.

Some categories of efficiency are defined, associated to the value of the EEI parameter (Table 5.4).

Energy efficiency category	Energy efficiency index	Energy efficiency category	Energy efficiency index
A	EEI<55	D	$100 \leq$ EEI ≤ 110
B	$55 \leq$ EEI < 75	E	$110 \leq$ EEI < 125
C	$75 \leq$ EEI < 90	F	EEI ≥ 125
D	$90 \leq$ EEI < 100		

Table 5.4: Energy efficiency categories based on the EEI index

If we assign an energy efficiency category to each interval of values of the KPI, it is possible to see how the energy efficiency category changes together with the variation of the internal temperature (Figure 5.9).

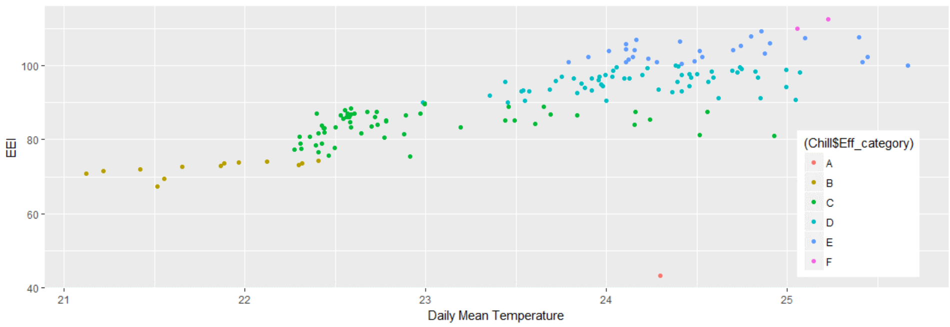


Figure 5.9: Variation of the energy efficiency category with the internal temperature

Chapter 6

Normalized Electricity Consumption for Lights

6.1 Definition

Visual comfort is defined as “a subjective condition of visual well-being induced by the visual environment” [1]. It depends on the physiology of the human eye, on the physical quantities describing the amount of light and its distribution in space, and on the spectral emission of the light source.

Visual comfort has been commonly studied through the assessment of some factors characterizing the relationship between the human needs and the light environment, such as the *amount of light*, the *uniformity of light*, the *quality of light in rendering colors*, and the *prediction of the risk of glare* for occupants. For each of them, a still growing number of indices and metrics have been proposed in literature and standards. Although the aforementioned factors are possibly correlated with each other, an index usually focuses only on one of them[2].

Modena’s case study only have the amount of light’s data available, so all other aspects of visual comfort will have to be overlooked in this paper. Thus, the KPI is defined as [3]:

$$\mathrm{E}^{\mathrm{norm}}_{\mathrm{light,\ t}} = \frac{\mathrm{E}_{\mathrm{light,\ t}}}{A * I_t^{\mathrm{VC(av)}}} \qquad \left[\frac{kWh}{m^2}\right]$$

[1] European standard EN 12665
[2] S.Carlucci et al., 2015
[3] D. Antonucci, 2017

where:
$E^{norm}_{light,\,t}$: is the normalized electric consumption of lights at time t;

A: is the area of illuminated space, equal to $1200\,m^2$ for the Modena's case study;

$I_t^{VC(av)}$: is the average value of visual comfort indexes at time t, defined as:

$$I_t^{VC(av)} = \begin{cases} 0.01 & \text{if the whole building is discomfortable at time } t \\ \frac{1}{N}\Sigma_{i=1}^{N}\mathrm{wf}_{i,t} & \text{otherwise} \end{cases}$$

with:
N: number of points where the visual comfort is evaluated;
$\mathrm{wf}_{i,t}$: is equal to 1 if there is visual comfort in zone i at time t, 0 otherwise.

6.2 Creation of the KPI

Earlier it was common to find light levels in the range 100 - 300 lux for normal activities. Today the light level is more common in the range 500 - 1000 lux, depending on the activity. For precision and detailed works, the light level may even approach 1500 - 2000 lux.

For example in an office, the recommended illumination is 500 lux, for a supermarket is 750 lux[4], so we expect to find an amount of light around this values in the main working areas of the shopping mall and around 200 lux in corridors, bathroom, warehouses[5].

In the Modena's case study, there are 6 sensors that constantly detect the illumination level.

In Figure 6.1 we can see that the values of the six sensors are quite different from each other and furthermore all of them are quite low. This is probably due to a wrong positioning of the sensors, which does not allow the capture of the correct illumination's value.

[4] www.illumenate.com/lightlevels.htm
[5] EN 12464-1:2011

Figure 6.1: Profile of the six illumination's sensors

In order to be able to test the KPI even with distorted illumination values, it was decided to take illumination's limits based directly on the data obtained from the sensors. In particular, the average values are:

- Lux1 = 355
- Lux2 = 250
- Lux3 = 178
- Lux4 = 102
- Lux5 = 261
- Lux6 = 25

We decided to use as a threshold a different value for each of them, equal to the 80% of their mean value.

To create the indicator, we operate at the hourly level: for each hour the index is equal to 1, minus 1/6 for each sensor that registers a value below the limit set for the specific indicator. If the end result is zero, that is all 6 areas are out of the comfort boundaries, we fix the value 0.01 instead.

The Figure 6.2 shows how daily consumption is almost constant during the months, while the indicator rises from September onwards, in other words when the hours of light begin to shrink.

The graphic of the external global radiation (Figure 6.3) shows the classic downward trend as the days shrink.

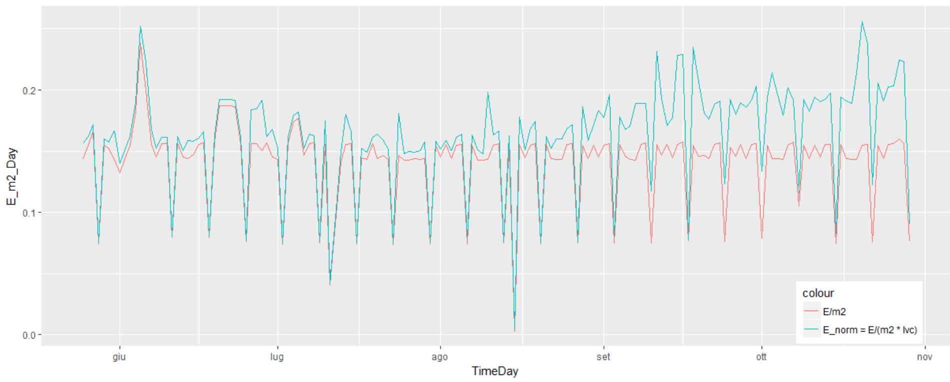


Figure 6.2: Specific consumption compared to the KPI

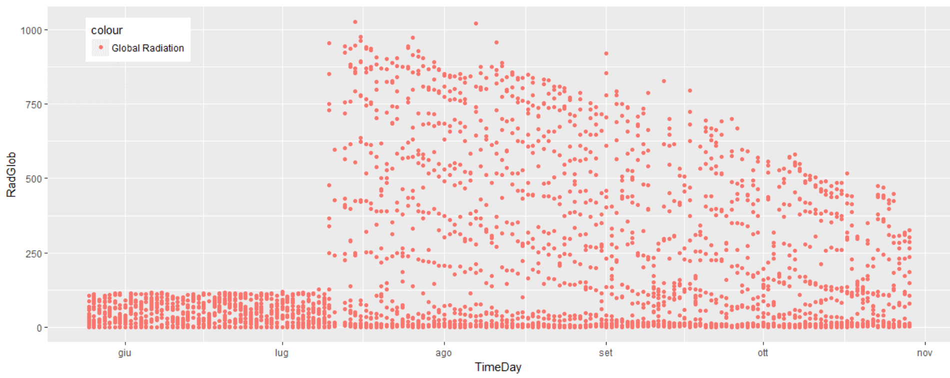


Figure 6.3: External global radiation

It is clear that by mid-July data is unusable. So taking the data up to August, it is possible to make a linear regression between the average daily I^{VC} during the opening hours of the shopping mall and the global average daily radiation.

There is a fairly clear correlation with an $R^2 = 77\%$ (Figure 6.4), which simply means that during the winter, since there is less natural radiation, we would have to spend more on lighting to achieve the same level of visual comfort that we have during the summer.

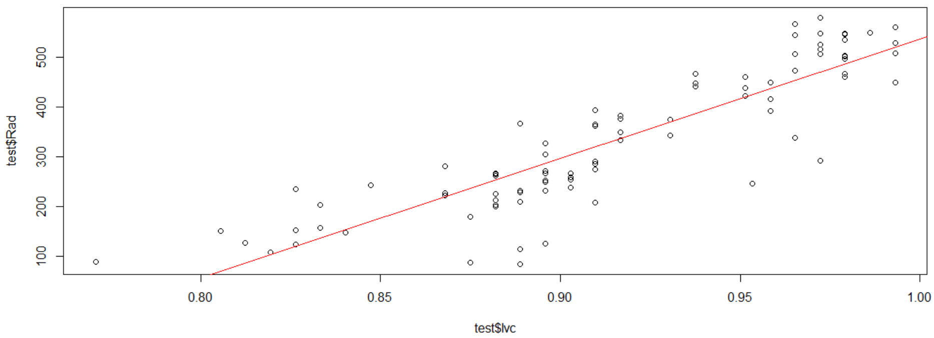


Figure 6.4: Linear regression between the mean value of I^{VC} during opening hours and the global average daily radiation

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Appendix A

Example of R script

Listing A.1: File Creator

```
Time_1 = "2017-03-25"
Hour_1 = "00.00"

Time_2 = "2017-10-31"
Hour_2 = "23.00"

data_file <- Download_all(Time_1,Time_2,Hour_1,Hour_2)

write.table(data_file,"Main.csv",sep=";",row.names = FALSE)

summary(data_file)
```

Listing A.2: Downloading and Preprocessing

```
rm(list=ls())
library(RODBC)
library(ggplot2)
library(lubridate)
library(Hmisc)

setwd("C:/Users/giacomo/Dropbox/Tesi/Lavoro")
```

```
#------------------------------DOWNLOAD------------------------------

Download_all <- function(Time_1,Time_2,Hour_1,Hour_2){


  start_time <- as.POSIXct(paste(Time_1,Hour_1,sep=" "),format="%Y-%m-%d %
      H.%M")
  end_time   <- as.POSIXct(paste(Time_2,Hour_2,sep=" "),format="%Y-%m-%d %
      H.%M")
  out        <- data.frame(Time=seq(from=start_time,to=end_time, by="hour"
      ))

  out$hour   <- hour(as.POSIXct(out$Time))
  out$day    <- weekdays(as.POSIXct(out$Time))
  out$month  <- months(as.POSIXct(out$Time))

#-----------------------EXTERNAL TEMPERATURE SENSOR--------------------

  id <- 797
  Name <- "Ext_Temperature"
  Operation <- "mean"

  Sensor <- DownloadDate_byTime(Time_1,Time_2,Hour_1,Hour_2,id, Operation)
  colnames(Sensor)[2] <- Name

  cat(paste("Dataset ", Name, " has been downloaded. \n",sep=""))

  out    <- merge(out, Sensor, by="Time", all.x=TRUE)

  #we will sum the hourly degree days to create the daily value, so we
      divide by 24h:
  Sensor$HDD_15C <- Sensor$Ext_Temperature
  Sensor$HDD_15C[Sensor$Ext_Temperature <  15] <- (15 - Sensor$HDD_15C[
      Sensor$Ext_Temperature < 15])/24
  Sensor$HDD_15C[Sensor$Ext_Temperature >= 15] <- 0

  Sensor$CDD_26C <- Sensor$Ext_Temperature
  Sensor$CDD_26C[Sensor$Ext_Temperature <= 26] <- 0
  Sensor$CDD_26C[Sensor$Ext_Temperature >  26] <- (Sensor$CDD_26C[Sensor$
      Ext_Temperature > 26] - 26)/24
```

```
  Sensor$Time <- floor_date(Sensor$Time, unit = "days")

#------------------------------HDD & CDD------------------------------

  #create a new file and add the date column
  Mean  <- data.frame(Time=seq(from=start_time,to=end_time, by="day"))

  #create mean daily temperature vector
  Mean_HDD_15C    <- c(tapply(Sensor$HDD_15C, Sensor$Time, FUN = sum))
  Mean_CDD_26C    <- c(tapply(Sensor$CDD_26C, Sensor$Time, FUN = sum))

  #add the vector to the file "Mean"
  Mean$HDD_15C  <- Mean_HDD_15C
  Mean$CDD_26C  <- Mean_CDD_26C

  #cut the hours
  Mean$TimeDay <- floor_date(Mean$Time, unit = "days")
  Mean$Time    <- NULL

  #create the Day column cutting the hours from the Time column
  out$TimeDay <- floor_date(out$Time, unit = "days")

  out   <- merge(out, Mean, by="TimeDay", all.x=TRUE)

  #For the mean value of the month we sum the mean value of all the days
  #Create the months column
  Mean$month <- months(as.POSIXct(Mean$TimeDay))

  #create a vector with the monthly value
  #we can't simply sum the mean values because we can have less data than
      the number of days (like for April we have only 5 days) so we take
      the mean value and we multiply for the number of days of that
      specific month.
  #In this case is easier to multiply the daily values for the number of
      days and then do the mean:
  Mean$CDD_26C <- Mean$CDD_26C*monthDays(as.Date(Mean$TimeDay))
  Mean$HDD_15C <- Mean$HDD_15C*monthDays(as.Date(Mean$TimeDay))
  cdd <- c(tapply(Mean$CDD_26C, Mean$month, FUN = mean))
  hdd <- c(tapply(Mean$HDD_15C, Mean$month, FUN = mean))
```

```
  #create the data frame with che months column and the mean value
  cdd_mean <- data.frame(month=names(cdd), CDD_specific_monthmean=cdd)
  hdd_mean <- data.frame(month=names(hdd), HDD_specific_monthmean=hdd)

  out      <- merge(out, cdd_mean, by="month", all.x=TRUE)
  out      <- merge(out, hdd_mean, by="month", all.x=TRUE)

#----------------------CDD & HDD HISTORICAL FILES---------------------

  #read the CDD & HDD files (monthly sum of the last 3 years - www.
      degreedays.net)
  CDD <- read.csv2("0CDD_26C.csv", header = T, sep = ";")
  HDD <- read.csv2("0HDD_15C.csv", header = T, sep = ";")

  #rename Time column
  colnames(CDD)[1] <- "Time"
  colnames(HDD)[1] <- "Time"

  #change the format of the time column
  CDD$Time <- as.POSIXct(CDD$Time, format="%d/%m/%Y")
  HDD$Time <- as.POSIXct(HDD$Time, format="%d/%m/%Y")

  #create a column with the names of the months
  CDD$month    <- months(as.POSIXct(CDD$Time))
  HDD$month    <- months(as.POSIXct(HDD$Time))

  #create a vector with the value of the monthly mean
  vectorCDD <- c(tapply(CDD$CDD, CDD$month, FUN = mean))
  vectorHDD <- c(tapply(HDD$HDD, HDD$month, FUN = mean))

  #create the data frame with che months column and the mean value
  CDD_mean <- data.frame(month=names(vectorCDD), CDD_historical_monthmean=
      vectorCDD)
  HDD_mean <- data.frame(month=names(vectorHDD), HDD_historical_monthmean=
      vectorHDD)

  out      <- merge(out, CDD_mean, by="month", all.x=TRUE)
  out      <- merge(out, HDD_mean, by="month", all.x=TRUE)

  #the file oreder now is alphabetic, reorder with the time
  out <- out[order(out$Time),]
```

```
#------------------------TEMPERATURE AND HUMIDITY-----------------------
   rm(id)
   rm(Name)

   #We use another file cause we need a file without NAs for the PPD
       function
   outTEMP    <- data.frame(Time=seq(from=start_time,to=end_time, by="hour
       "))
   outTEMP$month  <- months(as.POSIXct(outTEMP$Time))
   outTEMP$TimeDay <- floor_date(outTEMP$Time, unit = "days")

   id <- c(13,14,15,38,39,40,10,11,12,35,36,37)
   Name <- c("Temperature_Sens1", "Temperature_Sens2", "Temperature_Sens3"
       ,
             "Temperature_Sens4","Temperature_Sens5", "Temperature_Sens6",
             "Humidity_Sens1", "Humidity_Sens2", "Humidity_Sens3",
             "Humidity_Sens4","Humidity_Sens5", "Humidity_Sens6")
   Operation <- "mean"

   for (i in 1:length(id)){
     Sensor <- DownloadDate_byTime(Time_1,Time_2,Hour_1,Hour_2,id[i],
         Operation)
     colnames(Sensor)[2] <- Name[i]
     outTEMP    <- merge(outTEMP, Sensor, by="Time", all.x=TRUE)
     cat(paste("Dataset ", Name[i], " has been downloaded. \n",sep=""))
   }
   outTEMP

#------------------------------CLO value------------------------------


   #hipotetical clo values:::: we divide the clo value in 4 levels and we
       create a function of the external temperature

   #we take the mean temperature between 8am and 9pm, i.e. the hours when
       the supermarket is opent
   MeanTempDay <- c(tapply(out$Ext_Temperature[out$hour > 7 & out$hour <
       22], out$TimeDay[out$hour > 7 & out$hour < 22], FUN = mean))
   Daily         <- data.frame(TimeDay=names(MeanTempDay), MeanExtTemp=
       MeanTempDay)
```

```
Daily$TimeDay <- as.POSIXct(Daily$TimeDay)

Daily$clo                          <- c(as.factor(1))
Daily$clo[Daily$MeanExtTemp <= 17] <- 1.1
Daily$clo[Daily$MeanExtTemp > 17]  <- 0.9
Daily$clo[Daily$MeanExtTemp > 21]  <- 0.7
Daily$clo[Daily$MeanExtTemp >= 25]  <- 0.5


outTEMP   <- merge(outTEMP, Daily, by="TimeDay", all.x=TRUE)

#------------------------------PPD and PMV----------------------------

Met <- 1.6             # metabolic rate for a walking person [met]

Wme <- 0              # HIP:::: external work term equal to zero

v_air <- 0.2           #m/s.........hipotetical value


#we have to delete all the NA (otherwise the PMV function gives error)
outTEMP <- na.omit(outTEMP)

#HIP:::We take radiant temperature equal to the air temp
fA  <- PMV(outTEMP$Temperature_Sens1,outTEMP$Temperature_Sens1,outTEMP$
    Humidity_Sens1,v_air,Met,Wme,outTEMP$clo)
outTEMP$PPD1 <- fA$PPD
outTEMP$PMV1 <- fA$PMV

fB <- PMV(outTEMP$Temperature_Sens2,outTEMP$Temperature_Sens2,outTEMP$
    Humidity_Sens2,v_air,Met,Wme,outTEMP$clo)
outTEMP$PPD2 <- fB$PPD
outTEMP$PMV2 <- fB$PMV

fC <- PMV(outTEMP$Temperature_Sens3,outTEMP$Temperature_Sens3,outTEMP$
    Humidity_Sens3,v_air,Met,Wme,outTEMP$clo)
outTEMP$PPD3 <- fC$PPD
outTEMP$PMV3 <- fC$PMV

fD <- PMV(outTEMP$Temperature_Sens4,outTEMP$Temperature_Sens4,outTEMP$
    Humidity_Sens4,v_air,Met,Wme,outTEMP$clo)
```

```
outTEMP$PPD4 <- fD$PPD
outTEMP$PMV4 <- fD$PMV

fE <- PMV(outTEMP$Temperature_Sens5,outTEMP$Temperature_Sens5,outTEMP$
    Humidity_Sens5,v_air,Met,Wme,outTEMP$clo)
outTEMP$PPD5 <- fE$PPD
outTEMP$PMV5 <- fE$PMV

fF <- PMV(outTEMP$Temperature_Sens6,outTEMP$Temperature_Sens6,outTEMP$
    Humidity_Sens6,v_air,Met,Wme,outTEMP$clo)
outTEMP$PPD6 <- fF$PPD
outTEMP$PMV6 <- fF$PMV

#we save also the mean value
outTEMP$PPD <- (outTEMP$PPD1+outTEMP$PPD2+outTEMP$PPD3+outTEMP$PPD4+
    outTEMP$PPD5+outTEMP$PPD6)/6
outTEMP$PMV <- (outTEMP$PMV1+outTEMP$PMV2+outTEMP$PMV3+outTEMP$PMV4+
    outTEMP$PMV5+outTEMP$PMV6)/6

#I_TC as EURAC proposed (created with PPD method instead of the graphic
     one)
outTEMP$I_TC <- c(as.factor(1))

outTEMP$I_TC[outTEMP$PPD1 > 10] <- outTEMP$I_TC[outTEMP$PPD1 > 10] - 1/
    6
outTEMP$I_TC[outTEMP$PPD2 > 10] <- outTEMP$I_TC[outTEMP$PPD2 > 10] - 1/
    6
outTEMP$I_TC[outTEMP$PPD3 > 10] <- outTEMP$I_TC[outTEMP$PPD3 > 10] - 1/
    6
outTEMP$I_TC[outTEMP$PPD4 > 10] <- outTEMP$I_TC[outTEMP$PPD4 > 10] - 1/
    6
outTEMP$I_TC[outTEMP$PPD5 > 10] <- outTEMP$I_TC[outTEMP$PPD5 > 10] - 1/
    6
outTEMP$I_TC[outTEMP$PPD6 > 10] <- outTEMP$I_TC[outTEMP$PPD6 > 10] - 1/
    6

#we have to put <0.1 because the result of [1-6*(1/6)] is not zero
outTEMP$I_TC[outTEMP$I_TC <= 0.1] <- 1/10


outTEMP$Mean_Temperature <- (outTEMP$Temperature_Sens1 + outTEMP$
```

```
      Temperature_Sens2 + outTEMP$Temperature_Sens3 + outTEMP$Temperature
      _Sens4 + outTEMP$Temperature_Sens5 + outTEMP$Temperature_Sens6)/6
  outTEMP$Temperature_Sens1  <- NULL
  outTEMP$Temperature_Sens2  <- NULL
  outTEMP$Temperature_Sens3  <- NULL
  outTEMP$Temperature_Sens4  <- NULL
  outTEMP$Temperature_Sens5  <- NULL
  outTEMP$Temperature_Sens6  <- NULL

  outTEMP$Mean_Humidity <- (outTEMP$Humidity_Sens1 + outTEMP$Humidity_
      Sens2 + outTEMP$Humidity_Sens3 + outTEMP$Humidity_Sens4 + outTEMP$
      Humidity_Sens5 + outTEMP$Humidity_Sens6)/6
  outTEMP$Humidity_Sens1     <- NULL
  outTEMP$Humidity_Sens2     <- NULL
  outTEMP$Humidity_Sens3     <- NULL
  outTEMP$Humidity_Sens4     <- NULL
  outTEMP$Humidity_Sens5     <- NULL
  outTEMP$Humidity_Sens6     <- NULL

  outTEMP$month              <- NULL
  outTEMP$TimeDay            <- NULL

  out    <- merge(out, outTEMP, by="Time", all.x=TRUE)

  #create the column with the difference of internal and external
      temperature
  out$Difference_Temperature <- c(as.numeric(out$Mean_Temperature-out$Ext
      _Temperature))

# --------------------------Thermal Heating--------------------------

  id <- c(455,454,453,449,448,447)

  Name <- c("Heat_Energy_Geothermal_3_kWh",
            "Heat_Energy_Geothermal_2_kWh",
            "Heat_Energy_Geothermal_1_kWh",
            "Cold_Energy_Geothermal_3_kWh",
            "Cold_Energy_Geothermal_2_kWh",
            "Cold_Energy_Geothermal_1_kWh")

  for (i in 1:length(id)){
```

```
    ch   <- odbcDriverConnect("driver={SQL Server}; ###PRIVATE INFO###)

    dataset <- sqlQuery(ch, paste('select DateTimeStamp,FloatValue from
        dbo.tbLogTimeValues where parentid=',id[i]))

    odbcCloseAll()

    # Cleaning date ---------------------------------------------
    dataset$DateTimeStamp <- as.POSIXct(dataset$DateTimeStamp)

    # Delete non hourly observations
    dataset <- dataset[minute(dataset$DateTimeStamp) == 0 | minute(
        dataset$DateTimeStamp) == 1,]
    dataset$DateTimeStamp <- floor_date(dataset$DateTimeStamp, unit = "
        hours")

    # Hours difference between an observation and the previous one
    # First value fixed as NA
    dataset$deltatime <- c(NA,as.numeric(diff(dataset$DateTimeStamp)/
        3600))

    # Delete double observations
    dataset <- dataset[dataset$deltatime !=0,]

    # Energy difference over time difference with the previous obs.
    dataset$FloatValue<- c(NA,diff(dataset$FloatValue))/ dataset$
        deltatime

    # Change MWh to kWh
    dataset$FloatValue <- dataset$FloatValue*1000

    dataset$deltatime <- NULL

    colnames(dataset)<- c("Time", Name[i])

    out    <- merge(out, dataset, by="Time", all.x=TRUE)
    cat(paste("Dataset ", Name[i], " has been downloaded. \n",sep=""))

  }
```

```
  out$Heat_Geothermal_kWh  <- c(out$Heat_Energy_Geothermal_3_kWh+
                                out$Heat_Energy_Geothermal_2_kWh+
                                out$Heat_Energy_Geothermal_1_kWh)

  out$Cold_Geothermal_kWh  <- c(out$Cold_Energy_Geothermal_3_kWh+
                                out$Cold_Energy_Geothermal_2_kWh+
                                out$Cold_Energy_Geothermal_1_kWh)

  out$Cold_Energy_Geothermal_3_kWh <- NULL
  out$Cold_Energy_Geothermal_2_kWh <- NULL
  out$Cold_Energy_Geothermal_1_kWh <- NULL

  out$Heat_Energy_Geothermal_3_kWh <- NULL
  out$Heat_Energy_Geothermal_2_kWh <- NULL
  out$Heat_Energy_Geothermal_1_kWh <- NULL

  out

}
```

Listing A.3: Predicted percentage of dissatisfied - UNI EN ISO 7730

```
PMV <- function(T_a,T_r,Rh,v_air,Met,Wme,clo)  {

  M  <- Met*58.15                      # [W/m2]
  W  <- Wme*58.15
  MW <- M+W

  #saturated vapour pressure
  FNPS <- exp(16.6536 - 4030.183/(T_a+235))
  #water vapour pressure, Pa
  PA   <- Rh * 10 * FNPS

  T_aK  <- T_a+273               #air temp.     [K]
  T_rK  <- T_r+273               #radiant temp. [K]

  icl <- clo*0.155      #thermal insulation of the clothing [m2K/W]
  fcl <- NULL

  for(i in 1:length(icl)){
```

```
  if(icl[i] <= 0.078)      {fcl[i] <- 1    + 1.29*icl[i]}
  else                     {fcl[i] <- 1.05 + 0.645*icl[i]}
}


#first guess for surface temperature  of clothing
T_cl_1 <- T_aK + (35.5 - T_a) / (3.5 * icl + 0.1)

# calculation terms (AS IN THE UNI EN ISO 7730)
P1 <- icl * fcl
P2 <- P1 * 3.96
P3 <- P1 * 100
P4 <- P1 * T_aK
P5 <- 308.7 - 0.028 * MW + P2 * (T_rK/100)^4


#temperatures have to be divided by 100, oherwise the calculation
    diverges
XN <- T_cl_1 / 100
XF <- XN

# stop criteria
EPS <- 0.00015
maxiter <- 150

H_cF  <- 12.1*sqrt(v_air)        #heat transf. coeff. by forced
    convection
H_cN  <- NULL                    #heat transf. coeff. by natural
    convection
H_c   <- NULL
T_cl  <- NULL

for (i in 1:length(XF)){
  for (j in 1:maxiter){

    XF[i]   <- (XF[i] + XN[i])/2

    # heat transf. coeff. by natural convection
    H_cN[i] <- 2.38 * abs(100*XF[i] - T_aK[i]) ^ 0.25

    if (H_cF > H_cN[i])   {H_c[i] <- H_cF}
```

```
    else                 {H_c[i] <- H_cN[i]}

    # (AS IN THE UNI EN ISO 7730)
    XN[i] = (P5[i] + P4[i] * H_c[i] - P2[i] * XF[i] ^ 4) / (100 + P3[i]
        * H_c[i])

    if (abs(XN[i] - XF[i]) <= EPS) break
  }
  T_cl[i] <- 100 * XN[i] -273                   #surface temperature of
      the clothing
}



#----------------------------HEAT LOSS---------------------------

HL1 = 3.05 * 0.001 * (5733 - 6.99 * MW - PA)              #heat loss
    diff. through skin

HL2 <- 0.42 * (MW - 58.15)                                 #heat loss
    by sweating (comfort)

                                                           #if MW<58.15
                                                                --> HL2
                                                               =0

HL3 = 1.7 * 0.00001 * MW * (5867-PA)                       #latent
    respiration heat loss

HL4 = 0.0014 * MW * (34 - T_a)                             #dry
    respiration heat loss

HL5 = 3.96 * fcl * (XN^4 - (T_rK/100)^4)                   #heat loss
    by radiation

HL6 = fcl * H_c * (T_cl - T_a)                             #heat loss
    by convection



#-----------------------------------PMV + PPD--------------------
#thermal sensation trans coeff
TS = 0.303 * exp(- 0.036 * MW) + 0.028
```

```
  #predicted mean vote
  PMV = TS * (MW - HL1 - HL2 - HL3 - HL4 - HL5 - HL6)

  #predicted percentage of dissatisfied
  PPD = 100 - 95 * exp(- 0.03353 * PMV ^ 4 - 0.2179 * PMV^2)

  file <- NULL
  file$PMV <- PMV
  file$PPD <- PPD

  return(file)
}
```

Listing A.4: Download date by time

```
DownloadDate_byTime <- function(Time_1, Time_2,Hour_1, Hour_2, id,
    operation){

#############PRIVATE FUNCTION###################
  }
}
```

Listing A.5: Example: creation of a KPI

```
rm(list=ls())
library(RODBC)
library(ggplot2)
library(lubridate)
library(Hmisc)

setwd("C:/Users/giacomo/Dropbox/Tesi/Lavoro")

Main                        <- read.table("Main.csv", header=T, sep=";")
Main$Time                <- as.POSIXct(Main$Time)
Main$month_num    <- month(as.POSIXct(Main$Time))

Main <- na.omit(Main)
```

```
Area = 2280       # [m^2]

Main$ConsC_m2 <- Main$Cold_Geothermal_kWh/Area
Main$ConsH_m2 <- Main$Heat_Geothermal_kWh/Area


#########CREATE HDD & CDD FACTOR########

#if the HDD of the day is =0, that means that I'm not supposed to be
    heating so the factor will be 0,1 (that means that the consumption is
    multiplied by 10)
#if the historical monthly mean is equal to 0, that means that usually is
    not necessary to heat in that period, but if the HDD of the day is not
     zero aswell, you are supposed to consume some energy that wasn't
    planned. This means that we don't have to consider that energy
    normally: for the retrofit that energy is an anomaly so the factor
    will be 10, decreasing the consumption to one tenth.
#Obviously the same for the CDD
Main$f_HDD <- Main$HDD_specific_monthmean/Main$HDD_historical_monthmean
Main$f_HDD[Main$HDD_historical_monthmean == 0]   <- 10
Main$f_HDD[Main$f_HDD > 10]                                   <- 10
Main$f_HDD[Main$HDD_specific_monthmean == 0]     <- 0.1
Main$f_HDD[Main$f_HDD < 0.1]                                  <- 0.1

#If the mean temp of a month is really high but there are some days with
    low temperature (see the CDD daily plot for june: the middle of june
    is high, but the end of june is cold, actually we have HDD>0), we can'
    t multiply each day with the same factor, maybe is better to create a
    daily factor to compare with the historical mean
Main$f_dailyHDD <- Main$HDD_15C*(monthDays(Main$Time))/Main$HDD_historical
    _monthmean
Main$f_dailyHDD[Main$HDD_historical_monthmean == 0]   <- 4
Main$f_dailyHDD[Main$f_dailyHDD > 4]                        <- 4
Main$f_dailyHDD[Main$HDD_15C == 0]                        <- 0.25
Main$f_dailyHDD[Main$f_dailyHDD < 0.25]                   <- 0.25


#the same for the CDD:
Main$f_CDD <- Main$CDD_specific_monthmean/Main$CDD_historical_monthmean
Main$f_CDD[Main$CDD_historical_monthmean == 0]   <- 10
```

```
Main$f_HDD[Main$f_CDD > 10]                                    <- 10
Main$f_CDD[Main$CDD_specific_monthmean == 0]     <- 0.1
Main$f_HDD[Main$f_CDD < 0.1]                                  <- 0.1


Main$f_dailyCDD <- Main$CDD_26C*(monthDays(Main$Time))/Main$CDD_historical
    _monthmean
Main$f_dailyCDD[Main$CDD_historical_monthmean == 0]  <- 4
Main$f_dailyCDD[Main$f_dailyCDD > 4]                            <- 4
Main$f_dailyCDD[Main$CDD_26C == 0]                            <- 0.25
Main$f_dailyCDD[Main$f_dailyCDD < 0.25]                       <- 0.25

#
    ##############################################################################


#create a file with time step = days

Time_1 = "2017-03-25"
Hour_1 = "00.00"
Time_2 = "2017-10-31"
Hour_2 = "23.00"
start_time <- as.POSIXct(paste(Time_1,Hour_1,sep=" "),format="%Y-%m-%d %H
    .%M")
end_time   <- as.POSIXct(paste(Time_2,Hour_2,sep=" "),format="%Y-%m-%d %H
    .%M")

Daily <- data.frame(Time=seq(from=start_time,to=end_time, by="day"))
Daily$Time <- floor_date(Daily$Time,unit="days")

#create the daily consumption column summing all the values
Daily$ConsH_m2  <- c(tapply(Main$ConsH_m2 , Main$TimeDay, FUN = sum))
Daily$ConsC_m2  <- c(tapply(Main$ConsC_m2 , Main$TimeDay, FUN = sum))

#add the PMV to the daily file
Daily$PMV   <- c(tapply(Main$PMV, Main$TimeDay, FUN = mean))


######################################
#creation of the factors:
```

```
# using the thermal comfort idex
Main$f_H1 <- c(as.numeric(Main$ConsH_m2 / Main$I_TC))

Main$f_C1 <- c(as.numeric(Main$ConsC_m2 / Main$I_TC))


#In the factor2 we put also the f_CDD:
Main$f_H2 <- Main$f_H1/Main$f_HDD

Main$f_C2 <- Main$f_C1/Main$f_CDD


#factor3: with the mean PPD
Main$f_H3                         <- Main$ConsH_m2
Main$f_H3[Main$PPD > 10] <- c(as.numeric(Main$ConsH_m2[Main$PPD > 10] *10)
    )

Main$f_C3                          <- Main$ConsC_m2
Main$f_C3[Main$PPD > 10] <- c(as.numeric(Main$ConsC_m2[Main$PPD > 10] *10)
    )


# factor4: using the sign of the PMV
Main$f_H4                         <- Main$ConsH_m2
Main$f_H4[Main$PPD > 10] <-
  c(as.numeric(Main$ConsH_m2[Main$PPD > 10 ] *10^(- sign(Main$PMV[Main$PPD
       > 10]))))

Main$f_C4                          <- Main$ConsC_m2
Main$f_C4[Main$PPD > 10] <-
  c(as.numeric(Main$ConsC_m2[Main$PPD > 10] *10^(+ sign(Main$PMV[Main$PPD
      > 10]))))


#add the factor1 to the daily file
Daily$f_H1      <- c(tapply(Main$f_H1, Main$TimeDay, FUN = sum))
Daily$f_C1      <- c(tapply(Main$f_C1, Main$TimeDay, FUN = sum))

#add the factor2 to the daily file
Daily$f_H2      <- c(tapply(Main$f_H2, Main$TimeDay, FUN = sum))
Daily$f_C2      <- c(tapply(Main$f_C2, Main$TimeDay, FUN = sum))
```

```
#add the factor3 to the daily file
Daily$f_H3       <- c(tapply(Main$f_H3, Main$TimeDay, FUN = sum))
Daily$f_C3       <- c(tapply(Main$f_C3, Main$TimeDay, FUN = sum))

#add the factor3_sign to the daily file
Daily$f_H4  <- c(tapply(Main$f_H4, Main$TimeDay, FUN = sum))
Daily$f_C4  <- c(tapply(Main$f_C4, Main$TimeDay, FUN = sum))



#---------------------------PLOTS-------------------------

ggplot(data=Daily, aes(x=Time)) +
  geom_line(aes(y = ConsH_m2,    colour = "FH [kWh/(m2 day)]"))      +
  geom_line(aes(y = ConsC_m2,    colour = "FC [kWh/(m2 day)]"))      +
  geom_line(aes(y = f_H1,     colour = "FH1 = FH/I_TC" ))          +
  geom_line(aes(y = f_C1,     colour = "FC1 = FC/I_TC" ))          +
  geom_line(aes(y = f_H2,     colour = "FH2 = FH1 / f_HDD"))        +
  geom_line(aes(y = f_C2,     colour = "FC2 = FC1 / f_CDD"))        +
  theme(legend.position = c(0.8,0.8))


ggplot(data=Daily, aes(x=Time)) +
  geom_line(aes(y = ConsH_m2,       colour = "FH [kWh/(m2 day)]"))
                          +
  geom_line(aes(y = ConsC_m2,       colour = "FC [kWh/(m2 day)]"))
                          +
  geom_line(aes(y = f_H3,           colour = "FH3 = FH*10, se meanPPD>10"
      ))          +
  geom_line(aes(y = f_C3,           colour = "FC3 = FC*10, se meanPPD>10"
      ))          +
  geom_line(aes(y = f_H4,           colour = "FH4=FH*10^(-sgn(PMV)), se
      meanPPD>20")) +
  geom_line(aes(y = f_C4,           colour = "FC4=FC*10^(+sgn(PMV)), se
      meanPPD>20")) +
  theme(legend.position = c(0.8,0.8))


ggplot(data=Daily, aes(x=Time)) +
  geom_line(aes(y = ConsH_m2,       colour = "FH [kWh/(m2 day)]"))
```

```
                       +
geom_line(aes(y = ConsC_m2,       colour = "FC [kWh/(m2 day)]"))
                       +
geom_line(aes(y = f_H1,           colour = "FH1 = FH/I_TC" ))
                          +
geom_line(aes(y = f_C1,           colour = "FC1 = FC/I_TC" ))
                          +
geom_line(aes(y = f_H3,           colour = "FH3 = FH*10, se meanPPD>10"
    ))          +
geom_line(aes(y = f_C3,           colour = "FC3 = FC*10, se meanPPD>10"
    ))          +
theme(legend.position = c(0.8,0.8))
```